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NESC GN&C TDT Best Practices: Design Requirements for Satisfactory Handling Qualities of a Piloted Spacecraft

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Cornelius J. Dennehy

John Osborn-Hoff

May 19, 2022

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Dr. John Osborn-Hoff

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Dr. Cynthia H. Null

Foreword

It should come as no surprise to the reader that an unprecedented level of piloted spacecraft system development is taking place at NASA and with the Agency's Commercial Crew Program (CCP) industry partners. NASA's Orion spacecraft will soon fly its inaugural mission as a critical part of the Agency's Artemis Program to build a sustainable presence on the lunar surface and prepare us to move on to Mars in the near future. The SpaceX Dragon-2 spacecraft is successfully docking with the International Space Station (ISS), while Boeing is developing its CTS-100 spacecraft that will also take our astronauts to the ISS. In addition, NASA's Human Landing System (HLS) Program has the goal of landing humans on the Moon's surface. This new generation of spacecraft and human landers has sparked a renewed interest in piloted spacecraft handling qualities.

Cooper and Harper, who decades ago pioneered the use of pilot ratings for the evaluation of aircraft handling qualities, have defined these as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role." The same qualities apply to manual flight operations (i.e., "piloting") of spacecraft. The term "spacecraft handling qualities" captures the multi-disciplinary aspects of analyzing and characterizing the ease and precision with which a pilot can perform challenging functions, such as proximity operations, docking, and lunar/planetary landing. Flight vehicle handling qualities depend upon numerous interrelated factors, such as vehicle flight control system response, guidance cues, and inceptors.

Defining measurable and predictable spacecraft handling qualities has been a concern since the beginning of crewed spaceflight decades ago. A lack of sufficient understanding of spacecraft handling qualities can lead to increased crew training requirements, additional pilot in-flight mental workload, undesirable flight control system interactions, and an inability to perform the mission/task. Unsafe, high-risk vehicle operations can result from poor handling qualities. Spacecraft handling qualities apply to both nominal and emergency operations. Manual flight control capabilities, if designed with handling in mind, will serve to make a spacecraft fly more robustly in the face of equipment failures, such as attitude control thruster failures.

In my view, the requirements for spacecraft handling qualities must be an integral element of the guidance, navigation & control (GN&C) systems engineering process for a piloted spacecraft. Ideally, specific vehicle attributes, defined early in the design and development process, will make handling qualities as compatible as possible with human operations. The spacecraft GN&C team, along with other engineering disciplines, must balance analysis of automated flight control modes/tasks with in-depth examination and testing of allowable and appropriate pilot inputs, based on offline pilot models and human-in-the-loop simulations. Provisions for understanding, accommodating, and verifying spacecraft handling qualities should be incorporated directly into the spacecraft flight control system's design, not considered as an afterthought. This will be a challenge for the GN&C community of practice, because no established spacecraft handling qualities design standards exist.

All this points to the critical need for GN&C engineers to have easy access to a set of requirements that will enable a new generation of piloted spacecraft to be designed specifically for compatibility with human operation. This is why I am so very pleased to introduce Dr. John Osborn-Hoff's doctoral dissertation, "Requirements for Satisfactory Handling Qualities of Manned Spacecraft." In his thesis, Dr. Osborn-Hoff, a member of the NASA Engineering &

Safety Center (NESC) GN&C Technical Discipline Team (TDT), has formulated a proposed set of concise design requirements for crewed spacecraft, which yield satisfactory handling qualities when the pilot is performing manual flight control. I believe spacecraft GN&C practitioners will find the research Dr. Osborn-Hoff describes to be insightful and of practical value in their work designing manual operated flight control systems for NASA's future human spaceflight missions. I believe this NASA Technical Publication (TP) report will make a strong contribution to our GN&C community of practice and provide a referenceable source for defining spacecraft handling quality requirements.

This paper is organized into four parts:

1. This foreword, explaining the need for spacecraft handling qualities design requirements.
2. Dr. Osborn-Hoff's notes on his research.
3. A short set of high-level presentation charts, introducing the spacecraft handling qualities problem and providing an Apollo 9 docking case study. In addition, these charts will describe the handling qualities design requirements development methodology formulated by Dr. Osborn-Hoff, along with an example design requirement.
4. Dr. Osborn-Hoff's complete dissertation.

One last observation I'd like to make here is that while spacecraft GN&C technology trends are clearly moving toward onboard highly automated or even fully autonomous flight control systems, the expectation is that crewed spacecraft will always have some form of manual flight control available to pilots. To paraphrase Dr. Osborn-Hoff, even with today's extremely automated and autonomous spacecraft, there is a critical and relevant need to design manual flight control modes with satisfactory handling qualities for each operational function.

As the NASA Technical Fellow for GN&C, I urge the reader to invest the time to digest and consider how the information presented here will influence your own work developing piloted spacecraft flight control systems. The creation and wide dissemination of this report is consistent with the NESC's commitment to engineering excellence: i.e., capturing and passing along to NASA's next generation of engineers the experiences, lessons learned, and best practices emerging from the collective professional experiences of spacecraft handling quality subject matter experts. I believe this report will not only provide relevant guidance for early-career GN&C engineers who may have limited on-the-job experience, but also serve as a useful technical reference for more experienced GN&C engineers. Moreover, this report could provide valuable information and insights for spacecraft systems engineers and project managers.

Both Dr. Osborn-Hoff and I sincerely welcome your feedback on this report.

Cornelius J. Dennehy
NASA Technical Fellow for GN&C
May 2022

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Notes on Requirements for Satisfactory Handling Qualities of Manned Spacecraft

The bulk of this publication consists of a slightly expanded and lightly edited version of my doctoral dissertation, completed in the spring of 2018. The research contained within was substantially funded by the National Aeronautics and Space Administration (NASA) over many years while I was a civil servant in the employ of that organization at the Johnson Space Center. The original intent at the start of the project was to publish, simultaneously, my academic dissertation and a substantially similar NASA report, with the goal of making the information within widely available to the manned spacecraft engineering community.

Unfortunately, due to complicated circumstances, the originally planned NASA publication did not occur. This meant that the results of this NASA funded research remained largely unavailable to the engineering community. This is why I am extraordinarily pleased to have worked with Cornelius (Neil) Dennehy, the NASA GN&C Technical Fellow, and the NASA Engineering and Safety Center (NESC), to finally make the work available in the form of this publication.

Reviewing the dissertation four years after having completed it, what stands out as perhaps the most significant contribution is the framework for thinking about spacecraft manual control and handling qualities in general. Specifically, the definition of various control modes, the decomposition of spaceflight into a small number of regimes, and the notion of context consisting of the combination of a manual control mode and spaceflight regime. Having made that conceptual leap, it becomes relatively straightforward to consider what dynamic characteristics significantly influence handling qualities within each context.

A number of shortcomings in the research are also very apparent,[1] and these strongly suggest avenues for future research.

First, and most obvious, human-in-the-loop tests need to be performed using qualified pilots and a simulator that can be reconfigured to evaluate handling qualities associated with changes in various design parameters. The alternative approach taken in the dissertation, modeling historic spacecraft and interpreting contemporary accounts to determine whether handling was satisfactory, was used due to lack of resources for actual pilot evaluations. This technique yielded what I believe to be reasonable first estimates of design parameter critical values, but actual pilot evaluations would be far more authoritative.

Second, that human-in-the-loop simulator testing needs to include variations in control system lag. Because lag in historic vehicles was essentially impossible to evaluate, the results stated in the dissertation should be taken as assuming the associated control system lag is small enough to not significantly impact handling qualities. Ironically, manual control lag in spacecraft seems to be getting worse with increasing computer power. Recent spacecraft have many layers of avionics between inceptor and effector, many of which can be thought of as special-purpose computers running embedded software. And the primary flight software itself is now tasked with increasingly sophisticated automation, fault management, and control algorithms. The author is aware of at least one modern spacecraft that has encountered a handling qualities problem specifically due to control system lag. Available information to guide spacecraft designers in this

[1] As are, unfortunately, many typographical errors. I beg the reader's forgiveness.

area is somewhat minimal. Military Standard 8785C (Anonymous, 1980) states that Cooper-Harper Level 1, 2, and 3 handling qualities (for airplanes) have allowable response delay of 0.10, 0.20, and 0.25 seconds respectively. However, a more recent report (Smith & Sarrafian, 1986) suggests that allowable delay (for aircraft) is more complicated and appears to be a function of many factors, including response shape and the nature of the piloting task. Namely, low-precision low-stress tasks likely tolerate control system lag better than high-precision high-stress tasks. For spacecraft, this suggests that manual control of burns during powered flight, especially under high acceleration, docking, atmospheric entry, and powered lift landing all likely have less tolerance for control system lag than coasting flight attitude control. The results of an effective human-in-the-loop study would likely be in the form of a two-dimensional envelope for each manual control context showing the region of control authority and control system lag intersection in which handling qualities are satisfactory.

Finally, with only a single historic vehicle to reference, the dissertation is limited to providing only a summary of the Apollo Lunar Module design characteristics. With interest in planetary exploration growing, there is opportunity to reexamine manual control of powered lift landing in light of new control schemes and, of course, allowable control system lag.

It is my sincere hope that, despite its limitations, this report proves useful to the spacecraft engineering community and inspires future work in the area of spacecraft manual control and handling qualities.

John Osborn-Hoff
June 2022

Works Cited

1. Anonymous. (1980). Military Specification: Flying Qualities of Piloted Airplanes (MIL-F-8785C). United States Department of Defense.
2. Smith, R. E., & Sarrafian, S. K. (1986). Effect of Time Delay on Flying Qualities: An Update (TM-88264). National Aeronautics and Space Administration.

Overview Presentation

Publication of Design Requirements for Satisfactory Spacecraft Handling Qualities

Dr. John Osborn-Hoff
Member, NESC GN&C Technical Discipline Team
May 19, 2022

High-Level Summary

- NASA JSC supported research, through a graduate fellowship and other resources, into determining design requirements that yield satisfactory handling qualities for spacecraft
  - Initial plan was to publish results simultaneously as both Ph.D. dissertation and NASA JSC technical report
  - Research successful, but no publication occurred
    - Dissertation on publication hold pending Export Control review
    - NASA JSC publication didn't happen due to exit from civil service
- Results currently unavailable to both NASA and industry engineering communities
- New plan is to publish results as NASA Technical Publication (TP)
  - Consider this as a GNC TDT knowledge capture product
- Today: Asking for board approval to move ahead with plan to publish NASA TP document

Current State: NASA-sponsored research exists but is in publication limbo.
Objective: Initiate development of NASA TP document to get research published.

1

Contents

- How This Happened
  - Introduction and Background
  - The Publication Problem
- Overview of Research
  - The Problem Being Solved
  - Solution Approach
  - Case Study: Apollo 9 Docking
  - Example Design Requirement
  - Application of Research Results
- Proposed Publication Solution

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John Osborn: Background

- NASA JSC MOD/FOD Flight Controller
  - Space Shuttle, Space Station
- Exploration Vehicle GNC Development Engineering
  - Orion
  - SLS
  - SLS/Exploration Upper Stage
- Commercial Crew Program GNC Oversight
  - Boeing CST-100 independent piloting evaluation
- NESC GNC TDT Member

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The Publication Problem

- **NASA-supported research into spacecraft design for manual control with satisfactory handling qualities**
  - Graduate school fellowship and tuition
  - Simulator time, interviews, archives access
  - Work assignments and salary
- **Separated from NASA CS to finish Ph.D. dissertation**
  - Required to meet academic deadlines
  - Research essentially complete at separation
- **Graduation in Spring 2018**
  - Dissertation complete but on publication hold pending Export Control clearance
  - No NASA publication
  - Research results unavailable to NASA and engineering community

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Big-Picture Problem

- **NASA *Human-Rating Requirements for Space Systems* (NPR 8705.2C)**
  - Requirement (3.4.1) for manual control of flight path and attitude
  - Requirement (3.4.2) for satisfactory handling qualities
    - Defined as Cooper-Harper ratings of 1, 2, or 3 ("Level 1 Handling Qualities")
    - Verification is via human-in-the-loop testing with ratings assigned by pilots
- These performance requirements are inherited by individual programs (Orion, SLS, CCP, HLS, et cetera), but NASA has been unable to provide guidance on how to design a spacecraft that will achieve this performance when evaluated
  - Significant shortcoming compared to aircraft development
  - Each program attempts to solve its own case, not general solution

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Solution Approach (1/3)

- **Modeled on Robert Gilruth's approach to airplane handling**
  - *Requirements for Satisfactory Flying Qualities of Airplanes* (NACA Report 755, 1941)
  - Mapped measured aircraft dynamics to pilot feedback, organized by phase of flight
    - Approximately 16 aircraft used to gather data
    - Engineering judgment used to select most important design parameters
    - Pilot feedback used to determine critical values for those parameters
- **Challenges**
  - Spacecraft control modes vary widely
  - No funding!
  - No generic simulator

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Solution Approach (2/3)

Control Modes

- **Rotation**
  - Direct
  - Impulse
  - Proportional Rate
  - Discrete Rate
- **Translation**
  - Normal
  - Impulse

Spaceflight Regimes

- **Coasting Attitude Control**
- **Powered Flight with Reaction Control**
- **Powered Flight with Thrust Vector Control**
- **Docking**
- **Atmospheric Entry**
- **Powered Lift Landing**

Handling Context = Combination of Control Mode and Regime
Example: Docking with Impulse Translation, Entry with Proportional Rate
Note: Not all combinations are valid

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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)

Design Parameter: Numeric description of vehicle dynamic response to pilot input

Critical Value: Design parameter value at which handling qualities become unsatisfactory

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Solution Approach (3/3)

- **Model historic spacecraft to find vehicle dynamics**
  - Mercury, Gemini, Apollo CM/CSM, Apollo LM, Apollo Saturn, Shuttle, Shuttle MMU, Soyuz 7K-TM (ASTP)
- **Map dynamics with historic pilot feedback**
  - Post-mission debriefings, test reports, simulation studies, etc.
- **Shuttle simulator also used where appropriate**
  - Manual Thrust Vector Control Study
- **General philosophy**
  - Provide practical, easy-to-understand guidance to engineers
  - Go broad; provide best guesses and information across all areas
  - Assume subsequent work will refine answers with more detailed studies

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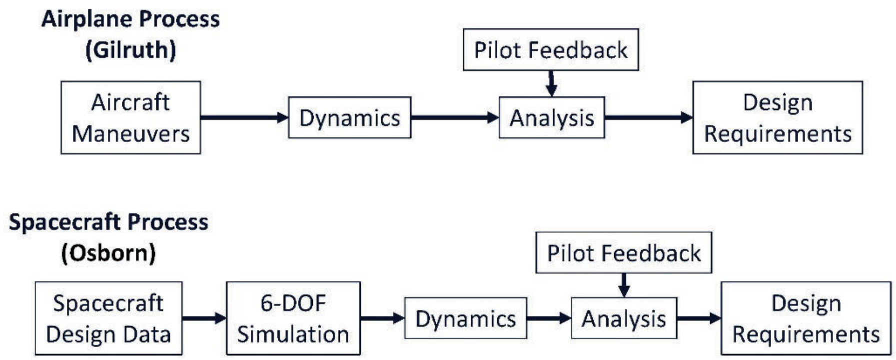
Requirements Derivation Process Overview



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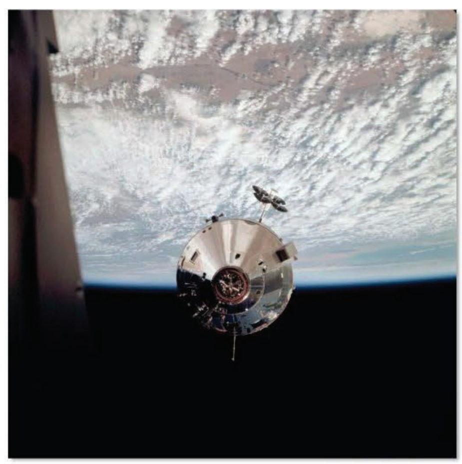
Case Study: Apollo 9 Docking



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CSM Active Docking Result

CSM Active Docking (Apollo 9 Debrief)

PLT: "Both the SCS and CMC DAP were good solid control systems, and the docking task was relatively easy as far as the aligning with the standoff cross and doing the actual contact."

Handling is Satisfactory

Note:

CSM	Command and Service Module
PLT	Pilot
SCS	Stability and Control System
CMC	Command Module Computer
DAP	Digital Auto-Pilot

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LM Active Docking Result

LM Active Docking (Apollo 9 Debrief)

CDR: "The light weight of the (LM) ascent stage made it so that I never really did stop the translation left/right and the horizontal components with respect to the docking probe and drogue. I had to thrust continually left and right and fore and aft, or whatever that other direction is, to keep myself within the boundaries of where I wanted to be prior to contact."

Handling is Unsatisfactory

Note:

LM	Lunar Module
CDR	Commander

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Example Requirement Derivation

Spaceflight Regime	Docking
Control Mode	Impulse Translation with Attitude Hold
Vehicles Analyzed	Gemini Apollo CSM (Heavy, Medium) Apollo 9 LM (Ascent Stage) Apollo CSM+DM (ASTP) Soyuz 7K-TM (ASTP) Shuttle (Medium)

Note: Non-Shuttle vehicles require manual hand controller pulsing to generate impulsive translation. Based upon Shuttle experience and a 1964 study, firing time is assumed to be 100 msec.

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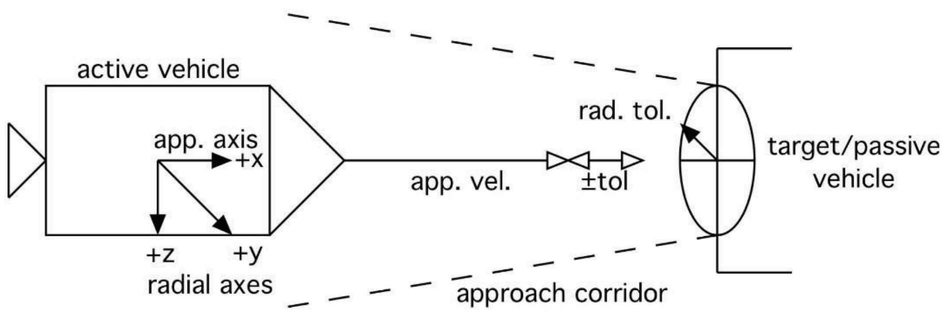
Docking Geometry



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Radial Position Control Authority Parameter and Analysis

$$k_{dri}\ (1/s) = \frac{\text{Minimum Radial Impulse (ft/s)}}{\text{Radial Misalignment Tolerance (ft)}}$$

Parameter is generic across spacecraft designs and defined such that numeric value increases with increased control authority.

Active Vehicle	Passive Vehicle	Parameter k_{dri} (1/s)	Handling (From Pilot Feedback)
Apollo CSM (Heavy)	Apollo LM	0.017	Satisfactory
Gemini	Agena	0.04	Satisfactory
Apollo 9 LM	Apollo CSM	0.065	Unsatisfactory but trainable
Shuttle	ISS	0.068	Unsatisfactory but trainable

Relevant Subset of Analysis Results

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Radial Position Control Authority Estimated Requirement

$$k_{dri}\ (1/s) = \frac{\text{Minimum Radial Impulse (ft/s)}}{\text{Radial Misalignment Tolerance (ft)}}$$

Radial Position Control Authority Parameter k_{dri} (1/s)	**Handling Quality** (Estimated)
$k_{dri} < 0.01$	Unsatisfactory
$0.01 < k_{dri} < 0.05$	Satisfactory
$0.05 < k_{dri} < 0.07$	Unsatisfactory but controllable with training
$k_{dri} > 0.07$	Unsatisfactory

Summary estimated requirement for spacecraft designers.
Other requirements derived similarly.

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Biomechanical Interface Guide

Guidance Provided for Human-Vehicle Interaction
- "Biomechanical Interface"
- Sampling/Update Rates
- Sign and Euler Sequence Conventions
- Torque/Force Curves
- Mode Selection

Flight Instruments
- Attitude Direction Indicator (ADI)
- Incremental Velocity Indicator (IVI)

Controllers (Inceptors)
- Rotational Hand Controller (RHC)
- Translational Hand Controller (THC)

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Original Key Contributions (1/2)

Spacecraft Manual Control Framework
- Handling context = regime and control mode
- Proposed nomenclature standardization

Definition of Design Parameters
- Generic (non-vehicle specific) parameters for dynamic characteristics that significantly affect handling
- Example: k_{dri} (docking radial impulse)

Estimation of Critical Values
- Parameter values that envelope satisfactory handling

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Original Key Contributions (2/2)

- **Compilation of design guidance for human-vehicle interaction (biomechanical interface)**
  - Cockpit displays (ADI, IVI)
  - Hand controllers (RHC, THC)
- **Summary design reference data for historic space vehicles**
- **Comprehensive bibliography of relevant papers, reports, and documents**

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Applications

- **Orion CSM**
  - Lockheed-Martin evaluation to determine if Orion meets proposed requirements for satisfactory handling qualities
  - Non-linear RHC shaping for better control during OME burns
- **SLS Exploration Upper Stage (EUS)**
  - SLS project currently tracking compliance with control authority design requirement to show high likelihood of satisfactory handling
  - Design changed post PDR to use both RCS strings for more control authority
- **Human Landing System (HLS)**
  - Collaboration agreement with Blue Federation
  - Multiple design inputs for manual control and handling qualities
- **NESC Academy GNC Webcast**
  - Seminar Webcast (April 7, 2021)
  - *Spacecraft Design for Manual Control*

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Need for Publication

- **Represents NASA-sponsored research**
  - Should be available for use by NASA and wider engineering community
- **Multiple manned spacecraft known to be under development**
  - Industry need for design guidance in manual control and handling qualities

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Requirements for Satisfactory Handling Qualities of Manned Spacecraft

John Osborn-Hoff

June 2018

Abstract

This document describes work to determine a proposed set of concise design requirements for manned spacecraft to yield satisfactory handling qualities when the pilot is performing manual control. This is done primary via the analysis of various historic spacecraft. Partial requirements verification is performed via the creation of a simulated pilot used to determine limits of satisfactory vehicle performance. Partial requirements validation is performed via example conceptual design of a spacecraft that is compliant with all relevant proposed requirements.

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Chapter 1

Introduction

> The things to do are: the things that need doing, that you see need to be done, and that no one else seems to see need to be done.
>
> *R. Buckminster Fuller*

1.1 Motivation and Goal

Vehicles such as bicycles, automobiles, and aircraft all exhibit dynamic qualities and considerable work over more than a century has focused on how to design them to be compatible with human operation. In other words, a large body of engineering knowledge exists on what dynamic characteristics those vehicles must exhibit in order to have satisfactory handling qualities. (Historically, with regards to aircraft, the term "flying qualities" has also been used.) For example, an aeronautical engineer, asked to design a small general aviation airplane, has a well-defined set of design requirements to follow. The resulting aircraft, when evaluated by a test pilot, will likely have only minor handling deficiencies.

The situation is different for spacecraft. Review of historic documents readily shows that spacecraft handling qualities have been a concern since the beginning of manned spaceflight over half a century ago. However, each spacecraft development program has focused on ensuring that the specific vehicle being designed has satisfactory handling qualities rather than solving the problem generally. While this is understandable from the standpoint of a program manager trying to complete a project within allowable budget and schedule, it has also created a long-term problem. Unlike the happy aeronautical engineer mentioned previously, each spacecraft designer must start from a position of ignorance with regards to how well a pilot can control his proposed vehicle.

This situation has caused problems. For example, a large research project was undertaken to ensure that the Apollo Lunar Module (LM) had satisfactory handling qualities during the final approach and lunar landing [98]. This project included the design, construction, and operation of an entire new aircraft, the Lunar Landing Research Vehicle (LLRV). However, the LM had such poor handling qualities when used as an active vehicle during docking [100] that, for future missions, it was operationally constrained to be the passive vehicle for docking except for contingency operations.

More recently, the author has flown simulations of several spacecraft under development that had significant handling problems. A common theme with these vehicles has been that they perform acceptably under automatic control but have insufficient control authority for human operation. In other words, the sense of a human pilot is that the vehicles take too long to respond to control inputs. Unfortunately, this insight tends to come late in the development process. The design will have had to mature sufficiently that a reasonably accurate simulator can be built. A general rule of system engineering and project management is that design changes become increasingly more expensive as time goes on. Thus, if we rely on this methodology, and handling defects are discovered in simulation, fixes are very expensive. Again in the author's experience the usual result is that the core vehicle is too far along in development to change and attempts to fix the problem usually focus on things like more sophisticated cockpit displays to help the pilot, extensive training to allow pilots to operate despite the handling deficiency, and so on. A far better option is to specify and design the vehicle from the beginning to be compatible with human operation.

The primary goal of this research project is to develop a set of proposed design requirements for manned spacecraft to yield satisfactory handling qualities. Such a set of requirements will enable new spacecraft to be designed specifically for compatibility with human operation.

1.2 Manual Control in the Modern Era

Space Shuttle operational experience has shown that manual control is rarely exercised. On a typical mission to the International Space Station manual control was used only for calibration of optical sights, small translational maneuvers during rendezvous, proximity operations, and docking, and during subsonic atmospheric flight during approach and landing. The vast majority of a nominal mission was conducted under fully automatic control. Pilot tasks largely consisted of system management, autopilot configuration, and monitoring. Vehicles currently under development are expected to be even more automated. An argument could be made, therefore, that manual control is not important and can, in fact, be readily eliminated from spacecraft system design as needlessly complicating.

In fact, modern spacecraft are extremely complicated vehicles with subsystems that interact in ways that are hard to foresee during the design phase. The Space Shuttle, for example, required that manual control be exercised in a very large number of malfunction scenarios. Historically, new flight techniques to increase safety or capability have required manual control when initially formulated and are only automated when fully proven to be useful and effective during simulated and actual operations. That process has historically taken a number of years and, in many cases, has never been completed. Manual control therefore plays a role in making the spacecraft more robust in the face of failures and the desire for ever more performance and mission capability.

Manual control also becomes relevant in severe malfunction scenarios. The author has personally been involved with work involving scenarios in which the automated control systems of a modern spacecraft have failed completely and the pilot is left with nothing but direct control of jet thrusters, a window, and a stop watch for doing maneuvers. In these situations piloting a modern, highly automated spacecraft becomes very much like piloting the fairly primitive, primarily manually controlled spacecraft of the 1960s.

Finally, future commercial manned spacecraft are likely to be developed under significant financial and schedule pressure. One strategy in that environment is to minimize vehicle automation, thereby saving the associated development costs, and relying on piloting skills for mission success.

In short, design for manual control using minimal automation continues to be relevant even with today's extremely automated vehicles. This situation is unlikely to change in the foreseeable future.

1.3 Prior Literature

The concept of writing a comprehensive set of design requirements for satisfactory fixed wing aircraft handling originated with Gilruth [71] in 1941. This report, appropriate to the publication date, is limited to relatively small propeller driven airplanes. Subsequent reports [28] [32] consider handling in the context of increasingly sophisticated aircraft. Other publications address rotary wing [2] and V/STOL [19] aircraft. Notably lacking is a comprehensive guide to designing manned spacecraft for satisfactory handling, a gap this work is intended to begin filling.

Quantification of ease of handling has for several decades been done by reference to the Cooper-Harper scale [59] published in 1969. A more recent report by Bailey, et al [38] describes applicability of the scale to spacecraft handling and describes a number of studies in the field.

Existing spacecraft handling studies have for the most part addressed single aspects of manual control, typically evaluating a single spacecraft design for manual control. For example, manual control of the Gemini spacecraft during atmospheric entry was evaluated in a 1963 report by Patterson, Nassiff, and Brown [114]. A similar report published in 1964 by Wingrove, Stinnett, and Innis [144] describes manual control evaluation of the Apollo Command Module (CM) spacecraft during atmospheric entry. Other reports are broadly similar, evaluating specific aspects of the atmospheric entry problem. However, none of these reports attempt to describe a design envelope in which handling is expected to be satisfactory.

A large number of studies examine spacecraft docking. Gemini spacecraft docking was evaluated using a fixed-base simulator and reported on in in a 1966 report by Riley, Jaquet, Bardusch, and Deal [120]. Another report on Gemini docking, this time using a motion-based simulator, was written by Riley, Jaquet, Pennington, and Brissenden [122].

Docking of the Apollo Command and Service Module (CSM) to the Lunar Module (LM) was reported on in a 1966 report by Pennington, Hatch, and Driscoll [115]. The inverse problem, docking of the LM to the CSM, was reported on in a 1967 report by Hatch, Pennington, and Cobb [76].

Again, as with atmospheric entry, numerous other reports exist and describe work done to evaluate particular aspects of the docking problem by none exist that attempt to describe a satisfactory design envelope expected to yield satisfactory handling.

In general, no existing literature addresses the problem of generalized spacecraft design for satisfactory handling for specific spaceflight regimes. These regimes include atmospheric entry and docking, as mentioned previously. In contrast, this work defines a set of proposed design requirements for all spaceflight regimes that are expected to yield satisfactory handling. In this way the work is inspired by Gilruth's original aircraft report [71] from nearly 80 years ago. The goal is to be broad, rather than deep, with an emphasis on the practical rather than theoretical. As with Gilruth, the expectation is that this work is merely a starting point for future research.

1.4 Methodology

Development of these design requirements will occur in three phases: Determination of requirements via the analysis of historic spacecraft, Partial verification of requirements via simulated pilot, and Partial validation of requirements via conceptual design of a compliant spacecraft.

1.4.1 Determination of Requirements

To determine requirements a taxonomy of manual control is first developed. This consists of a defined set of control system modes for spacecraft operation along with a defined set of spaceflight regimes. These spaceflight regimes are conceptually similar to the phases of flight for airplanes such as take-off, climb, cruise, turn, approach, and landing. A spaceflight mission consists of operations within and transitions between these regimes. Requirements are then defined to have applicability within the context of the intersection of a control system mode and spaceflight regime. As an example, some requirements would be applicable during docking while other requirements would be applicable during atmospheric entry. Not all combinations of control system mode and spaceflight regime are valid.

Within each valid context a set of design parameters are then defined. These parameters describe physical or dynamic characteristics of the vehicle that affect handling in some way. The parameters are generic in that they are not tied to the design of a specific vehicle. Thus, for example, a parameter may describe angular acceleration as opposed to thrust. In this case the pilot is assumed to be responding to angular acceleration which, in turn, is a product of thrust, vehicle layout, and mass properties.

Then, for each parameter, estimates for one or more critical values are determined. These critical values are points at which handling appears to transition between satisfactory and unsatisfactory. For example, a parameter describing angular acceleration may have two critical values describing a range in which handling is satisfactory.

Determination of critical values is done via the analysis of historic spacecraft. A six degree of freedom simulator is used to find the dynamic characteristics of vehicles and, hence, the values of the previously defined design parameters. Sources such as post-flight crew debriefings are then used to describe specific values as either satisfactory or unsatisfactory. These results are tabulated to determine the critical values at which handling transitions between satisfactory and unsatisfactory.

A similar process is used to describe requirements for biomechanical interfaces such as hand controllers and flight instruments.

1.4.2 Partial Verification of Requirements

Given sufficient institutional support the next step would be to verify these critical values with a cadre of test pilots and a reconfigurable simulator. Lacking that, a partial verification is performed using a software model of a human pilot.

As part of the determination of requirements, results from a human-in-the-loop test using the Space Shuttle mission simulator were used to determine critical values for the regime of powered flight with thrust vector control. Ancillary data from that test is used to model a human pilot.

To determine if the simulated pilot acts like a human pilot, its performance is compared directly to human pilot performance from the human-in-the-loop test. Both pilots, human and simulation, should have similar limits for satisfactory handling qualities.

Once performance comparable to a human is demonstrated, the simulated pilot is used to evaluate limits of satisfactory handling where no human-in-the-loop data are available. With the available data this approach is viable in two other spaceflight regimes: powered flight with reaction control and coasting flight attitude control.

Partial verification of requirements is performed by showing that the performance limitations of the simulated pilot are reached at approximately the critical values found for design parameters via analysis of historic spacecraft.

1.4.3 Partial Validation of Requirements

Finally, validity of the proposed requirements is partially demonstrated via the conceptual design of a spacecraft that is fully compliant with all relevant requirements. This is effectively a proof by example that the proposed requirement set is not self-contradictory. In other words, we show that satisfying the requirements in one spaceflight regime do not make it impossible to satisfy the requirements of another spaceflight regime. A self-contradictory requirement set would tend to indicate either a lack of validity or, less likely, that designing a spacecraft to have satisfactory handling qualities across all spaceflight regimes is impossible.

The chosen spacecraft is a four person taxi designed to transport crew to and from the International Space Station. This vehicle will be operable across all defined spaceflight regimes except for powered lift landing. Generally speaking, designing a vehicle capable of both lunar landing and atmospheric entry is very, very difficult due to the conflicting nature of the mission performance requirements. Thus these two spaceflight regimes are assumed to be incompatible. Since designing a second spacecraft is beyond the scope of this work, and since the capability for atmospheric entry is far more common than powered lift landing, the former is chosen for the conceptual design.

1.5 A Guide to Chapters

The following information is provided to assist the reader with finding specific information in the text.

Chapter 1, *Introduction*, contains this overview.

Chapter 2, *Spaceflight Control Modes and Flight Regimes*, defines the taxonomy used to divide spaceflight into contexts for specific requirements. An example mission decomposition is provided for further clarification.

Chapter 3, *Mathematical Preliminaries*, documents the math associated with computing spacecraft mass properties and forming six degree of freedom simulation.

Chapter 4, *Historic Spacecraft Analysis*, documents the process of defining requirement design parameters and determining critical values associated with spacecraft dynamics by spaceflight regime and control system mode.

Chapter 5, *Biomechanical Interfaces*, documents requirements and guidelines associated with spacecraft hand controllers and flight instruments.

Chapter 6, *Human-in-the-Loop Testing*, documents testing performed in the Shuttle Mission Simulator used in the development of requirements for powered flight with thrust vector control.

Chapter 7, *Simulation of Human Pilot Performance*, documents the creation of the software model of a human spacecraft pilot and associated use to partially verify selected design requirements.

Chapter 8, *Example Design of a Compliant Spacecraft*, documents the design process and methodology of a requirements compliant spacecraft thereby providing partial requirements validation.

Chapter 9, *Conclusions*, provides summary conclusions for this research project.

Appendices A through H provide design and performance data for various historic spacecraft: Mercury, Gemini, Apollo CSM. Saturn S-IVB, Apollo LM, Soyuz 7K-TM, Space Shuttle, and Manned Maneuvering Unit.

Appendix I, *Pilot Performance Plots and Model Data*, provides reference data for human and simulated pilot performance discussed in Chapters 6 and 7.

Appendix J, *Historic Crew Debriefing Comments*, provides excerpts from historic post-flight crew debriefings that is used in Chapter 4 to analyze the performance of historic spacecraft.

Appendix K, *Glossary of Acronyms and Terminology*, provides a reference for acronyms and terminology used throughout this document.

Chapter 2

Spaceflight Control Modes and Flight Regimes

2.1 Chapter Overview

This chapter describes a taxonomy of spacecraft control modes and spaceflight regimes conceptually similar to aircraft phases of flight. These control modes exist for both rotation and translation. Subsequent chapters will address design requirements for satisfactory handling qualities in the context of a specified spaceflight regime and control mode. This chapter also describes hand controllers used for rotation and translation. Finally, for additional clarity, an example space mission is decomposed into spaceflight regimes.

2.2 Rotational Control Modes

Rotational control is typically performed using a 3-degree of freedom device known as a Rotational Hand Controller (RHC). The RHC is typically positioned for use by the crew member's right hand and is approximately aligned with vehicle body axes. It can be rotated in positive and negative directions about the roll, pitch, and yaw axes. To pitch the vehicle the pilot pushes the controller forward (-pitch) or pulls the controller aft towards himself (+pitch). To roll the pilot moves the controller to the right (+roll) or left (-roll). To yaw, the pilot twists the controller to the right (+yaw) or to the left (-yaw) similar to a motorcycle throttle. Springs are typically used to provide kinesthetic feedback and to hold the controller in a neutral position commonly known as “detent.” This name comes about because there is a noticable breakout torque required to move the controller out of the neutral position. In other words, an RHC is conceptually similar to a standard aircraft control stick except that yaw is controlled with a twisting motion of the hand instead of rudder pedals. A typical RHC is shown in Figure 2.1.

Consider a typical spacecraft that uses fixed thrust jet thrusters (“jets”) for attitude control. For simplicity, assume a single dedicated jet for each type of rotation for a total of six (positive and negative roll, pitch, and yaw). Each jet can be on or off but not throttled. Jets are fired electrically. Control modes answer the question of what happens when the pilot moves the RHC to command rotation.

The simplest possible system is one in which displacing the RHC in any axis commands the corresponding jet to fire for as long as the jet is held out of the neutral (“detent”) position. As a result, the spacecraft will perform angular acceleration for as long as the RHC is held out of detent.

Consider a simple pitch up maneuver. Assume the spacecraft starts with zero attitude rate and pilot desires to pitch up and stop at a new attitude. Using this control mode the pilot pulls back on the RHC, thereby causing the +pitch jet to fire, until the desired pitch rate is achieved. The pilot then returns the RHC to detent and spacecraft continues to pitch at a constant rate. When spacecraft approaches the desired attitude the pilot pushes the RHC forward, causing the -pitch jet to fire, and the spacecraft decelerates to a stop. When the pitch rate is zero the pilot must quickly return the RHC to detent to avoid further acceleration. With the RHC in detent the spacecraft will tend to drift in attitude due to small residual attitude rates. Thus periodic RHC inputs are required to keep the attitude within desired limits.

This type of control system is often known as *Direct* because it has historically been implemented by embedding switches within the RHC that, when closed, sent electrical power directly to the firing coils of the appropriate jets. Although this document, consistent with historic usage, uses the name *Direct*, the reader should be aware that this mode is also commonly known as *Acceleration* for obvious reasons.

Direct was implemented in very early spacecraft, X-15 and Mercury, but it rapidly became apparent that pilots would generally use it by rapidly moving the RHC in and out of detent to get a series of short pulses of thrust. This technique was adopted in an attempt to exercise fine attitude control. Engineers soon automated this manual technique. Moving the RHC out of

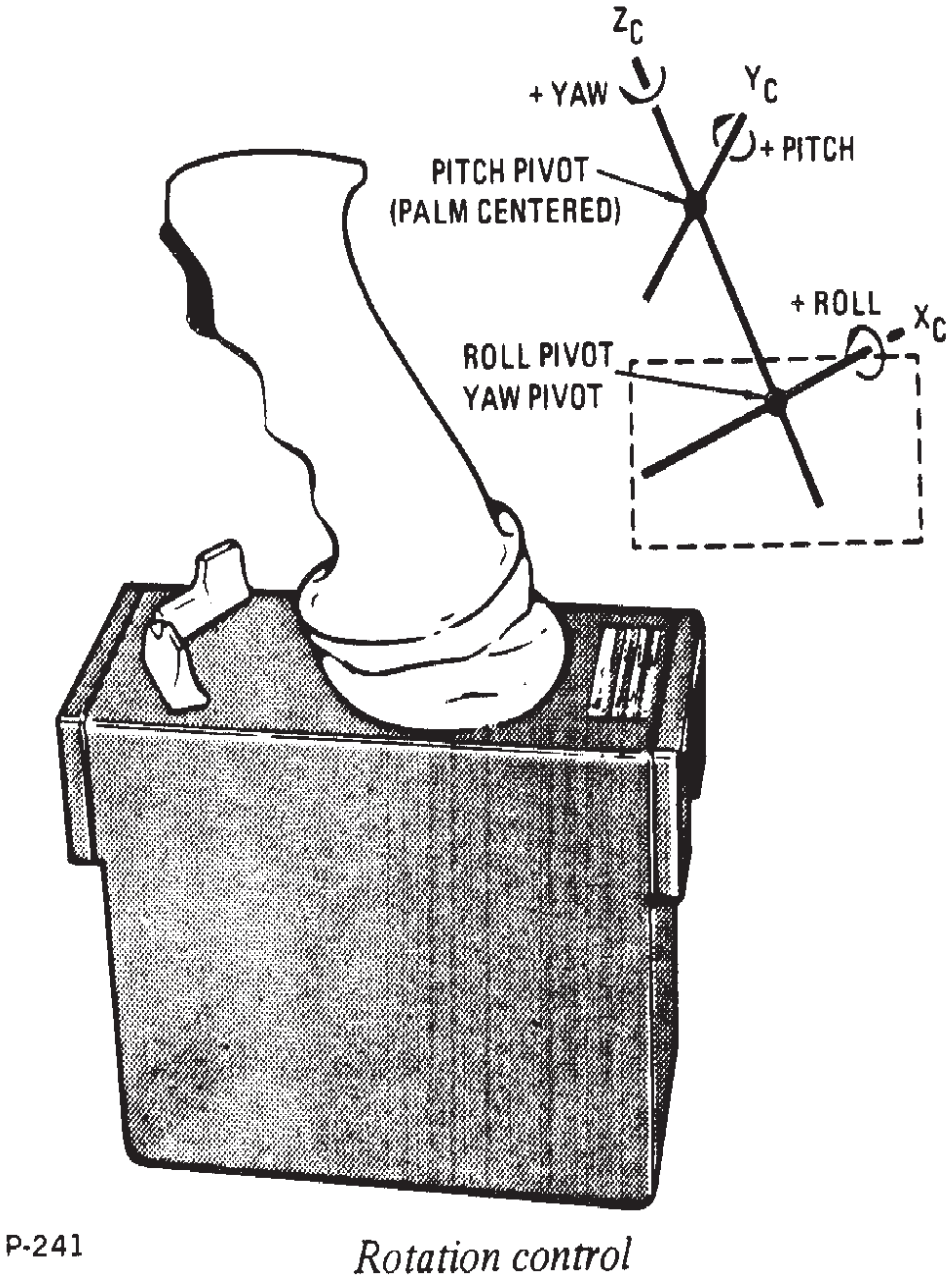

Figure 2.1: Apollo Rotational Hand Controller (RHC) [11]

detent would create a single, short burst of thrust from the appropriate jet. To fire again, the pilot would return the RHC to detent, thereby resetting the firing logic, and then displace it again. Automation allowed for much shorter bursts of thrust than could be commanded by a human physically moving the RHC and this control mode became known as *Minimum Impulse* or just *Impulse* for obvious reasons. This document uses the name *Impulse* in recognition of the fact that later spacecraft, such as the Space Shuttle, allow variable size rotational impulses under software control. *Impulse* was first implemented on the Gemini spacecraft.

To perform the previously described pitch maneuver using the *Impulse* control mode, the pilot pulls back on the RHC however many times as required to achieve the desired pitch rate returnin the RHC to detent after each pulse. When the spacecraft approaches the desired attitude the pilot pushes forward on the RHC the same number of times to decelerate to a stop. As with *Direct*, the spacecraft will tend to drift in attitude due to residual attitude rates.

In both *Direct* and *Impulse*, the pilot is controlling RCS jet firings in order to achieve desired attitude rates. It was recognized early in the space age that it should be easier to control rotation rate directly to manage attitude and that proved to be the case. A sensor is used to measure angular displacement of the RHC in each axis. This is interpreted by the control system as a commanded angular rate proportional to RHC displacement. This type of control system is widely known as *Proportional Rate*. Jets are automatically fired to eliminate the error between the RHC commanded atitude rate and the actual attitude rate. The RHC commanded rate includes zero if the RHC is in detent. Stopping an attitude maneuver is thus a simple matter of returning the RHC to the detent position.

To perform the previously described pitch maneuver using the *Proportional Rate* control mode the pilot simply pulls back on the RHC to command a +pitch rate. The control system commands jet to fire to achieve the commanded pitch rate. Once achieved, jets stop firing and spacecraft continues to rotate at the desired rate. The pilot continues to hold the RHC out of detent to command the rate. When the spacecraft approaches the desired attitude the pilot returns the RHC to detent, thereby commanding zero rotation rate, and the control system fires jets to decelerate and stop the rotation.

Proportional Rate is also suitable for thrust vector control of attitude. The pilot still commands an attitude rate proportional to RHC displacement but the control system changes the direction of the thrust vector to null the resulting attitude rate error.

Proportional Rate was first implemented on the Mercury spacecraft and is particularly useful for controlling the vehicle when a disturbing torque is present. This would tend to occur when, for example, the large translational thrust associated with the deorbit maneuver is not aligned through the spacecraft center of mass.

When properly designed, *Proportional Rate* is considered relatively easy to fly but it has the disadvantage of high propellant usage. To understand why, consider a pilot holding the RHC out of detent to command an attitude rate. It is very difficult to hold the controller perfectly still for a long period of time; a pilot's hand will naturally move back a forth a little bit. Unfortunately, each movement is interpreted by the spacecraft as a new rate command. An error between the current and commanded rate is computed and a jet is fired to eliminate the error. This regular firing of jets can use large quantities of propellant. Gemini pilots, especially, used this control mode only under specific circumstances in order to conserve the very limited available propellant.

A solution for this problem was implemented on the Space Shuttle for attitude control while in orbit. Rather than commanding a rate proportional to RHC displacement this new control mode commands only a single attitude rate for as long as the RHC is displaced away from detent. The pilot's hand can wiggle slightly but this has no effect upon the attitude rate and no propellant is wasted needlessly firing jets. This control mode is known as *Discrete Rate*.

These four rotational control modes (Direct, Impulse, Proportional Rate, and Discrete Rate) are sufficient for manual attitude control of spacecraft and are all analyzed in this document with respect to handling qualities. Other control modes are possible and several have been implemented. For example, Project Mercury implemented a control mode in which jet thrust, and hence angular acceleration, was proportional to the amount of RHC displacement. This was feasible due to the propellant used, decomposing hydrogen perioxide (H_2O_2). Throttling could be performed using a simple flow control valve to restrict propellant flowing across the catalyst bed. This control mode, which could be called *Proportional Acceleration*, has not been used since and is not analyzed here. A related system, implemented on the Apollo Lunar Module (LM), would pulse the RCS jets with increasing frequency proportional to RHC displacement. This could also be described as a Proportional Acceleration control mode. This design has also not been implemented since and is not analyzed here.

In summary, the rotational control modes are as follows:

Direct Continuous jet firing for as long as the RHC is displaced from neutral resulting in constant angular acceleration. Spacecraft drifts in attitude when RHC is neutralized.

Impulse Single impulsive jet firing per RHC displacement from neutral. RHC must be returned to neutral to reset firing logic. Spacecraft drifts in attitude when jet is not firing.

Proportional Rate Rotation rate is proportional to magnitude of RHC displacement away from neutral up to a maximum. Zero rate commanded when RHC is in neutral, effectively resulting in attitude hold.

Discrete Rate Rotation rate is a fixed value if RHC displaced away from neutral, zero otherwise. Attitude held when no rate commanded.

2.3 Translational Control Modes

Translational control is typically performed using a 3-degree of freedom device known as a Translational Hand Controller (THC). The THC is typically positioned for use by the left hand and is aligned with vehicle body axes. Pushing or pulling the THC along a particular axis commands translation along the corresponding body axis. Thus, pushing forward on the THC will usually command a +X translation, moving it to the left will command a -Y translation. Springs are normally used to provide kinesthetic feedback and to hold the controller in the neutral position also known as "detent."

The THC is a discrete device in that pushing or pulling it will close a switch commanding a translation to occur. Fractional displacement is usually not measured.

An example THC is shown in Figure 2.2. This particular THC, from the Apollo Command Module (CM), was also used to command certain abort actions via rotation of the handle. This function is separate from the topic of manual control and is not discussed further in this document.

Historically, the THC operated only in one mode. Displacing the THC would cause the appropriate translational jets to fire for as long as the THC

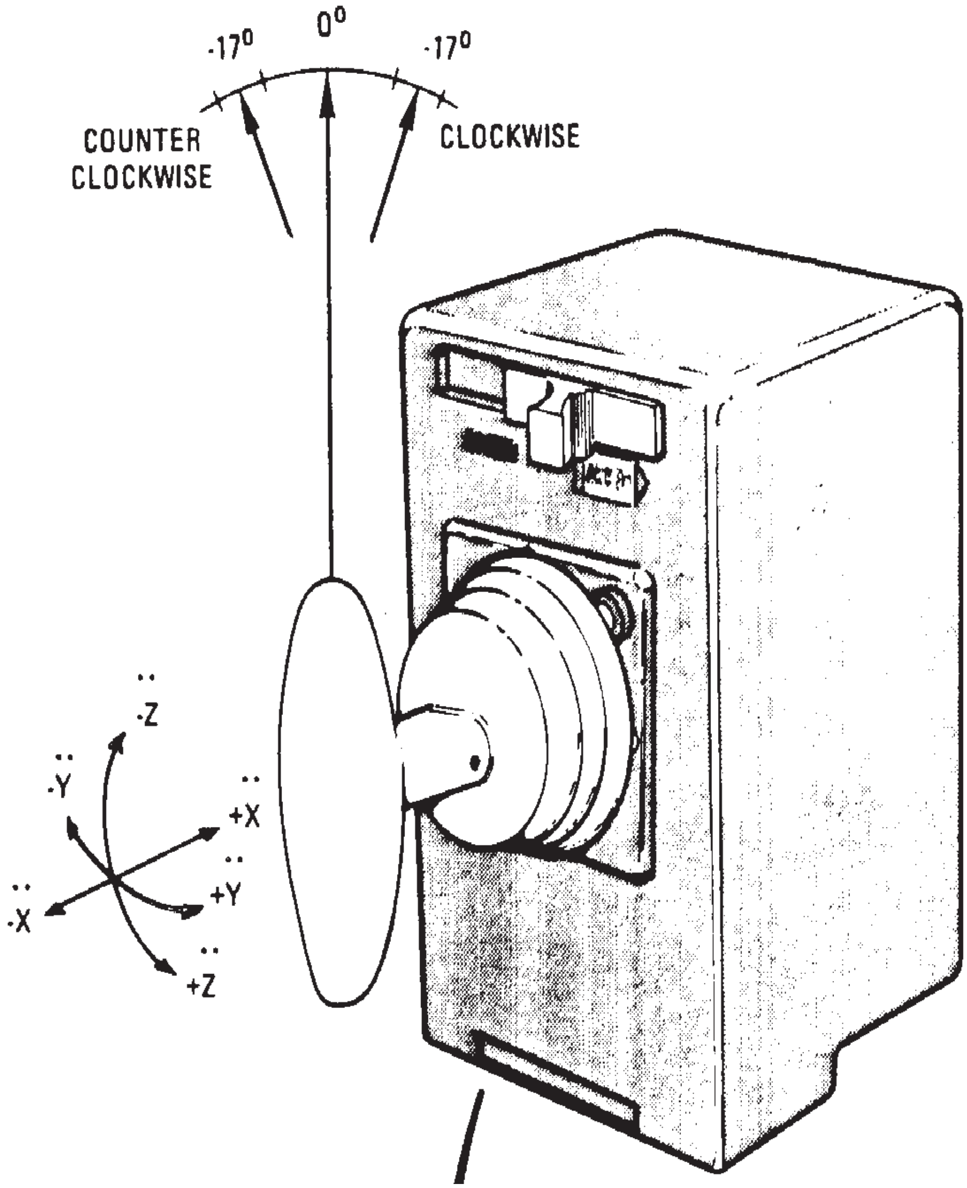

Figure 2.2: Apollo Translational Hand Controller (THC) [11]

was held out of detent. This behavior was used for the Gemini and Apollo spacecraft with success. The THC would be held out of detent for large translational maneuvers and manually pulsed for small maneuvers.

The Space Shuttle added an impulse firing mode similar to that used for rotational control. Displacing the THC when using this control mode resulted in a single, impulsive translational jet firing. The magnitude of the impulsive translational pulse is software selectable with the Space Shuttle and other vehicles currently under development. This mode naturally became known as *Impulse*. Retroactively, the previously unnamed default control mode became known as *Normal*.

In practice, *Normal* is used for relatively large translational maneuvers such as changing the spacecraft's orbit. In contrast, *Impulse* is used for precise maneuvering around another vehicle or during proximity operations and docking.

In summary, the translational control modes are as follows:

Normal Continuous jet firing for as long as the THC is displaced from neutral resulting in constant translational acceleration.

Impulse Single impulsive jet firing per THC displacement from neutral. THC must be returned to neutral to reset firing logic.

2.4 Spaceflight Regimes

It has long been recognized that characteristics that make for satisfactory airplane handling qualities vary depending upon phase of flight. Gilruth [71], for example, distinguishes between elevator control in steady flight and in landing. It follows that requirements for satisfactory handling of spacecraft may also vary depending upon what task the pilot is controlling the spacecraft to accomplish.

The following system of six spaceflight regimes was devised to encompass all the manual control tasks that a pilot and spacecraft could perform during any foreseeable mission. The word *regime* is used as something of a synonym to *phase*, as in "phase of flight," to emphasize the differences between aerodynamic and space flight.

2.4.1 Coasting Flight Attitude Control

In this spaceflight regime the spacecraft is maneuvered to desired attitudes or held in a single attitude. Such attitude maneuvering may take place in preparation for many reasons including preparation for a translational maneuver or to point the vehicle at an external target such as a star, the Earth, or the sun.

2.4.2 Powered Flight with Reaction Control

During this spaceflight regime the spacecraft is performing a translational maneuver of non-trivial duration. The translation engine(s) do not gimbal and will tend to create a perturbing moment unless the thrust vector passes directly through, or multiple thrust vectors are parallel to, the center of mass. However, since the center of mass is moving as the engine burns propellant, this in-trim condition is rare. Attitude control, including overcoming perturbance caused by translation, is performed using RCS jets.

2.4.3 Powered Flight with Thrust Vector Control

During this spaceflight regime the spacecraft is performing a translational maneuver of non-trivial duration. Attitude control is performed by gimbaling the translation engine to point the thrust vector away from the center of mass and create a moment. Gimbaling is done using a perpendicular pair of electromechnical or hydraulic actuators. A vehicle with a single gimbaling engine can control in pitch and yaw. Roll is controlled using the RCS jets. A vehicle with two or more gimbaling engines can create a roll moment and thus perform attitude control about all three axes.

An illustration of powered flight with thrust vector control, using a single gimbaling engine, is shown in Figure 2.3.

2.4.4 Proximity Operations and Docking

Proximity operations occur when two vehicles are sufficiently close that the active vehicle is maneuvering relative to and near the passive vehicle. This is conceptually similar to formation flight with aircraft. A typical purpose for proximity operations is to position the active spacecraft within the approach corridor for docking or to maneuver away from the passive vehicle

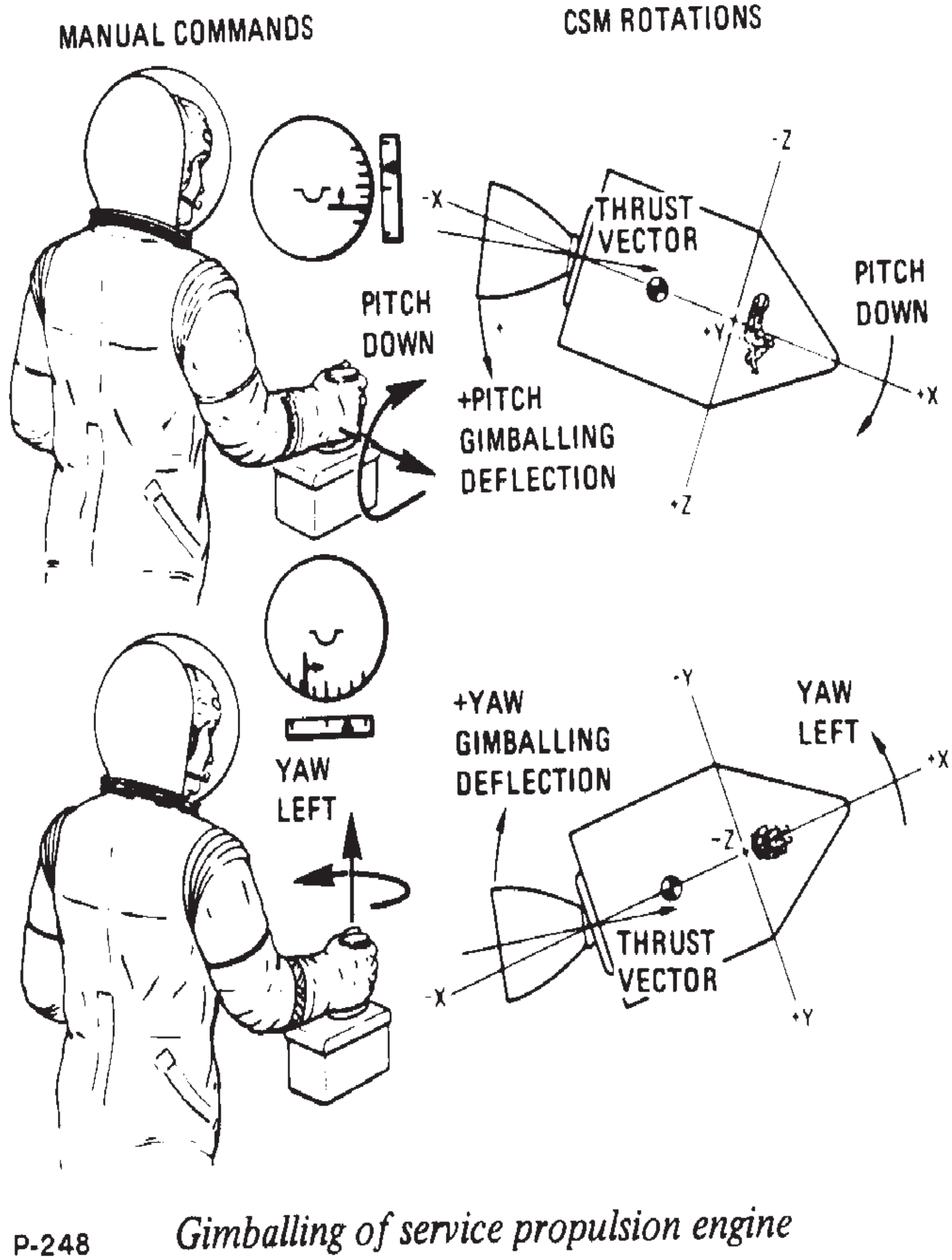

Figure 2.3: Apollo Manual Thrust Vector Control (TVC) [11]

for subsequent separation. Occasionally the active vehicle will station keep, maintaining a fixed position relative to the passive vehicle for an extended period of time.

2.4.5 Atmospheric Entry

During the atmospheric entry regime the spacecraft has entered the atmosphere and, as a result, is generating aerodynamic lift. The piloting task is to roll the spacecraft around the velocity vector thereby pointing the lift vector up or down and left or right. The vertical component of lift is used to raise the spacecraft into less dense atmosphere, extending gliding range, or lower it into more dense atmosphere, shortening gliding range. The horizontal component of lift, left or right, is used to turn the trajectory left or right. In this way a single degree of freedom, roll, is used to guide the spacecraft to the desired landing site.

2.4.6 Powered Lift Landing

In this regime, the spacecraft is approximately vertical (thrust vector pointing upwards) and performing a controlled descent to a planetary surface in vacuum or near vacuum. The spacecraft pitches and rolls to point the lift vector away from vertical and create a horizontal component of lift. The vertical component of lift is used to control the descent rate and the horiztonal component of lift is used to control horizontal translation. This is conceptually similar to helicopter flight except that a lander operating in a reduced gravity field such as the moon must pitch or roll more to create equivalent horizontal acceleration.

2.5 Example Mission Decomposition

To further illustrate the use of spaceflight regimes, we decompose a typical Apollo lunar mission.

2.5.1 Launch through Trans-Lunar Injection

After liftoff the Saturn V rocket has no manual control capability during first stage flight. (Manual control during the early part of an Earth launch is typically impossible due to the extremely small tolerances for aerodynamic side loads.) After second stage ignition the vehicle is largely exoatmospheric and manual control capability exists in the *powered flight with thrust vector control* regime from this point through orbit insertion. After engine cutoff the vehicle is in Earth orbit and manual control capability exists in the *free flight attitude control* regime. At ignition for the translunar injection burn we return to the *powered flight with thrust vector control* regime.

2.5.2 Transposition and Docking, Extraction, and Coast

After the translunar injection burn the Apollo Command and Service Module (CSM) separates from the Saturn launch vehicle third stage and Lunar Module (LM), maneuvers a hundred feet or so away, turns around, approaches, and docks with the LM housed within the third stage. This transposition and docking maneuver is performed in the *proximity operations and docking* regime.

Pyrotechnic bolts are then fired to separate the docked CSM/LM combined vehicle from the Saturn third stage. A brief separation maneuver is performed and the CSM/LM stack enters the *coasting flight attitude control* regime.

2.5.3 Mid-Course Maneuvers and Lunar Orbit Injection

During the coast to the moon, small translational maneuvers may need to be performed to adjust the trajectory. These may be performed via the RCS, in which case the vehicle is in the *powered flight with reaction control* regime, or with the large gimbaling Service Propulsion System (SPS) engine, in which case the vehicle is in the *powered flight with thrust vector control* regime.

To enter lunar orbit the spacecraft uses the SPS engine and enters the *powered flight with thrust vector control* regime for the Lunar Orbit Insert burn.

2.5.4 LM Separation, Landing, Ascent, and Rendezvous

The LM undocks from the CSM and both vehicles briefly fly in formation while in the *proximity operations and docking* regime.

After separation, the LM performs *coasting flight attitude control* before starting the descent. At Powered Descent Initiation (PDI) the LM enters the *powered flight with reaction control* regime to descend from orbit. (Note: The Apollo LM Descent Propulsion System (DPS) engine is gimbaled but the gimbal rate is very slow and the gimbal system is used to keep the thrust vector pointing through the center of mass as propellant is burned. This is known as keeping the engine "in trim.") During the final phases of descent the braking from orbital velocity is complete and the piloting task becomes performing the landing. During the landing maneuver the spacecraft is in the *powered lift landing* regime.

When the surface mission is complete the LM ascent stage separates from the descent stage and ascends into orbit using the Ascent Propulsion System (APS) engine. This engine is not gimbaled and therefore the vehicle is in the *powered flight with reaction control* regime during lunar ascent.

Once in orbit the spacecraft enters periods of *coasting flight attitude control* separated by translational burns using the RCS to rendezvous with the waiting Command and Service Module (CSM). These translational RCS burns are in the *powered flight with reaction control* regime.

At the end of the rendezvous the vehicles are in formation flight and docking is performed in the *proximity operations and docking* regimes.

2.5.5 Trans-Earth Injection

The Apollo CSM separates from the now-empty LM and performs the large Trans-Earth Injection (TEI) burn using the (gimbaling) SPS engine within the *powered flight with thrust vector control* regime.

Mid-course maneuvers to adjust the Earth-return trajectory may be performed using the RCS (*powered flight with reaction control*) or SPS engine (*powered flight with thrust vector control*).

2.5.6 Entry, Descent, and Landing

Nearing Earth, the Command Module (CM) separates from the Service Module (SM) for entry. While still exoatmospheric, the CM is in the *coasting flight attitude control* regime. Once the CM enters the atmosphere to the extent that aerodynamic effects become significant, it enters the *atmospheric entry* flight regime. This is typically considered to occur when aerodynamic deceleration reaches 0.05g (approximately 1.6 ft/s^2).

At the end of the atmospheric entry the CM deploys parachutes for landing and manual control is no longer available.

Chapter 3

Mathematical Preliminaries

3.1 Chapter Overview

To analyze the dynamics of historic spacecraft we require the ability to perform six degree of freedom (6-DOF) numeric simulation. This chapter summarizes the mathematics associated with computing mass properties and simulating rotational and translational dynamics.

3.2 Coordinate Systems and Vector Definitions

Figure 3.1 illustrates the coordinate frame used throughout this document. Most sources describe this as the Guidance, Navigation, and Control (GNC) coordinate system with the origin at the center of mass. The X-axis points forward, out the nose of the spacecraft, and is the direction the pilot is

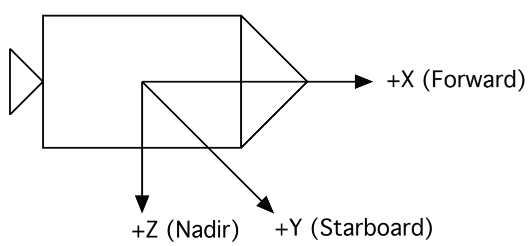

Figure 3.1: Spacecraft Body Axes (Side View)

generally looking when exercising manual control. The Y-axis points out the starboard side of the vehicle, parallel to the pilot's laterally extending right arm. The Z-axis points in the nadir (down) direction, out the bottom of the vehicle to complete the right-handed coordinate system. Thus, if the pilot were asked to thrust in the -Y direction, the Translational Hand Controller (THC) would be moved to the pilot's left. This system has the advantage that all positive rotations are in the natural direction for most people in the United States. Specifically, positive roll is to the right, positive pitch is up, and positive yaw is to the right.

It should be noted that while these basis vector directions are considered standard for operations in the modern era, many other coordinate systems are in use. Manufacturers, by convention, often define a structural coordinate frame in which the origin is forward of all structure and the X-axis points aft, Y-axis to starboard, and Z-axis zenith (up). This is often used to define the location of equipment on the spacecraft. Early Mercury program documentation defines a left-handed coordinate system. For clarity, all coordinate information in this document has been converted to the system defined previously (X-axis forward).

3.3 Mass Properties

In general, mass property data has been sourced from various historic documents. As a general rule, data becomes more vague as programs become older. Data for Shuttle and Apollo, for example, is broken down by all significant points during the mission. Gemini data are typically given only for a few points during the mission and lacks products of inertia. Mercury data are typically given only for one point, separation from the launch vehicle, and also lacks products of inertia. In these cases extensive work was done to estimate weights and center of mass locations for various spacecraft components and regular geometric models were used to compute displaced moments and products of inertia. Specifics of data sourcing, cited or estimated, are given in the appendices for each spacecraft considered.

Moments and products of inertia are defined as follows:

$$I_{xx} = \int_m (y^2 + z^2)\, dm \tag{3.1}$$

$$I_{yy} = \int_m (x^2 + z^2)\, dm \tag{3.2}$$

$$I_{zz} = \int_m (x^2 + y^2)\, dm \tag{3.3}$$

$$I_{xy} = I_{yz} = \int_m xy\, dm \tag{3.4}$$

$$I_{yz} = I_{zy} = \int_m yz\, dm \tag{3.5}$$

$$I_{xz} = I_{zx} = \int_m xz\, dm \tag{3.6}$$

The inertia matrix, sometimes known as the inertia tensor, is then defined as:

$$\mathbf{I} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \tag{3.7}$$

When estimating mass properties of spacecraft, we often do so by building composite bodies using the *parallel axis theorem* as derived in Fowler [41]. Let d_x, d_y, d_z be the coordinate of the center of mass of a displaced object with regards to the origin of a new reference frame, and let the primed moments and products of inertia be those about the displaced object's center of mass, and let the mass of the displaced object be m. The new moments and products of inertia are computed as follows:

$$I_{xx} = I_{x'x'} + (d_y^2 + d_z^2)m \tag{3.8}$$

$$I_{yy} = I_{y'y'} + (d_x^2 + d_z^2)m \tag{3.9}$$

$$I_{zz} = I_{z'z'} + (d_x^2 + d_y^2)m \tag{3.10}$$

$$I_{xy} = I_{x'y'} + d_x d_y m \tag{3.11}$$

$$I_{yz} = I_{y'z'} + d_y d_z m \tag{3.12}$$

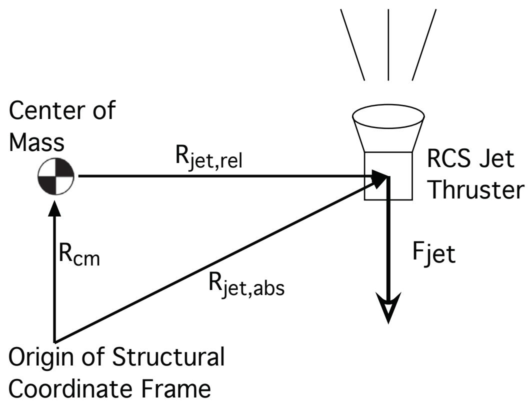

Figure 3.2: Location and Thrust Vectors

$$I_{xz} = I_{x'z'} + d_x d_z m \tag{3.13}$$

The center of mass of a composite object is then computed as follows:

$$\mathbf{R}_{cm} = \frac{\sum_i m_i \mathbf{R}_i}{\sum_i m_i} \tag{3.14}$$

3.4 Moments and Forces

Moments due to Reaction Control System (RCS) jet thrusters are computed by determining the position of the jet relative to the spacecraft's center of mass. The moment vector for the jet is the relative position vector crossed with the thrust force vector. Several jets are often fired simultaneously and the total vector moment is simply the sum of the individual moments. These data are all in the body frame and are used to compute angular acceleration.

Figure 3.2 illustrates the geometry associated with location and thrust vectors. The illustration is in the structural frame of the spacecraft. Vector $\mathbf{R}_{cm}$ is the position, in that frame, of the spacecraft's center of mass. Vector $\mathbf{R}_{jet,abs}$ is the location of a jet in that same frame. Vector $\mathbf{R}_{jet,rel}$ is the position of the jet with respect to the center of mass.

$$\mathbf{R}_{cm} + \mathbf{R}_{jet,rel} = \mathbf{R}_{jet,abs} \tag{3.15}$$

Solving for $\mathbf{R}_{jet,rel}$

$$\mathbf{R}_{jet,rel} = \mathbf{R}_{jet,abs} - \mathbf{R}_{cm} \tag{3.16}$$

Vector $\mathbf{F}_{jet}$ is the force due to thrust caused by firing the jet. It is also in the structural coordinate frame and is in the anti-plume direction.

To compute the moment created by firing a jet, we use the cross product

$$\mathbf{M}_{jet} = \mathbf{R}_{jet,rel} \times \mathbf{F}_{jet} \tag{3.17}$$

Total force and moment due to firing multiple jets is simply the sum of the individual vectors.

$$\mathbf{F}_{jet,total} = \sum_i \mathbf{F}_{jet,i} \tag{3.18}$$

$$\mathbf{M}_{jet,total} = \sum_i \mathbf{M}_{jet,i} \tag{3.19}$$

The total vector force due to jet(s) is in the body frame and is rotated to the inertial frame to compute linear acceleration. Acceleration is then integrated to compute velocity, which is in turn integrated to compute position. The vector acceleration is computed as follows where m is the mass of the spacecraft:

$$\mathbf{a} = \frac{\mathbf{F}_{jet,total}}{m} \tag{3.20}$$

Jet position and thrust direction are generally taken directly from historic design documentation but are estimated for some older vehicles due to the lack of exact documentation. Details are noted in the appendix associated with that particular spacecraft.

3.5 Rigid Body Rotational Dynamics

As derived in Fowler [41], the dynamics of a rigid rotating body can be described using *Euler's Equations*. In this formulation, the body is rotating about its center of mass and the moments and products of inertia are defined within a rotating, body-fixed reference frame. The body is rotating with vector angular velocity $\boldsymbol{\omega}$ and vector angular acceleration $\boldsymbol{\alpha}$. The total applied moments about the x, y, and z axes are M_x, M_y, and M_z respectively.

$$
\begin{aligned}
M_x =& I_{xx}\alpha_x - I_{xy}\alpha_y - I_{xz}\alpha_z - \\
& \omega_z(-I_{yx}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z) + \\
& \omega_y(-I_{zx}\omega_x - I_{zy}\omega_y + I_{zz}\omega_z)
\end{aligned} \tag{3.21}
$$

$$
\begin{aligned}
M_y =& -I_{yx}\alpha_x + I_{yy}\alpha_y - I_{yz}\alpha_z - \\
& \omega_z(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z) - \\
& \omega_x(-I_{zx}\omega_x - I_{zy}\omega_y + I_{zz}\omega_z)
\end{aligned} \tag{3.22}
$$

$$
\begin{aligned}
M_z =& -I_{zx}\alpha_x - I_{zy}\alpha_y + I_{zz}\alpha_z - \\
& \omega_y(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z) + \\
& \omega_x(-I_{yx}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z)
\end{aligned} \tag{3.23}
$$

And in matrix form

$$
\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \mathbf{I} \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} + \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \mathbf{I} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{3.24}
$$

We wish to solve Euler's equations for the angular acceleration about each body axis (α_x, α_y, α_z). This is done using a numeric integrator. We assume that mass properties, including the moments and products of inertia, are constant and that at any integration step we know the angular rate about each body axis (ω_x, ω_y, ω_z) because it is the result of integrating the previous angular acceleration.

We first define three variables to simplify Euler's equations at follows:

$$
\begin{aligned}
c_x =& \omega_z(-I_{yx}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z) + \\
& \omega_y(-I_{zx}\omega_x - I_{zy}\omega_y + I_{zz}\omega_z)
\end{aligned} \tag{3.25}
$$

$$
\begin{aligned}
c_y =& \omega_z(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z) - \\
& \omega_x(-I_{zx}\omega_x - I_{zy}\omega_y + I_{zz}\omega_z)
\end{aligned} \tag{3.26}
$$

$$
\begin{aligned}
c_z =& \omega_y(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z) + \\
& \omega_x(-I_{yx}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z)
\end{aligned} \tag{3.27}
$$

This allows us to rewrite Euler's equations as:

$$M_x = I_{xx}\alpha_x - I_{xy}\alpha_y - I_{xz}\alpha_z - c_x \tag{3.28}$$

$$M_y = -I_{yx}\alpha_x + I_{yy}\alpha_y - I_{yz}\alpha_z - c_y \tag{3.29}$$

$$M_z = -I_{zx}\alpha_x - I_{zy}\alpha_y + I_{zz}\alpha_z - c_z \tag{3.30}$$

By defining the following vectors:

$$\mathbf{M} = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} \tag{3.31}$$

$$\boldsymbol{\alpha} = \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} \tag{3.32}$$

$$\mathbf{C} = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} \tag{3.33}$$

We can write Euler's equations as a matrix equation:

$$\mathbf{M} = (\mathbf{I} \times \boldsymbol{\alpha}) + \mathbf{C} \tag{3.34}$$

We then solve this equation for $\boldsymbol{\alpha}$:

$$\boldsymbol{\alpha} = \mathbf{I}^{-1} \times (\mathbf{M} - \mathbf{C}) \tag{3.35}$$

The vector angular acceleration $\boldsymbol{\alpha}$ is then numerically integrated to yield vector angular body rate $\boldsymbol{\omega}$ at the next time step. To determine vehicle attitude as a set of Euler angles, the vector angular body rate is converted to Euler rates and subsequently integrated to determine Euler angles.

For single-axis rotations, the equations of rotational motion reduce to the following equations which are trivially solved for α_x, α_y, or α_z.

$$M_x = I_{xx} \times \alpha_x \tag{3.36}$$

$$M_y = I_{yy} \times \alpha_y \tag{3.37}$$

$$M_z = I_{zz} \times \alpha_z \tag{3.38}$$

3.6 Reference Frame Conversions

To integrate our attitude, we require the ability to convert body rates to Euler rates. To integrate velocity and position, we require the ability to convert a force vector from the body frame to the inertial frame. Both of these tasks are done using rotation matrices.

3.6.1 Rotation Matrices

We first define a set of rotation matrices (**ROT1**, **ROT2**, and **ROT3**) used to rotate vectors about the x, y, and z axes respectively.

$$\mathbf{ROT1}(\psi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin\psi \\ 0 & -\sin\psi & \cos\psi \end{bmatrix} \tag{3.39}$$

$$\mathbf{ROT2}(\theta) = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \tag{3.40}$$

$$\mathbf{ROT3}(\phi) = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.41}$$

3.6.2 Body Rates to Euler Rates

The standard Euler rotation sequence for manned spacecraft is pitch, followed by yaw, followed by roll (PYR). This results in several intermediate reference frames denoted with subscripts a through d. Frame a is the inertial reference frame, b is after $\mathbf{ROT2}(\theta)$ (pitch), c is after a subsequent $\mathbf{ROT3}(\psi)$ (yaw), and d, the body frame, is after a subsequent $\mathbf{ROT1}(\phi)$ (roll).

The Euler rates are thus defined in their respective reference frames as follows:

$$\boldsymbol{\omega}_{pitch,a} = \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} \tag{3.42}$$

$$\boldsymbol{\omega}_{pitch,d} = ROT1(\phi) \times ROT3(\psi) \times ROT2(\theta) \times \boldsymbol{\omega}_{pitch,a} \tag{3.43}$$

$$\boldsymbol{\omega}_{yaw,b} = \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} \tag{3.44}$$

$$\boldsymbol{\omega}_{yaw,d} = ROT1(\phi) \times ROT3(\psi) \times \boldsymbol{\omega}_{yaw,b} \tag{3.45}$$

$$\boldsymbol{\omega}_{roll,c} = \begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix} \tag{3.46}$$

$$\boldsymbol{\omega}_{roll,d} = ROT1(\phi) \times \boldsymbol{\omega}_{roll,c} \tag{3.47}$$

The total body attitude rate is computed as the sum of the individual rates:

$$\boldsymbol{\omega} = \boldsymbol{\omega}_d = \boldsymbol{\omega}_{roll,d} + \boldsymbol{\omega}_{pitch,d} + \boldsymbol{\omega}_{yaw,d} \tag{3.48}$$

By substituting terms and performing matrix multiplication, we can write the total body rate in terms of Euler rates as follows:

$$\boldsymbol{\omega} = \begin{bmatrix} 1 & \sin\psi & 0 \\ 0 & \cos\psi\cos\phi & \sin\phi \\ 0 & -\cos\psi\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} \tag{3.49}$$

Let the Euler rate vector (in x,y,z order) be defined as:

$$\boldsymbol{\omega}_e = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{3.50}$$

And let the Euler rate to body rate conversion matrix be defined as:

$$
\mathbf{C}_{eb} = \begin{bmatrix} 1 & \sin\psi & 0 \\ 0 & \cos\psi\cos\phi & \sin\phi \\ 0 & -\cos\psi\sin\phi & \cos\phi \end{bmatrix} \tag{3.51}
$$

We can therefore write:

$$
\boldsymbol{\omega} = \mathbf{C}_{eb} \times \boldsymbol{\omega}_e \tag{3.52}
$$

To convert body rate to Euler rates, we define the body rate to Euler rate conversion matrix as:

$$
\mathbf{C}_{be} = \mathbf{C}_{eb}^{-1} \tag{3.53}
$$

And thus:

$$
\boldsymbol{\omega}_e = \mathbf{C}_{eb}^{-1} \times \boldsymbol{\omega} = \mathbf{C}_{be} \times \boldsymbol{\omega} \tag{3.54}
$$

Note however that a singularity occurs if $det(C_{eb}) = 0$ which, in turn, occurs if $\psi = \pm 90$ degrees, corresponding to $yaw = \pm 90$ degrees. This condition is considered acceptable because that attitude is rarely required in practice.

3.6.3 Body Frame to Inertial Frame

For computing linear translation, we need to relate the net thrust force as defined in the body frame into the inertial frame. To do that, we compute the direction cosine matrix associated with the pitch, yaw, roll Euler sequence. We first define the matrix $\mathbf{C}_{ib}$ for converting from inertial to body:

$$
\mathbf{C}_{ib} = ROT1(\phi) \times ROT3(\psi) \times ROT2(\theta) \tag{3.55}
$$

$$
\mathbf{C}_{ib} = \begin{bmatrix} \cos\psi\cos\theta & \sin\psi & -\cos\psi\sin\theta \\ -\cos\phi\sin\psi\cos\theta + \sin\phi\sin\theta & \cos\phi\cos\psi & \cos\phi\sin\psi\sin\theta + \sin\phi\cos\theta \\ \sin\phi\sin\psi\cos\theta + \cos\phi\sin\theta & -\sin\phi\cos\psi & -\sin\phi\sin\psi\sin\theta + \cos\phi\cos\theta \end{bmatrix} \tag{3.56}
$$

Because this is an orthogonal DCM the inverse and transpose are equivalent. Thus, we can write the matrix to convert from body frame coordinates to inertial coordinates, $\mathbf{C}_{bi}$ directly as:

$$\mathbf{C}_{bi} = \mathbf{C}_{ib}^{-1} = \mathbf{C}_{ib}^{T} \tag{3.57}$$

$$\mathbf{C}_{bi} = \begin{bmatrix} \cos\psi\cos\theta & -\cos\phi\sin\psi\cos\theta + \sin\phi\sin\theta & \sin\phi\sin\psi\cos\theta + \cos\phi\sin\theta \\ \sin\psi & \cos\phi\cos\psi & -\sin\phi\cos\psi \\ -\cos\psi\sin\theta & \cos\phi\sin\psi\sin\theta + \sin\phi\cos\theta & -\sin\phi\sin\psi\sin\theta + \cos\phi\cos\theta \end{bmatrix} \tag{3.58}$$

Therefore, to convert body frame vector force $\mathbf{F}_b$ to the inertial frame force vector $\mathbf{F}_i$, we compute:

$$\mathbf{F}_i = \mathbf{C}_{ib}^{-1} \times \mathbf{F}_b = \mathbf{C}_{ib}^{T} \times \mathbf{F}_b = \mathbf{C}_{bi} \times \mathbf{F}_b \tag{3.59}$$

Chapter 4

Historic Spacecraft Analysis

4.1 Chapter Overview

This chapter documents the process of proposing a set of estimated design requirements for satisfactory handling qualities. This is done via the analysis of historic spacecraft in combinations of spaceflight regime and control mode. Within each of these contexts one or more design parameters are defined to quantify some aspect of vehicle response to pilot input. Parameter values are determined for a variety of historic spacecraft or, in some cases, simulated spacecraft. Contemporary pilot commentary or other information is interpreted to assign a rating of 'satisfactory' or 'unsatisfactory' to each case. Results are tabulated to estimate critical paramter values at which handling transitions between satisfactory and unsatisfactory.

4.2 Definition of Satisfactory Handling

NASA specifies [33] requirements for manual control capability and handling qualities for manned spacecraft:

> 3.4 System Control Requirements - Human-Rated Spacecraft
>
> 3.4.1 The crewed space system shall provide the capability for the crew to manually control the flight path and attitude of their spacecraft, with the following exception: during the atmospheric portion of Earth ascent when structural and thermal margins

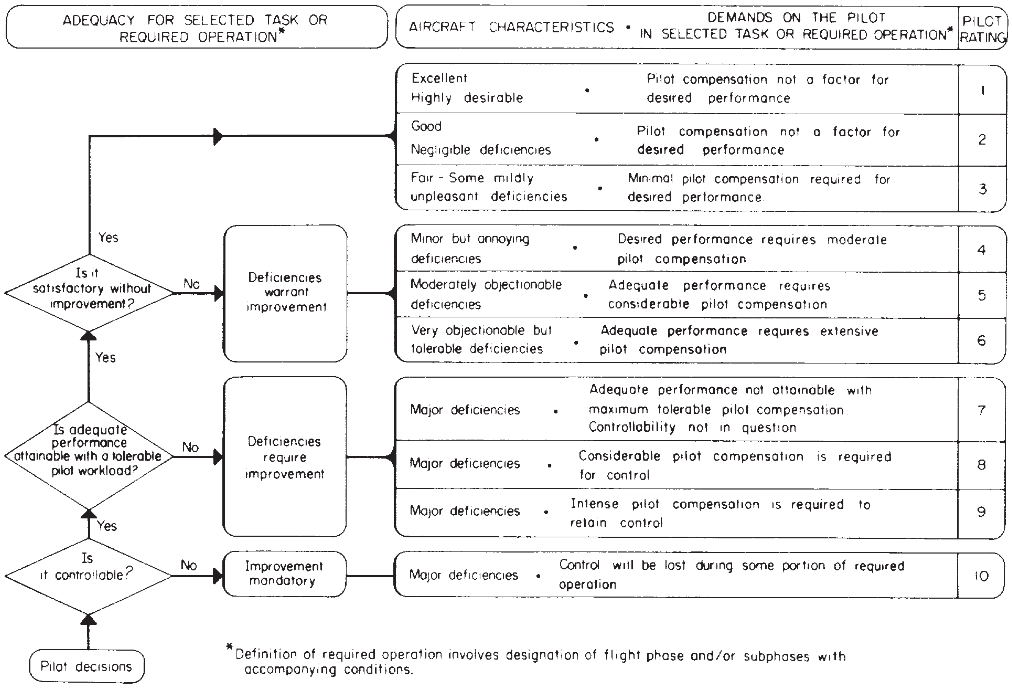

Figure 4.1: Cooper-Harper Rating Scale (Original) [59]

have been determined to negate the benefits of manual control.

> 3.4.2 The crewed spacecraft shall exhibit Level 1 handling qualities (Handling Qualities Rating (HQR) 1, 2 and 3), as defined by the Cooper-Harper Rating Scale, during manual control of the spacecraft's flight path and attitude.

This requirement references the Cooper-Harper rating scale [59]. The scale was created to quantify a pilot's rating of an aircraft's handling and has also been used for spacecraft evaluation. An earlier scale, known as the Cooper scale [58], also exists and is cited in some older spacecraft handling studies.

The heart of the Cooper-Harper scale is a flowchart used by the pilot to assign a rating. The original version from [59] is shown in Figure 4.1. A redrawn version, easier to read, is shown in Figure 4.2.

To assign a rating to a particular scenario (vehicle, configuration, environment, task, performance criteria, etc.), the pilot enters the flowchart at

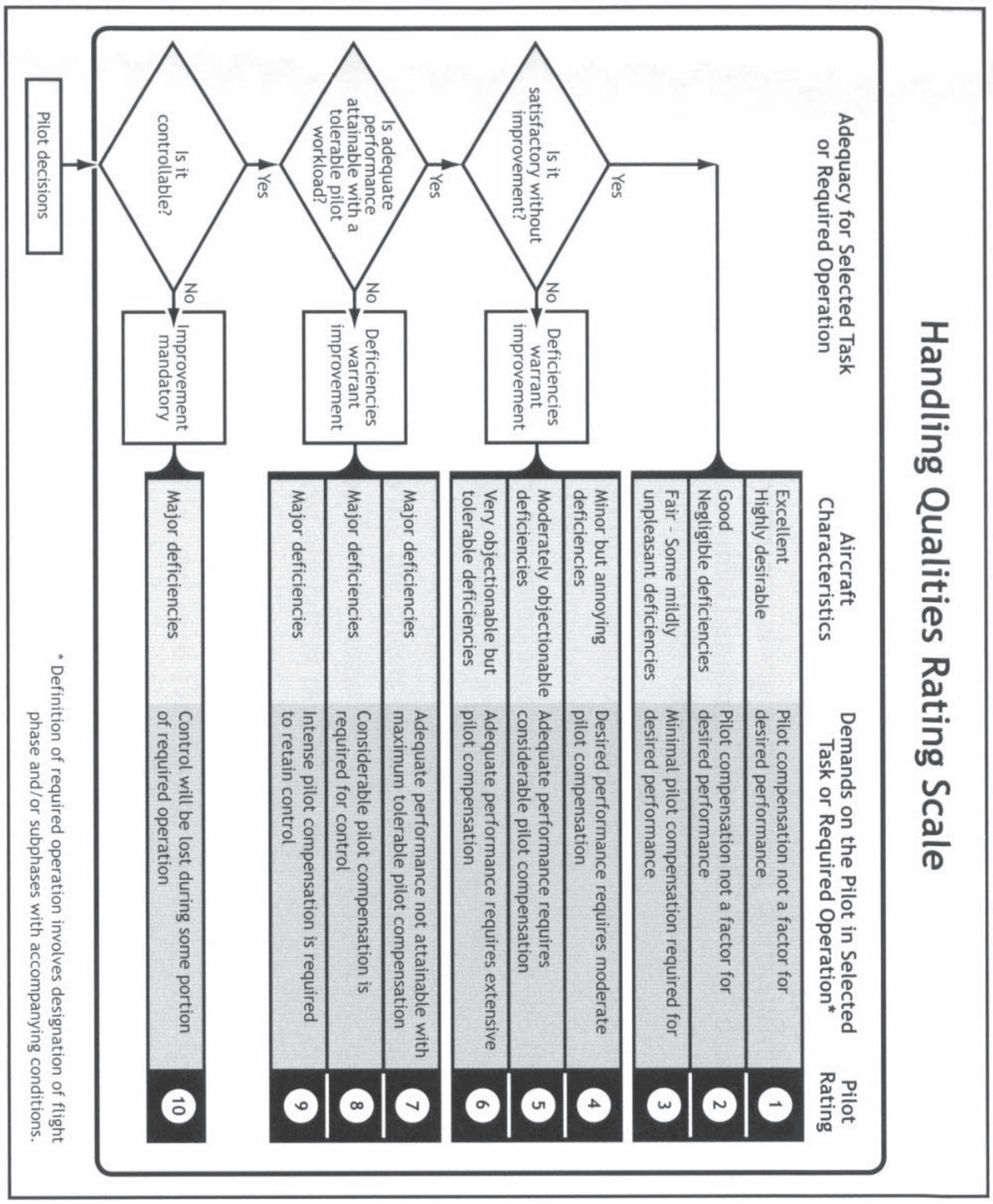

Figure 4.2: Cooper-Harper Rating Scale (Redrawn) [48]

the lower left and makes a series of decisions resulting in a numeric rating from 1 (Ideal) to 10 (Worst). The last decision diamond asks "Is it satisfactory without improvement?" Responding yes to this question will result in a rating of 1, 2, or 3. This group of ratings has, over time, become informally known as "Level 1" although this terminology does not appear within the Cooper-Harper report. (Level 2 consists of ratings 4 - 6, and Level 3 of ratings 7 - 9.)

This work generally avoids discussion of specific Cooper-Harper ratings and limits itself to the less precise evaluation of *satisfactory* or *unsatisfactory*. Satisfactory being a Cooper-Harper rating of 3 or better, unsatisfactory being a Cooper-Harper rating of 4 or worse. Thus, the primary goal of this work is to propose a set of design requirements that, if followed, are expected to result in the majority of test pilots assigning Cooper-Harper ratings of 1, 2, or 3 when performing handling evalations.

4.3 Derivation of Design Parameters

Design parameters are defined in this work to quantify some aspect of a spacecraft's design relevant to handling qualities. The following characteristics are taken into account.

First, they should be generic in the sense that the requirement is applicable to spacecraft generally and not limited to one design. For example, a generic requirement would specifiy a characteristic such as angular acceleration as opposed to thrust magnitude or angular moment.

Second, numeric values should increase or decrease in intuitive ways. For example, control authority should increase with larger, not smaller, numeric values. This is enforced even at the cost of less intuitive units.

Third, when a design parameter describes the relationship between two characteristics we assume linearity. For example, with regards to rotational control authority, a linear relationship is assumed between angular acceleration and maximum angular rate.

4.4 Estimating Minimum Manual Impulse Time

Experience has shown that pilots will tend to make manual control inputs in an impulsive style when no automated impulse control mode exists [111]

[85]. For example, the Mercury 6 (MA-6) pilot, in his post flight debriefing (see page 252), states the following:

> When the fly-by-wire one-pound thruster was not actuating in yaw, I was using a real fast flip of the high thruster in the mode that the one-pound thruster was not operating to control. I couldn't control this as accurately as you can with the one-pound thruster, not nearly as well, so what I did several times was when I would overshoot in rate with the 24-pounder, I would use my one-pounder on the other side to bring it back into zero and stop right on zero.
>
> [...]
>
> The manual control system was not as crisp and sharp in flight as it was in the trainer, as John Conlon predicted. It was more of a mushy, inaccurate type system. I wound up using it either on or off with fast blips to try and control the action of the capsule rather than going to intermediate settings, and trying to get capsule control that way.

In other words, when trying to perform a fine maneuver using the direct control mode, the pilot will tend make as small an input as possible. We desire estimates of these minimum manual impulse durations for purposes of directly comparing spacecraft in which the (automated) impulse control mode is available to those in which the pilot must make impulsive inputs manually.

4.4.1 Rotational Impulse Time

Automated impulse attitude control has been available in most spacecraft with the notable exceptions of the X-15, Mercury, and MMU.

To estimate the minimum manual impulse time for rotation, we note the following comment from the Apollo 7 crew debriefing (see page 290) by Walter Schirra:

> I know on Mercury I wanted less than a 1 pound thruster, for example. We didn't have pulses as such, but we used a small thruster. They were great. I'd say that in Mercury, we got about two tenths of a degree per second for a minimum fly-by-wire thrust in a 1-pound thruster.

Using the 1 lb thrusters, the Mercury spacecraft performs angular acceleration at approximately 0.54 deg/s^2 in roll, 0.46 deg/s^2 in pitch and yaw. This results in a mean angular acceleration of approximately 0.49 deg/s^2. Using Schirra's incremental angular velocity of 0.2 deg/s, this yields a minimum manual impulse time for rotation of approximately 0.4 s (400 ms).

4.4.2 Translational Impulse Time

Automated impulse translational control is relatively new for spacecraft. Among all the spacecraft analyzed in this work only the Space Shuttle is equipped with it.

Two sources of data are considered to estimate the manual minimum impulse time for translation.

The first is a 1964 paper by Riley and Suit [123] that examines manual control of spacecraft docking. The THC is described as a "finger-tip" controller requiring 3/8 in (0.375 in) deflection to register an input. This minimum deflection is comparable to the Shuttle THC. The paper lists minimum Translational Hand Controller (THC) input times for two pilots along all six input axes, making three inputs each per direction, for a total of 36 minimum input times. The mean value of all times is 0.074 s (74 ms) with a standard deviation of 0.031 s (31 ms).

The second source is documentation associated with several incidents during the Space Shuttle program. As originally designed, the Shuttle THC was sampled every 0.16 s (160 ms). If the THC was deflected and returned to neutral between two samples the flight software would miss the input and no translation would occur.

During the STS-82 mission the crew performed a procedure calling for a large number of THC inputs to separate from the Hubble Space Telescope. Post-flight analysis of in-cabin video and telemetry determined that the crew performed a sequence of very rapid inputs and only 10 of 21 were recognized by flight software. Later, during STS-112 docking to the International Space Station, two THC inputs were missed by flight software resulting in docking contact being made at a velocity greater than the desired limit. This resulted in the Space Shuttle Program authorizing a software change that shortened the THC sampling interval to 0.08 s (80 ms). No known missed THC inputs occurred after this software change.

This evidence suggests that minimum impulse time THC inputs for a Shuttle-type controller are longer than 0.08 s (80 ms), because none were missed at this sampling period, but shorter than 0.16 s (160 ms), because a large number were missed at this sampling period. The data from Riley and Suit suggest the actual value is closer to 80 than 160 ms.

This document therefore assumes that the minimum manual impulse time for translation is 0.1 s (100 ms). This value is within one standard deviation of the mean value presented by Riley and Suit [123].

4.5 Coasting Flight Attitude Control

Coasting flight attitude control is concerned with two piloting tasks: performing an attitude maneuver or maintaining attitude within some tolerance. Any rotation coupling into translation is neglected and the effectors are assumed to be fixed thrust ("on-off") Reaction Control System (RCS) jets. A good narrative description of the initial development of RCS attitude control for extremely high altitutde aircraft is by Gelzer and Peebles [69].

4.5.1 With Direct Control

We consider two critical design parameters for direct control: control authority and rotational coupling angle.

Control authority, in this context, refers to the angular acceleration that results when the pilot displaces the Rotational Hand Controller (RHC) away from neutral. If the angular acceleration is too small the vehicle will take an excessive amount of time to reach the desired maneuvering rate and will take an excessive amount of time to decellerate to a stop. The pilot may experience a tendency to overshoot the desired attitude if the maneuvering rate is large compared to the angular acceleration. Conversely, if the angular acceleration is too large the pilot may have difficultly performing fine attitude control. The pilot will tend to have difficulty reducing the angular rates to near zero. Thus it follows that there should be a range of control authorities that yield satisfactory handling.

Thus we define the design parameter k_{acd} (Attitude Control Authority Direct) to be the mean angular acceleration about the primary body axes in units of deg/s^2 in response to continuous RCS jet firing.

$$k_{acd} = MeanAngularAccelerationMagnitude(deg/s^2) \tag{4.1}$$

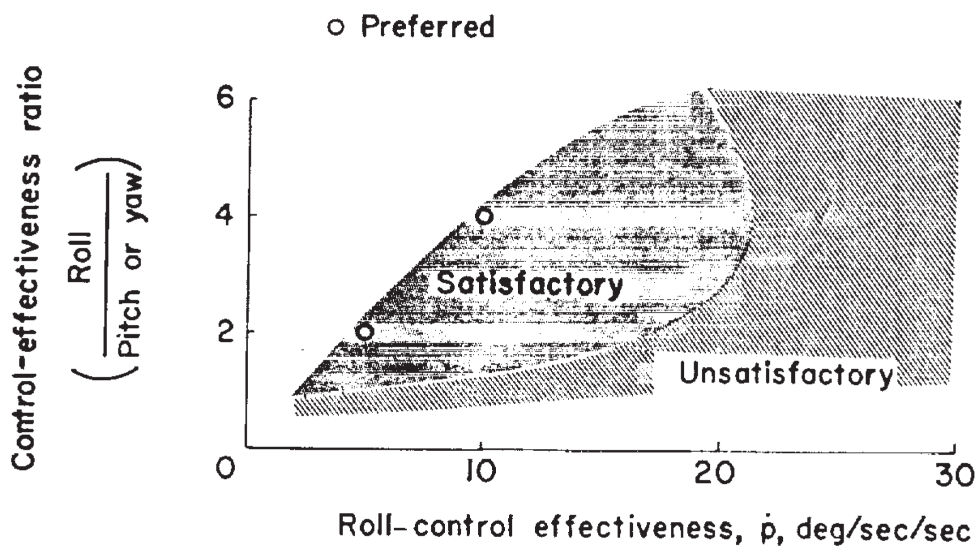

Figure 4.3: Region of Statisfactory Control (Stillwell) [111]

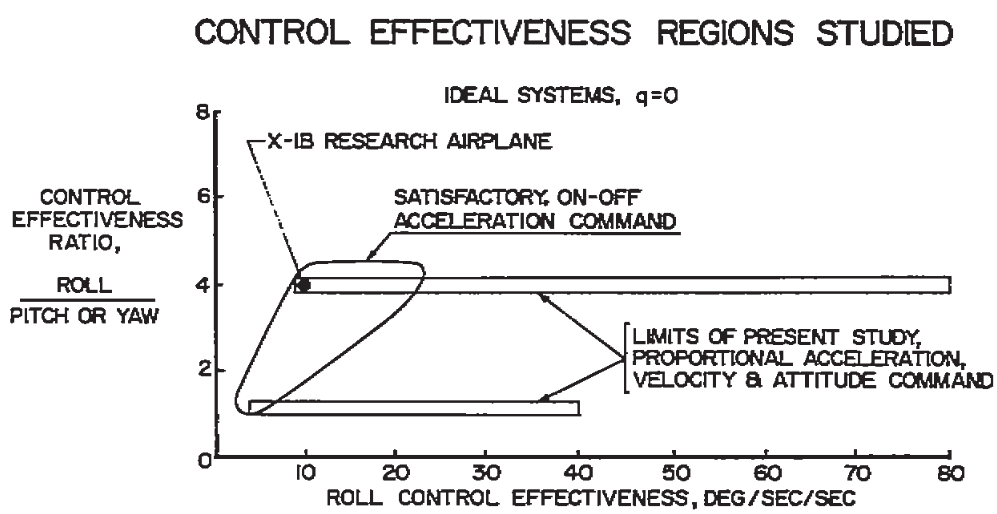

Figure 4.4: Region of Statisfactory Control (Holleman) [78]

Figures 4.3 and 4.4, from Stillwell [111] and Holleman [78] respectively, illustrate regions of satisfactory control as determined in the late 1950s for aircraft experiencing very short exoatmospheric periods on ballistic trajectories, such as the X-15. Subsequent experience has shown that significantly lower control authority is acceptable, even desirable, for fine attitude control while in orbit. See, for example, attitude control on the Mercury spacecraft using the small 1 *lb* ASCS thrusters. That configuration has a mean angular acceleration of approximately 0.5 deg/s^2, significantly below the defined satisfactory region on these charts, and was praised by pilots as offering very satisfactory control. The Mercury MA-7 pilot (John Glenn) states the following in his post-flight debrief:

> Those one-pound thrusters are the best ones for control in orbit. You can control right on the money with those.

Note also the Stillwell [111] reports that lower control authority than that presented on the chart was not evaluated but that the satisfactory region probably extends further in that direction. Thus we disregard the minimum values for satisfactory control authority presented in these figures.

However, the figures also address the ratio of roll to pitch or yaw control authorities. The general trends are, first, that as control authority decreases the ratio tends towards 1:1 for satisfactory control. Second, that as control authority increases the ratio becomes progressively less important. The trends in these charts probably reflect both the experience of the pilots, almost exclusively atmospheric, and the primary mission task of rapidly maneuvering and maintaining attitude for atmospheric entry. In contrast, flown spacecraft known to have satisfactory handling have exhibited a wide range of ratios. For example, Mercury using ASCS Low Thrust jets had a ratio of approximately 1.2:1, while it also had a ratio of approximately 0.3:1 when using ASCS Low and High thrust jets simultaneously. Probably the most that can be said on this topic is that this ratio appears to be of secondary importance for handling but that, given the choice, the designer should probably aim for a ratio close to 1:1 at the low control authorities expected in a spacecraft with satisfactory handling using this control mode.

Values of control authority were determined for historic spacecraft via a six degree-of-freedom numeric simulation. The spacecraft begins at rest and short jet firing is simulated. Values are taken at the end of the jet firing.

As discussed previously (see page 50), a firing time of 0.4 *s* is used for the simulation to correspond to a manual minimum impulse.

Analysis of historic vehicle mean control authorities yields the following:

0.0 deg/s^2 **(Theoretical Value)**
This theoretical value equal to having no control authority is defined to have unsatisfactory handling for any purpose.

0.01 deg/s^2 **(Interpolated Value)**
This interpolated value is halfway between 0.0 and 0.02 deg/s^2 and is the estimated crossover point at which there is sufficient control authority for precision attitude control only.

0.02 deg/s^2 **(Space Shuttle Medium Weight Vernier RCS)**
The author has flown this configuration in a simulator and his judgement is that this control authority is satisfactory for precision control at very slow attitude rates but is unsatisfactorily small for general purpose attitude control.

0.3 deg/s^2 **(Interpolated Value)**
This interpolated value is halfway between 0.02 and 0.5 deg/s^2 (0.26 rounded to 0.3 deg/s) and is the estimated crossover point at which control authority becomes large enough for general purpose use.

0.5 deg/s^2 **(Mercury ASCS Fly-By-Wire Low)**
This value is described as being "Excellent" (Mission MR-4) and that it requires a long wait to accelerate for maneuvering at 3 deg/s (MA-7).

0.8 deg/s^2 **(Space Shuttle Medium Weight Primary RCS)**
The author has flown this configuration in a simulator and his judgement is that this control authority is satisfactory for general purpose attitude control but that the response feels sluggish at natural maneuvering rates for large attitude maneuvers.

1.7 deg/s^2 **(Interpolated Value)**
This interpolated value is halfway between the 0.8 and 2.5 deg/s^2 and is the estimated crossover point at which handling no longer feels sluggish at natural maneuvering rates.

2.5 deg/s^2 **(Apollo 7 Service Module RCS)**
The Apollo 7 crew described this control authority as "A good mode and I like it." It is therefore considered satisfactory for general purpose attitude control. No mention is made of sluggish response.

5.3 deg/s^2 **(Gemini OAMS)**

This control authority is described as "Good authority" and "Really good. Good and crisp." (Mission GT-5), and "Pretty strong." (GT-6). Handling is therefore considered to be satisfactory with no sense of sluggishness.

8.2 deg/s^2 **(Gemini Entry with One RCS Ring)**

This authority is described as "Easier to control" (GT-3) and "Stronger than OAMS." (GT-6). Handling is considered to be satisfactory.

8.9 deg/s^2 **(Mercury ASCS Fly-By-Wire High)**

The pilot of Mercury mission MA-7 describes this control authority as having a reasonable acceleration for maneuvering at 3 deg/s. Handling is considered to be satisfactory.

8.9 deg/s^2 **(MMU)**

The STS-41B MMU pilot gives a Cooper-Harper Rating of 3 to this control authority in his post-flight debriefing. Handling is therefore considered to be satisfactory.

12.7 deg/s^2 **(Interpolated Value)**

This interpolated value is halfway between 8.9 and 16.5 deg/s^2 and is the estimated crossover point at which control authority becomes too large for satisfactory handling.

16.5 deg/s^2 **(Gemini Entry with Two RCS Rings)**

The GT-3 crew stated that "You tend to over control until you get the hang of it." Handling is considered to be unsatisfactory due to excessive control authority.

The results of analyzing historic spacecraft performing coasting flight attitude control using direct attitude control are summarized in Table 4.1. Values of k_{acd} between 0.02 and 0.3 deg/s^2 are estimated to have satisfactory handling for precision attitude control only. Control authorities between 0.3 and 12.7 deg/s^2 are estimated to have satisfactory handling for general purpose attitude control.

The second design parameter is the rotational coupling angle illustrated in Figure 4.5. Conceptually, rotational coupling occurs when a commanded rotation about one body axis also results, as a side effect, in rotation about one or both of the remaining body axes. For example, suppose that when

Control Authority $k_{acd}(deg/s^2)$	Handling Quality (Estimated)
$k_{acd} < 0.01$	Unsatisfactory
$0.01 < k_{acd} < 0.3$	Satisfactory For Precision Control Only
$0.3 < k_{acd} < 12.7$	Satisfactory for General Use
$12.7 < k_{acd}$	Unsatisfactory

Table 4.1: Direct Attitude Control Authorities Estimated Handling

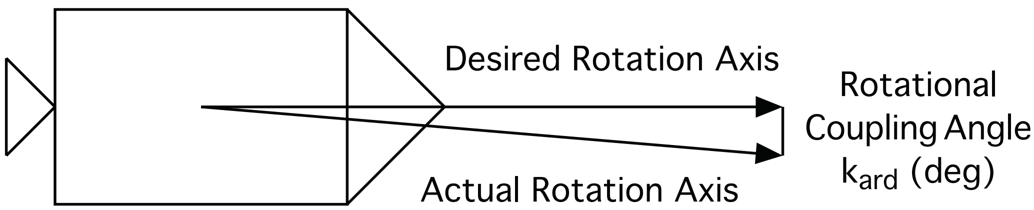

Figure 4.5: Rotational Coupling Angle

jets are fired to yaw the vehicle also, to a lesser degree, also rolls and pitches. Such a vehicle is said to exhibit rotational coupling. These side-effects are in effect undesired feedback loops. For example, suppose a pilot attempts to control yaw but, as a result of coupling, also introduces attitude errors in roll. Fixing the roll error could subsequently cause yaw and pitch errors. In this way a feedback loop is formed. It is obvious that rotational coupling is undesirable for satisfactory handling but history, and the personal experience of the author, has shown that some amount of rotational coupling can still allow for satisfactory handling.

Note that rotation can couple back into into rotation or to translation. Similarly, translation can couple back into translation or into rotation. In general we use the phrase *rotational coupling* as shorthand for rotation to rotation coupling and *translational coupling* as shorthand for translation to translation coupling. Coupling between rotation and translation is named explicitly, as in *translational to rotational coupling.* The terms "coupling" (without descriptor) and, as sometimes seen in literature, "cross coupling" are avoided due to ambiguity as to what is coupling into what.

Thus we define the design parameter k_{ard} (Attitude Rotational Coupling Direct) to be the angle, in units of *deg*, between the desired rotation axis, such as +Y for +Pitch, and the actual rotation vector that results from a momentary jet firing. The value is found by computing the mean of the angles resulting from short positive and negative roll, pitch, and yaw rotations from rest.

$$k_{ard} = MeanRotationalCouplingDirect(deg) \tag{4.2}$$

Analysis of historic vehicle rotational coupling yields the following:

1.5 *deg* **(Mercury ASCS Fly-By-Wire Low (Roll))**
The MA-7 pilot (Schirra) says, in debrief, that "I think the only thing that I can say about this (180 degree roll) maneuver is that you do get pure roll without coupling. Rates in the other axes stay roughly at zero." Although not specified, the context of the comment and his stated preference for low thrust control suggests that it was done with the ASCS low thrust jets. This coupling angle is considered to be satisfactory.

1.3 *deg* **(Gemini OAMS)**
The GT-5 crew stated that OAMS Direct did not have significant coupling. Handling is considered to be satisfactory.

3.5 *deg* **(MMU)**
The STS-41B debriefing states that the MMU pilot gave it a Cooper-Harper Rating of 3. This is considered to be satisfactory.

8.0 *deg* **(Apollo CSM+LM Stack)**
The Apollo 9 crew describes this configuration as having noticeable rotational coupling but does not describe it as a significant impairment to satisfactory handling. Handling is still considered to be satisfactory.

9.7 *deg* **(Space Shuttle Medium Weight Primary RCS)**
The author has flown this configuration in the simulator and his judgement is that the spacecraft is satisfactorally controllable but that considerable effort is required to overcome the perturbing feedback caused by rotational coupling. A notable problem is that Shuttle coupling is irreversible in some cases. For example, left yaw couples into right roll and pitch up. Right yaw, which you need to stop a previous left yaw input, couples into left roll (stopping the roll) and pitch up (making pitch up worse). This coupling angle is considered to have satisfactory handling qualities.

Rotational Coupling Angle $k_{ard}(deg)$	Handling Quality (Estimated)
$k_{ard} < 14.3$	Satisfactory
$14.3 < k_{ard}$	Unsatisfactory

Table 4.2: Direct Attitude Control Coupling Estimated Handling

14.3 *deg* (Interpolated Value)

This interpolated value is halfway between 9.7 and 18.9 *deg* and is the estimated crossover point at which the coupling angle becomes too large for satisfactory handling.

18.9 *deg* (Space Shuttle Medium Weight Primary RCS Tail-Only)

The author has flown this configuration in the simulator and his judgement is that the spacecraft does not have satisfactory handling qualities due to the effort required to compensate for coupling.

The results of analyzing coupling in historic spacecraft performing coasting flight attitude control using direct are summarized in Table 4.2. Values of k_{ard} less than 14.3 *deg* are estimated to have satisfactory handling. Values greater than 14.3 *deg* are estimated to have unsatisfactory handling due to excessive perturbing feedback.

4.5.2 With Impulse Control

As stated earlier, pilots will tend to pulse the hand controller when operating in direct in order to get the smallest possible impulse for fine attitude control. As also stated, the estimated minimum manual RHC impulse is 0.4 *s* (400 *ms*). An automated impulse control system allows for fine control using larger thrust RCS jets because it can fire for much shorter times. For example, the Gemini impulse mode commands a 20 *ms* jet firing. Aside from workload reduction, the finer control this automation allows is obvious.

Older spacecraft, such as Gemini and Apollo, implement a time-based impulse system. The Gemini minimum impulse duration was 20 *ms*, Apollo was 14 *ms*. The resulting angular acceleration magnitude obviously varies with mass properties, thrust moment arm, and so on. This mode was generally refered to as "minimum impulse." The Space Shuttle implemented a software configurable rotation impulse size. The magnitude varied depending upon mission requirements but could be as small at 0.001 deg/s. The Shuttle adopted the "pulse" nomenclature for this mode, perhaps taking into account that magnitudes other than the minimum were available. For clarity, this work uses the word "impulse" for both systems.

In the context of impulse attitude control, control authority is the magnitude of incremental angular rate that a single impulse will create. The mean angular rate magnitude is the mean value for all six rotations (positive and negative roll, pitch, and yaw).

If a spacecraft has too little rotational impulse control authority it will require an excessive number of RHC inputs to maneuver at acceptable rates. An indication of this is the pilot switching to direct for large attitude maneuvers and switching back to impulse for fine control, including maintaining attitude. On the other hand, excessive control authority reduces the ability of the pilot to hold attitude within acceptable limits. Effectively, the pilot will begin a form of limit cycling by making constant RHC inputs to maintain attitude.

We define the design parameter k_{aci} (Attitude Control Authority Impulse) to be the mean incremental angular rate magnitude for a single impulse about all six axes.

$$k_{aci} = MeanIncrementalAngularRateMagnitude(deg/s) \tag{4.3}$$

Analysis of historic vehicle rotational impulse control authority yields the following:

0.004 deg/s **(Apollo CSM+LM Heavy)**

The Apollo 9 crew states in debrief that, prior to undocking the LM, "We had been maneuvering the spacecraft; and with the tremendous mass of the vehicle, the minimum impulse was almost imperceptible on the rate needles." This control authority value is considered to be insufficient and unsatisfactory.

0.01 deg/s **(Interpolated Value)**

This interpolated value is halfway between 0.004 and 0.02 deg/s and is the estimated crossover point at which there is sufficient control authority for satisfactory handling qualities.

0.02 *deg/s* **(Apollo CSM Medium)**
The Apollo 9 CSM Pilot states in debrief that, during formation flight with the just undocked LM, "I went to minimum impulse or free drifting mode. There was very little effect, and it's obvious that you could stationkeep in minimum impulse with no problem at all." This control authority is considered to be satisfactory.

0.04 *deg/s* **(Apollo CM Single RCS)**
The Apollo 9 commander states in debrief that "One thing that might be worth pointing out is that the single ring pulse is a real nice control system; it is snappy. You can really hear the thrusters banging, and it gives you real fine control of the spacecraft. It is not an over-control situation, but you do not have to wait there very long for it and it will bring you right where you want to go." This control authority is considered to be satisfactory.

0.05 *deg/s* **(Gemini Orbit OAMS)**
The Gemini GT-3 pilot, Young, stated in debrief that "I thought pulse mode was just beautiful. It did just exactly what I expected it to." The GT-4 crew stated that "I think Pulse was the best mode on the spacecraft for the orbit phase. We were able to save all kinds of fuel, it worked fine, and it was just what the doctor ordered." This control authority is considered to be satisfactory.

0.05 *deg/s* **(Apollo LM Ascent+Descent Mean)**
The Apollo 9 commander states in debrief that "The maneuver to the burn attitude was done manually using pulse mode, which was the flight control mode used during almost 99 percent of the flight. We operated in PNGCS[1] pulse. We flew to local vertical attitude and it was a good chance to see how the spacecraft really performed in this semi-heavyweight configuration. There was a fair amount of fuel left in the descent stage and the ascent stage. I think this mode is certainly adequate for the kind of maneuvers that take place in orbit."

0.08 *deg/s* **(Gemini Entry Single Ring RCS)**
The Gemini GT-6 commander states in debrief that "It was very difficult to take tiny pulses and put it where I was used to putting it,

[1] Primary Guidance Navigation and Control System

Control Authority $k_{aci}(deg/s)$	Handling Quality (Estimated)
$k_{aci} < 0.01$	Unsatisfactory
$0.01 < k_{aci} < 0.19$	Satisfactory
$0.19 < k_{aci}$	Unsatisfactory

Table 4.3: Impulse Attitude Control Authority Estimated Handling

meaning the needles really nulled out on rates, as I had on the OAMS system. So there is that much more control authority in the pulse mode on the RCS system." He also stated that "Approaching 400,000 feet the spacecraft seemed very easy to fly, although it took a little more activity, in pulse mode, to keep a fairly stable attitude in that sense." This value of control authority is considered to be satisfactory.

0.19 deg/s (Apollo 9 LM Docking)
The Apollo 9 commander states in debrief that, with regards to the LM ascent stage, "With the ascent stage only, the pulse was still a very effective mode. It gave a little snappier response than it did when the descent stage was hooked on." This control authority is considered to be satisfactory.

The results of analyzing historic spacecraft performing coasting flight attitude control using impulse attitude control are summarized in Table 4.3. Values of k_{aci} between 0.01 and 0.19 deg/s are estimated to yield satisfactory handling qualities. Unfortunately there is no known upper value at which handling is known to be unsatisfactory. The value is probably bounded by the allowable error when holding attitude and the limit cycling phenomenon discussed earlier. If pressed, the author would estimate the actual value to be roughly 0.5 deg/s for holding attitude within 2 deg in all axes. Assuming limit cycling in all three axes this would result in a new RHC input about every five seconds, which seems tolerable for a short period of time.

Rotational coupling is described in detail in the section analyzing direct attitude control. We define the design parameter k_{ari} (Attitude Rotational Coupling Impulse) to be the angle, in units of deg, between the desired rotation axis, such as +Y for +Pitch, and the actual rotation vector that results from a momentary jet firing. This is found by computing the mean of the angles resulting from roll, pitch, and yaw rotations.

$$k_{ari} = MeanRotationalCouplingAngle(deg) \tag{4.4}$$

Values of coupling angle were determined for historic spacecraft via a six degree-of-freedom numeric simulation.

1.2 *deg* **(Gemini Entry Single Ring RCS)**
The lack of commentary in post-flight debriefings concerning rotational coupling, despite significant commentary concerning other handling issues, suggests that this degree of rotational coupling yields satisfactory handling.

1.3 *deg* **(Gemini Orbit OAMS)**
The lack of commentary in post-flight debriefings concerning rotational coupling, despite significant commentary concerning other handling issues, suggests that this degree of rotational coupling yields satisfactory handling.

1.4 *deg* **(Apollo LM Ascent+Descent Mean)**
The lack of commentary in post-flight debriefings concerning rotational coupling, despite significant commentary concerning other handling issues, suggests that this degree of rotational coupling yields satisfactory handling.

2.1 *deg* **(Apollo LM Ascent Mean)**
The lack of commentary in post-flight debriefings concerning rotational coupling, despite significant commentary concerning other handling issues, suggests that this degree of rotational coupling yields satisfactory handling.

6.8 *deg* **(Apollo CSM Medium)**
The lack of commentary in post-flight debriefings concerning rotational coupling, despite significant commentary concerning other handling issues, suggests that this degree of rotational coupling yields satisfactory handling.

9.6 *deg* **(Apollo CM Single Ring RCS)**
The lack of commentary in post-flight debriefings concerning rotational coupling, despite significant commentary concerning other handling issues, suggests that this degree of rotational coupling yields satisfactory handling.

Rotational Coupling Angle $k_{ari}(deg)$	Handling Quality (Estimated)
$k_{ari} < 15.5$	Satisfactory
$15.5 < k_{ari}$	Unsatisfactory

Table 4.4: Impulse Attitude Control Coupling Estimated Handling

9.7 deg **(Shuttle Medium Pri RCS)**
The author has flown this configuration in the simulator and his judgement is that the spacecraft is satisfactorally controllable but that considerable effort is required to overcome the perturbing feedback caused by rotational coupling.

12.1 deg **(Shuttle Medium Vern RCS)**
The author has flown this configuration in the simulator and his judgement is that the spacecraft is satisfactorally controllable but that considerable effort is required to overcome the perturbing feedback caused by rotational coupling.

15.5 deg **(Interpolated Value)**
This interpolated value is halfway between 12.1 and 18.9 deg and is the estimated crossover point at which the coupling angle becomes too large for satisfactory handling.

18.9 deg **(Shuttle Medium Pri Tail-Only RCS)**
The author has flown this configuration in the simulator and his judgement is that the spacecraft does not have satisfactory handling qualities due to the effort required to compensate for rotational coupling.

4.5.3 With Proportional Rate Control

Proportional rate control using RCS effectors was being investigated as early as 1958 in simulation [78] and was determined to be significantly easier to fly than direct control. It was ultimately added to the third X-15 airframe as part of the MH-96 adaptive stability system and was generally praised by pilots for use in very low dynamic pressure environments. Following that it was incorporated into Mercury and all subsequent NASA manned spacecraft.

The most significant design parameter in this control mode is control authority. Engineering judgement suggests that there is a relationship between angular acceleration and the maximum attitude rate at which the spacecraft maneuvers. By analogy, consider than a very slow car, such as a Ford Model-T, is satisfactory with very poor brakes. In contrast, a very fast car, such as a Ferrari 812 Superfast, needs extremely powerful brakes to have satisfactory handling. Lacking any other information we also choose to the make the relationship linear. We also desire a parameter that increases numerically with control authority.

Thus we define the parameter k_{acpr} (Attitude Control Proportional Rate) to describe proportional rate control authority. As shown in equation 4.5, it is defined to be the RCS generated angular acceleration divided by the maximum commandable maneuver rate.

$$k_{acpr}(1/s) = \frac{RCS Angular Acceleration(deg/s^2)}{Maximum Maneuver Rate(deg/s)} \tag{4.5}$$

Analysis of historic vehicle proportional rate control authority yields the following:

0.05 $1/s$ **(Shuttle Entry Bank, No Yaw Jet Control, 6** deg/s **Max Rate)**

The author used a high-fidelity desktop simulator, normally used to train astronauts, to informally measure and evaluate proportional rate control during atmospheric entry. The Shuttle normally used a combination of RCS jets and aerosurfaces to perform banking maneuvers during entry at low dynamic pressures. However, certain failures require the disabling of RCS yaw jets and the reliance upon pure aerodynamic control. In this mode, angular acceleration is approximately 0.3 deg/s^2. With a maximum maneuver rate of 6 deg/s this yields unsatisfactory handling. There is a severe tendency to overshoot the desired attitude and the pilot is required to learn special compensation techniques to fly with adequate performance, yielding an estimated Cooper-Harper rating of 5. Although the spaceflight regime is different the banking maneuvers were flown without regard to guidance or entry trajectory making them roughly equivalent to orbital attitude control. This control authority is considered to be unsatisfactory.

0.1 $1/s$ **(Interpolated Value)**

This interpolated value is halfway between 0.17 and 0.05 $1/s$ and is the estimated crossover point at which there is sufficient control authority for satisfactory proportional rate attitude control.

0.17 $1/s$ **(Shuttle Entry Bank, Normal AeroJet Control, 6** deg/s **Max Rate)**

The author used a high-fidelity desktop simulator, normally used to train astronauts, to informally measure and evaluate proportional rate control during entry. The Shuttle normally used a combination of RCS jets and aerosurfaces to perform banking maneuvers during entry at low dynamic pressures. In this mode, angular acceleration is approximately 1 deg/s^2. With a maximum rate of 6 deg/s this yields satisfactory handling. There is a tendency to overshoot if banking aggressively, but this is easily controlled by deliberately ramping down the maneuver rate as you approach the desired attitude, yielding an estimated Cooper-Harper rating of 3. Although the spaceflight regime is different the banking maneuvers were flown without regard to guidance or entry trajectory making them roughly equivalent to orbital attitude control. This control authority is considered to be satisfactory.

0.53 $1/s$ **(Gemini (Early) OAMS All Axes)**

From the Gemini GT-3 debriefing, Young states that "Rate command was dead beat. It was just right on the money. When you let go after putting in a full rate command of 10 deg/s, it just stopped right now. You couldn't ask for any better control system." From the GT-5 debriefing, Cooper states that "Rate command has tremendous torquing. Boy, it's strong and it's instantaneous and you can just stop it right on the money. Really good." Later, he states "In the spacecraft you don't have to let off even a degree early. When you let go, it stopped right there just like you put on the brakes. [...] You almost had the feeling that the OAMS rate command was almost bending the adapter section. It had just high torquing rate." Conrad states that "I was extremely impressed with how nice a control system it was. We made several maneuvers using this control system and didn't have any gripes with that system at all." From the GT-6 debriefing, Schirra states that rate command was "Very crisp." This control authority is considered to be satisfactory.

0.70 $1/s$ **(Mercury RSCS Orbit All Axes)**

From the MR-4 debriefing, "The rate command system seemed to work much better to me than the manual system. [...] But the rates did damp out pretty well to within the limits that the system was designed to work, around 2 to 3 deg/s." From the MA-6 debriefing, "Rate command is a good mode for re-entry or for retrofire but is no good in orbit. You do not need that type of control." From the MA-7 debriefing, "It responded very well." This control authority is considered to be satisfactory.

0.70 $1/s$ **(Apollo CSM Heavy All Axes, 2.0** deg/s **Max Rate)**
From the Apollo 11 debriefing, Collins states that "[Handling characteristics were] absolutely normal. I docked in CMC[2], Auto, Narrow Deadband, with a 2 deg/s rate." This control authority is considered to be satisfactory.

0.82 $1/s$ **(Gemini (Early) RCS Single Ring All Axes)**
From the GT-5 debriefing, Cooper states that "The trainer doesn't have anywhere near the brute power that the actual RCS rate command has." From the GT-6 debriefing, Schirra states that "Rate command was stronger and had more authority than rate command on the OAMS." From the GT-7 debriefing, Borman states that "I think it is a very good mode." This control authority is considered to be satisfactory. (Note the difference in language used by Cooper (GT-5) and Schirra (GT-6) here versus the 0.53 $1/s$ control authority associated with OAMS attitude control. The stronger language here, with all other factors held constant, tends to support the definition of control authority being used.)

1.12 $1/s$ **(Apollo LM Pre-PDI All Axes, 4** deg/s **Max Rate)**
From the Apollo 9 debriefing, McDivitt states that "When the Command Module began his RCS separation burn, I began tracking him in PGNCS[3] Rate Command. [It] provides a very good control system. I was in fine (4 deg/s max) scaling. I was able to track him as he moved away; the rates went to about 1 deg/s and he was easily tracked in this mode." He later adds that "The DAP operation was smooth with no overshoot. It appeared to be a very fine control system, both for attitude holding, automatic maneuvers, and manually commanded rate command." This control authority is considered to be satisfactory.

[2] Command Module Computer
[3] Primary Guidance Navigation and Control System

Control Authority $k_{acpr}(1/s)$	Handling Quality (Estimated)
$k_{acpr} < 0.1$	Unsatisfactory
$0.1 < k_{acpr}$	Satisfactory

Table 4.5: Proportional Rate Attitude Control Authorities Estimated Handling

2.78 $1/s$ **(Apollo CSM Heavy All Axes, 0.5** deg/s **Max Rate)**
From the Apollo 9 debriefing, Scott states "Both the SCS[4] and the CMC DAP[5] were good solid control systems, and the docking task was relatively easy as far as aligning with the standoff cross and doing the actual contact." From the Apollo 10 debriefing, Young states that "The CSM handled perfectly [for docking]. The handling characteristics are just exactly what they were in the simulator. It's easy to fly in auto control. There was nothing to it." (Note that 'auto' in this case refers to proportional rate, not fully automatic control.) This control authority is considered to be satisfactory.

The results of analyzing historic spacecraft performing coasting flight attitude control using proportional rate model are summarized in Table 4.5. The author estimates that values of k_{acpr} below 0.1 $1/s$ are likely to result in unsatisfactory handling due to sluggish response and difficulty controling overshoot. Values above 0.5 $1/s$ appear to yield excellent handling.

4.5.4 With Discrete Rate Control

Historically, discrete rate control was first used to manually control the attitude of the Saturn S-IVB upper stage while the Apollo CSM was still attached in the event of a Saturn guidance failure. This capability was used only once, during the Apollo 7 mission, for a control test. During coasting flight after reaching orbit the crew enabled manual control, performed simple attitude maneuvers, and reenabled automatic control. Subsequently, discrete rate control was implemented for the Space Shuttle for use during orbital coasting flight.

[4]Stabilization and Control System
[5]Dightal Auto-Pilot

Spacecraft (Configuration)	Angular Accel (deg/s^2)	Discrete Mnvr Rate (deg/s)	Control Authority $(1/s)$
S-IVB Roll (Apollo 7)	1.91	0.5	3.8
S-IVB Pitch (Apollo 7)	0.47	0.3	1.6
S-IVB Yaw (Apollo 7)	0.94	0.3	3.1
S-IVB Mean (Apollo 7)	N/A	N/A	2.8
Shuttle Primary RCS (All Jets)	0.89	0.5	1.8
Shuttle Primary RCS (Tail Only Jets)	0.60	0.13	4.6
Shuttle Vernier RCS	0.02	0.2	0.1

Table 4.6: Historic Rotational Control Authorities (Discrete Rate)

As with proportional rate control, we desire a control authority design parameter that numerically increases with increasing control authority, and we assume that there is a handling qualities relationship between the discrete maneuver rate and angular acceleration capability. We also asume this relationship is linear.

Thus we define the parameter k_{acdr} (Attitude Control Discrete Rate) to describe discrete rate control authority. As shown in equation 4.6, it is defined to be the RCS generated angular acceleration divided by the discrete angular rate.

$$k_{acdr}(1/s) = \frac{RCS Angular Acceleration(deg/s^2)}{Discrete Angular Rate(deg/s)} \tag{4.6}$$

Table 4.6 presents summary control authority data for discrete rate control of historic spacecraft. Shuttle maneuvering rates are the maximum rates with reasonable expectation of being manually flown in those configurations as of STS-133. The Primary RCS All Jets configuration rate is used for manual maneuvers in preparation for translational burns. The Primary RCS

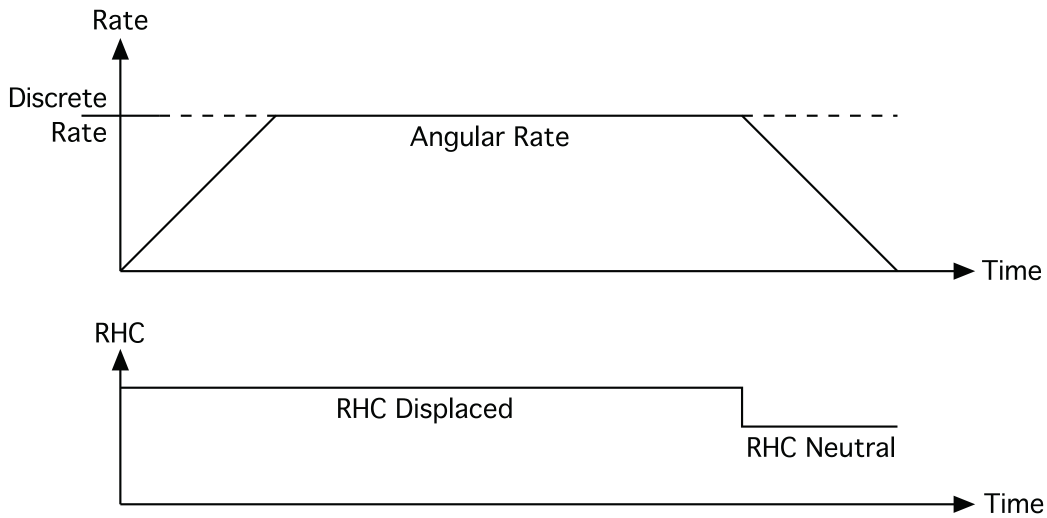

Figure 4.6: Normal Discrete Rate Control (Good Control Authority)

Tail Only configuration is used for manually flown proximity operations in the vicinity of the ISS. The Vernier configuration is for general purpose use.

Figure 4.6 conceptually illustrates normal discrete rate control. The pilot displaces the RHC causing the spacecraft to fire RCS jets and perform angular acceleration up to the discrete rate. Once the discrete rate is achieved the RCS jets stop firing and the spacecraft coasts at the discrete rate until the RHC is neutralized. This commands zero angular rate and RCS fire to slow the spacecraft to a stop. This behavior is observed when the spacecraft has enough control authority that it can stop quickly when the RHC is returned to neutral. This allows the pilot to not worry about overshoot; she can simply wait until the spacecraft is very close to the desired attitude and neutralize the RHC to immediately stop the rotation.

When insufficient control authority exists, several compensatory behaviors may be observed. Most benignly, the pilot will, though experience, have a good mental model for how much angular distance is required to stop from the discrete rate and will therefore lead the vehicle by that amount by returning the RHC to neutral early and allowing the spacecraft to decelerate and stop at the desired attitude. The author denotes this as Type 1 compensation behavior.

A second compensatory behavior may be observed when a small attitude maneuver, less than the angular distance required to accelerate to discrete

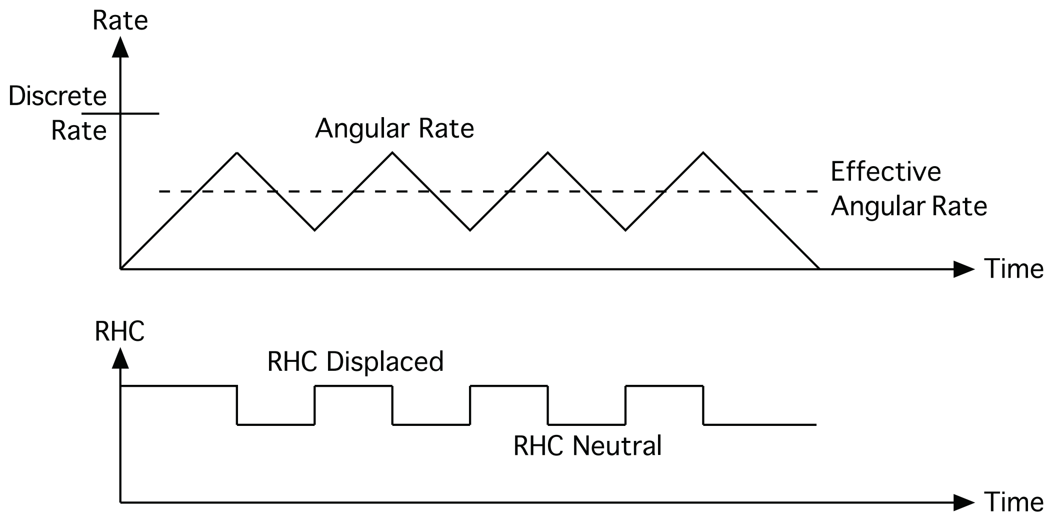

Figure 4.7: Abnormal Discrete Rate Control (Low Control Authority)

rate, is required. (This often happens when the pilot attempts to lead the attitude as described previously but misjudges the required distance.) The behavior is for the pilot to note the angular distance between the current and desired attitudes, estimate the midpoint, and use crossing the midpoint as the cue for returning the RHC to neutral. The author denotes this as Type 2 compensation behavior.

The third observable behavior used to cope with poor control authority is conceptually illustrated in Figure 4.7. The pilot cycles the RHC between the displaced and neutral positions causing the spacecraft to alternate between angular acceleration and deceleration. By doing so the pilot can achieve an effective maneuvering rate below the discrete rate. This shortens the angular distance required to stop, and hence the required lead, when the RHC is finally returned to neutral. This technique may be useful to fly to a very precise attitude with poor control authority but it requires virtually continuous RCS jet firing and is therefore extremely inefficient in propellant usage. The author denotes this as Type 3 compensation behavior.

Observation of any of these three compensatory behaviors are an indication that the spacecraft has insufficient control authority for satisfactory handling in the discrete rate mode. To achieve satisfactory handling the angular acceleration must be increased, the discrete rate decreased, or both.

Unfortunately there appears to be very little historic pilot commentary

Spacecraft Config	Mean Angular Accel (deg/s^2)	Discrete Rate (deg/s)	k_{acdr} ($1/s$)
Shuttle Pri RCS (All)	0.893	0.576	1.55
Shuttle Pri RCS (Tail Only)	0.603	0.389	1.55
Shuttle Vern RCS	0.02	0.013	1.55

Table 4.7: Discrete Rate Equivalence Evaluation

from which an evaluation of handling can be made. Therefore an informal evalation of discrete rate attitude control was performed by the author using a desktop simulator equipped with flight-like hand controls normally used to train Space Shuttle pilots. The simulator emulates Space Shuttle orbital flight software and dynamics.

The first task was to evaluate any differences in perceived control authority with k_{acdr} held constant. A limited number of angular accelerations were available by configuring the spacecraft's attitude control system. For each value of angular acceleration the discrete maneuver rate, a software parameter, was varied to yield the same value of k_{acdr}. The lowest Saturn S-IVB control authority, 1.55 ($1/s$) was used with the Shuttle configured to use Primary All, Primary Tail-Only, and Vernier RCS jets to give variable angular acceleration. The three configurations are documented in Table 4.7.

Each run began with the attitude displaced in all three axes away from the desired attitude. The task was to fly to the desired attitude with less than 1 degree of attitude error per axis. Each configuration was judged to have Cooper-Harper Level 1 handing qualities because virtually no pilot compensation was required to perform that task with satisfactory performance. In each case it was easy to wait until the attitude was within the desired error and return the RHC to neutral. The (simulated) spacecraft appeared to have negligable overshoot.

This result supports the use of the linear relationship used to define k_{acdr} as shown in equation 4.6. It is also compatible with the lack of any reported control problems during the Saturn S-IVB control test on Apollo 7.

The second task was to evaluate low proportional rate control authorities using the same fly-to maneuver described previously. General attitude con-

Control Authority $k_{acdr}(1/s)$	Handling Quality (Estimated)
$k_{acdr} < 0.1$	Unsatisfactory
$0.1 < k_{acdr}$	Satisfactory

Table 4.8: Discrete Rate Attitude Control Authorities Estimated Handling

trol using Vernier RCS at k_{acpr} equal to 0.1, as on a normal Shuttle mission, was judged to have Cooper-Harper Level 1 handing qualities, although with a Rating of 3. This was due to the noticable overshoot tendency that required additional pilot compensation to overcome. Type 1 and 2 compensation were used to manage the overshoot tendency.

At lower control authorities, k_{acpr} equal to 0.07 and 0.05, the overshoot tendency was judged to be significantly worse and required Type 3 compensation behavior. Handling was judged to be Cooper-Harper Level 2 and unsatisfactory.

In conclusion, satisfactory handling for proportional rate attitude control appears to require that k_{acpr} be approximately 0.1 $(1/s)$ or greater. This result is summarized in Table 4.8.

4.6 Powered Flight with Reaction Control

The primary characteristic of powered flight with reaction control is that the translational thrust force vector is in general not directed through the vehicle's center of mass. As a result powered flight creates an attitude perturbing moment that must be countered in order to perform attitude control. An equivalent condition occurs when multiple thrust sources, such as RCS jets, are used for translation and create a non-zero net moment. Examples of this include Gemini +X and Shuttle +X RCS translation.

A significant historic case is the Apollo Lunar Module (LM) ascent stage. The Ascent Propulsion System (APS) engine was fixed (non-gimbaling), meaning that the entire ascent from lunar surface to orbit was conducted in this flight regime. This presents a challenge because, as approximately half the total liftoff mass is consumed as propellant during ascent, the center of mass location moves significantly. There is, as a result, no single direction in which to point the APS thrust vector so as to avoid creating a perturbing moment and, since APS thrust is large, the perturbing moment could potentially also grow large enough to present a control problem. The design fix was to point the thrust vector such that the center of mass moves through the thrust vector when approximately the 50% of the propellant has been consumed. At liftoff the perturbing moment is in the pitch up direction. The moment then decreases as the center of mass moves towards and through the thrust vector. The perturbing moment then begins increasing in the pitch down direction. This design limits the magnitude of the worst case perturbing moment to the smallest possible value.

The dominant perturbing moment for historic spacecraft in this flight regime is in pitch. Therefore, consider a typical spacecraft with a pitch up pertubing moment. It follows that it will have more attitude control authority in the direction of the perturbing moment, pitch up, and less attitude control authority in the opposing direction, pitch down.

To evaluate handling in this regime we assume that the critical values for satisfactory control authority determined for coasting flight attitude control still hold in powered flight despite the presence of a perturbing moment. For example, a minimum value of angular acceleration must still be achieved despite having to overcome an opposing perturbing moment. A variety of historic vehicles using direct, proportional rate, and discrete rate control are evaluated and shown to be compliant with this constraint. Impulse is inappropriate to use in this regime because it is optimized for fine attitude control during coasting flight and would normally lack sufficient control authority.

4.6.1 With Direct Control

Two historic cases exist for direct rotational control in this regime.

The first case is a contingency deorbit procedure for the Apollo CSM. The deorbit burn is normally done using the Service Module (SM) Service Propulsion System (SPS) engine, followed shortly by the Command Module (CM) separating from the SM. The CM RCS, which is designed for attitude control only, not translation, is then used during exoatmospheric coast and atmospheric entry. In the event that the Service Module could not complete the deorbit burn using the SM SPS or SM RCS, there was a contingency capability known as the "hybrid deorbit" in which the CM RCS was used for translation. Although never performed in reality, it was a standard procedure that was simulated and known to be controllable. To perform the maneuver the CM would separate from the SM and rotate to the deorbit attitude. The

Spacecraft Config	-Pitch CA $k_{acd}(deg/s^2)$	+Pitch CA $k_{acd}(deg/s^2)$	Required CA $k_{acd}(deg/s^2)$
Apollo CM Hybrid Deorbit (1 CM RCS System)	3.92	1.70	$0.3 < k_{acd} < 12.7$
Apollo CM Hybrid Deorbit (2 CM RCS Systems)	7.85	3.41	$0.3 < k_{acd} < 12.7$
Apollo LM Liftoff (2 jet unbalanced)	12.63	23.81	$0.3 < k_{acd} < 12.7$
Apollo LM Docking (2 jet unbalanced)	28.48	14.83	$0.3 < k_{acd} < 12.7$

Table 4.9: Historic Powered Flight RCS with Direct Control

attitude control system would then be put into direct and one crewmember would continuously command pitch down with one Rotational Hand Controller (RHC) while a second crew member would alternate between pitching up and neutralizing the second RHC to control attitude. This works because pitch up and pitch down jets both fire in approximately the -Z direction. The pitch down jet, which has less control authority, is located forward of the center of mass. The pitch up jet, which has more control authority, is located aft of the center of mass. The spacecraft translates in the +Z direction pitching up and down as the pitch up jets are cycled on and off to maintain attitude. The overall effect is +Z translation with pitch down perturbing moment.

The second case is Apollo Lunar Module (LM) ascent from the lunar surface with a failed guidance, navigation, and control system. Discussion of this failure is documented in Tindall [137]. In this memo Tindall notes "Without a rate command attitude control system it is extremely doubtful they could achieve orbit even if they had trained throughly in the technique." This is assumed to mean that the vehicle would have unsatisfactory handling if flown in this control mode.

These results are summarized in Table 4.9. Note that the Apollo CM hybrid deorbit meets the assumed requirement for satisfactory handling with either one or two CM RCS systems in use. This is consistent with the procedure being known to be usable by the crew. In contrast the Apollo LM

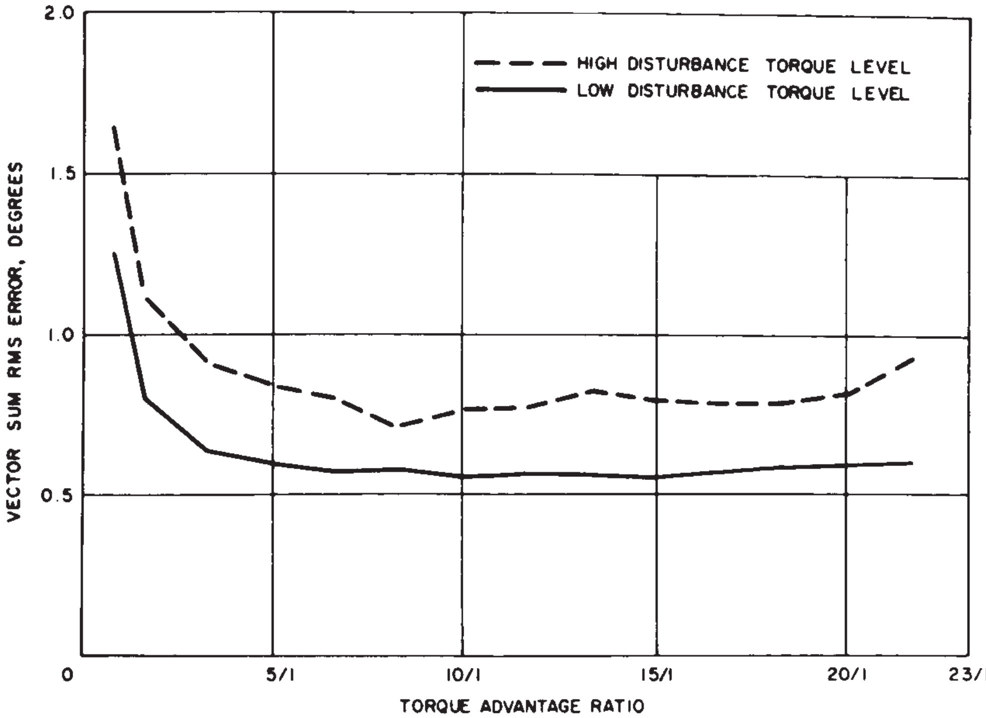

Figure 4.8: Vector Sum RMS Error as Function of TAR [44]

during lunar ascent, using the direct control mode, only barely meets the handling requirement at liftoff for pitch down and exceeds it for all other cases. This is consistent with contemporary documention suggesting that it was known to be unsatisfactory. (Note that the 'docking' configuration for the LM has nearly the same mass properties as at the end of ascent powered flight. Also, 'unbalanced' refers to a special mode in which upward firing RCS jets are disabled during ascent so as to maximize performance.)

An additional design parameter in this context comes from Besco [44]. He defines the *Torque Advantage Ratio* (TAR) as the ratio of direct control torque to disturbance torque. (An equivalent measure, more consistent with this work, is the ratio between direct angular acceleration and the angular acceleration created by the disturbance moment.) Besco describes a test in which the piloting task is to perform attitude hold in the presence of a disturbing torque. Attitude error as a function of TAR, for two levels of disturbance torque, is shown in Figure 4.8. As can be seen, attitude error

Torque Advantage Ratio (TAR) k_{tar}	Handling Quality (Estimated)
$k_{tar} < 3$	Unsatisfactory
$3 < k_{tar}$	Satisfactory

Table 4.10: Torque Advantage Ratio (TAR) Estimated Handling

increases significantly below a ratio of approximately 3 to 1. Besco notes that error is minimized for TAR between 7 and 10.

Thus we define the design parameter k_{tar}, as per Besco, in Equation 4.7. The critical value, as seen in Table 4.10, is an approximation of the inflection point at which attitude error was shown to increase significantly with further reduction.

$$k_{tar} = \frac{DirectControlTorque}{DisturbanceTorque} \tag{4.7}$$

The Apollo CM hybrid deorbit case discussed previously can be described as a direct control angular acceleration of 2.81 deg/s^2 combined with a disturbing angular acceleration of 1.11 deg/s^2 (both in pitch). This yields k_{tar} = 2.5. Although close, this value is not considered satisfactory per the stated requirement stated here. Recall that a vehicle can have unsatisfactory handling but still be controllable.

4.6.2 With Proportional Rate Control

Table 4.11 summarizes the control authorities for several historic vehicles performing proportional rate attitude control during translational flight. All vehicles appear to meet the requirement for satisfactory handling by having sufficient rotational control authority despite a perturbing moment.

4.6.3 With Discrete Rate Control

Historically, only the Space Shuttle employed discrete rate in this regime. The Shuttle could use either two or four +X (aft firing) jets for significant translational maneuvers when the Orbital Maneuvering System (OMS) engines were unavailable. In general, two +X jets (2+X) would be used for

Spacecraft Config	-Pitch CA $k_{acpr}(1/s)$	+Pitch CA $k_{acpr}(1/s)$	Required CA $k_{acpr}(1/s)$
Gemini	0.41	0.46	$0.1 < k_{acpr}$
Apollo CSM Heavy (2 deg/s)	0.52	0.47	$0.1 < k_{acpr}$
Apollo LM Ascent Stage (Liftoff)	3.16	5.95	$0.1 < k_{acpr}$
Apollo LM Ascent Stage (Docking)	7.12	3.71	$0.1 < k_{acpr}$

Table 4.11: Historic Powered Flight RCS with Proportional Rate Control

Spacecraft Config	-Pitch CA $k_{acdr}(1/s)$	+Pitch CA $k_{acdr}(1/s)$	Required CA $k_{acdr}(1/s)$
Shuttle Medium 2+X 0.5 deg/s Rate	1.76	2.14	$0.1 < k_{acdr}$
Shuttle Light 4+X 0.5 deg/s Rate	1.94	2.22	$0.1 < k_{acdr}$

Table 4.12: Historic Powered Flight RCS with Discrete Rate Attitude Control

relatively small orbital maneuvers, such as for rendezvous, while four +X jets (4+X) would be used for large deorbit burns.

Table 4.12 shows historic discrete rate control authorities for a Space Shuttle performing a rendezvous burn (medium weight, two +X jets, nose and tail control) and a deorbit burn (light weight, four +X jets, nose and tail control). In both cases the Shuttle meets the requirement for satisfactory handling despite the presence of a perturbing moment.

Spacecraft	Max Gimbal Angle (deg)	Gimbal Rate (deg/s)	Time to Max (s)
Apollo SPS	4.5	5.7	0.8
Shuttle OMS (Yaw)	7.0	5.0	1.4
Shuttle OMS (Pitch)	6.0	5.0	1.2
Shuttle MPS (Yaw)	8.5	8.0	1.1
Shuttle MPS (Pitch)	10.5	8.0	1.3

Table 4.13: Historic Engine Gimbal Characteristics

4.7 Powered Flight with Thrust Vector Control

The distinguishing characteristic of powered flight with thrust vector control is that attitude control is performed using the moment created by pointing the thrust vector away from the center of mass. Since the moment can be varied continuously from zero (thrust through center of mass) to a maximum value (engine at maximum gimbal limit), this regime is ideally suited for proportional rate attitude control.

Note that in order to simplify analysis we generally assume a single thrusting and gimbaling engine. In such a vehicle thrust vector control is typically used to control pitch and yaw while roll is controlled via RCS. This is obviously not the case for the Space Shuttle Main Propulsion System (MPS) with three engines, or Shuttle Orbital Maneuvering System (OMS) with two engines. In these systems a software component known as the "TVC Mixer" take as input the desired roll, pitch, and yaw commands and outputs the TVC gimbal positions for all engines. Roll is performed by making the thrust vectors non-parallel by biasing one engine positive in pitch and the other negative in pitch thereby creating a roll moment. The Shuttle control system prioritizes pitch over roll in that the applied roll bias is limited to the remaining actuator travel after the pitch position has been determined.

To analyze thrust vector control we first note the historic similarities in gimbal systems. This is shown in Table 4.13. (Note that all actuators are electric except for the Shuttle MPS which uses hydraulic actuators.) The mean time from null to maximum deflection is about 1.2 seconds. This appears to be a satisfactorily quick time for the spacecraft to go from zero to maximum angular acceleration and is assumed to not change significantly for future vehicles.

Consider the angular acceleration resulting from a gimbaling engine at maximum actuator deflection. Numeric simulations of vehicles using with low angular acceleration in that configuration show that in response to pilot input the engine will tend to gimbal to maximum deflection and stay there until nearly at the desired angular rate. As the desired rate is approached the engine will rapidly gimbal to the null position. In other words, the critical design parameter for thrust vector control appears to be the angular acceleration resulting from the engine(s) at maximum gimbal deflection. If we neglect the time required to gimbal from null to maximum, or vice versa, we then have a system conceptually similar to coasting flight attitude control using RCS jets and a proportional rate controls sytem.

$$k_{tvc}(1/s) = \frac{TVCMaxAngularAcceleration(deg/s^2)}{MaxAngularRate(deg/s)} \tag{4.8}$$

Therefore we define the design parameter k_{tvc} to be the mean pitch and yaw angular acceleration resulting from the thrusting engine at maximum deflection divided by the maximum angular rate of the vehicle that can be commanded. This is conceptually similar to the definition of control authority used earlier for proportional rate control during coasting flight and is shown in Equation 4.8.

Table 4.14 shows historic values for k_{tvc} for configurations known to manually flown. The Apollo 7 crew reported that their burn was "Easy to control." The Apollo 9 crew reported that "the [attitude error] needles could be nulled without difficulty." These cases are therefore judged to have satisfactory handling qualities.

The table entry for STS-135 refers to testing performed by the author using the Shuttle Mission Simulator (SMS) that is documented in Chapter 6. In brief, the author rated this configuration as having satisfactory handling qualities.

In conclusion, the Apollo 7 and 9 configurations have significantly more control authority than the STS-135 case and are therefore compatible with author's assessment that the Shuttle also exhibits satisfactory handling. Data

Vehicle	Mean PY Accel (deg/s^2)	Max Mnvr Rate (deg/s)	k_{tvc} ($1/s$)
Apollo 7 (SPS Burn 5)	19.5	0.7	27.9
Apollo 9 (SPS Burn 3)	5.2	0.7	7.4
Shuttle STS-135 (2 OMS Deorbit)	0.33	2.0	0.2

Table 4.14: Historic TVC Maximum Angular Accelerations

Control Authority $k_{tvc}(1/s)$	Handling Quality (Estimated)
$k_{tvc} < 0.1$	Unsatisfactory
$0.1 < k_{tvc}$	Satisfactory

Table 4.15: Powered Flight with TVC Estimated Handling

from the Shuttle simulator testing indicates that the lowest value of k_{tvc} that yields satisfactory handling is 0.1 $1/s$. This result is described in detail in Chapter 6 and is presented here in Table 4.15.

4.8 Docking

In this section we consider the handling qualities of an active spacecraft performing an approach and docking to a passive spacecraft or space station.

Docking can be thought of as the final of three steps to bring two spacecraft together. The first step, rendezvous, brings the active vehicle from an arbitrarily large range to within the proximity of the target vehicle. Rendezvous is purely an orbital mechanics process consisting of, from a piloting viewpoint, a series of translational maneuvers, so-called 'rendezvous burns,' at specific times. During rendezvous the target can be thought of as a point in space. Thus rendezvous consists of coasting flight attitude control (page 53) and some combination of powered flight with reaction control (page 74) and powered flight with thrust vector control (page 80). During a typical mission to the International Space Station (ISS) the Space Shuttle would perform rendezvous for about two days.

The second step, proximity operations, is the process of manually maneuvering the active vehicle with respect to the target vehicle, usually for the purpose of preparing to dock. In contrast to rendezvous, the target is now a three dimensional object and orbital mechanics can be thought of as a perturbing influence upon relative motion. As an example, the Shuttle's transition between rendezvous and proximity operations occured when the Shuttle came to relative motion stop approximately 600 feet below the ISS. At this point the Shuttle began maneuvering with respect to the station to position itself approximately 600 feet in front of and at the same altitude as the ISS within the so-called 'approach corridor.' (The ISS docking mechanism was located on the front of the station.)

The third step, docking, consists of flying the active vehicle along the approach corridor and making contact within the constraints imposed by the docking mechanism. These constraints typically consist of attitude and attitude rate tolerance, radial (perpendicular to the approach) position and rate tolerance, and approach rate tolerance.

When comparing proximity operations to docking, docking appears to be more constraining to spacecraft design. Research has indicated that pilots appear to prefer increased translational control authority at larger distances from the target when coarse alignment and positioning is being performed [120]. However, translational requirements can always be met with longer RCS jet firing times. (Although one could imagine a spacecraft with such limited translational control authority that proximity operations become difficult, such a spacecraft is unlikely to meet other mission requirements.) In contrast, fine translational control during docking is limited by the minimum translational impulse the RCS jet is capable of producing. In other words, one could easily imagine a spacecraft design that is suitable for all other tasks but which is incapable of the fine translational control required for docking. With this in mind, this document limits itself to handling qualities associated with docking under the assumption that a spacecraft that is satisfactory for docking will likely also be satisfactory for proximity operations.

With regards to rotational control modes during docking, numerous studies compared modes without attitude hold (direct, impulse) to modes with attitude hold (proportional rate, discrete rate) [74] [125] [142] [82] [116] [120] and determined that modes with attitude hold yield improved handling and are more tolerant of coupling and variation in control authority. This result makes intuitive sense in that a six degree of freedom control problem is, coupling aside, reduced to a three degree of freedom control problem. We assume that docking will be performed in a stabilized attitude and we need only address translational control.

With regards to translational control authority, studies generally show improvement in radial position error at contact for smaller values of linear acceleration or when using a translational impulse mode [74] [125] [94] [142] [123] [120] [76]. However, there appears to be a lower limit at which last moment trajectory corrections prior to contact become difficult because of insufficient control authority [125]. This result also makes intuitive sense in that there is a satisfactory range of control authority in which below some critical value the spacecraft is too sluggish and above some critical value the spacecraft becomes hard to control with the required precision.

Because translation during docking requires precise control, this section assumes that the pilot will make the shortest possible THC input when using normal translational control. Recall that an automated impulse translation mode only became available with the Space Shuttle, all previous vehicles are limited to normal translation.[6] To estimate the size of these inputs we use the estimated minimum manual impulse time, 0.1 s, derived on page 50.

4.8.1 Attitude Hold and Rotational to Translational Coupling

A 2008 conference paper by Bailey, et al [39] documents an investigation into how RCS design affects handling during docking. Dockings were flown using both direct and discrete rate (with attitude hold) attitude control, translation was normal. The authors report improved pilot ratings when using discrete rate, as would be expected. However, they note that the improvement was relatively small. To explain this they note the workload associated with monitoring the vehicle's attitude within the attitude hold deadband and coping with the rotational to translational coupling effects as attitude control jets fire at the edge of the attitude deadband. This is an interesting result because this effect is not addressed at length in older reports from the 1960s.

To explain this it should first be noted that, assuming fully functional RCS, the Apollo CSM and LM both generate pure couples about all axes

[6] Recall that normal translation is a mode in which continuous RCS jet firing occurs for as long as the THC is displaced. See page 27 for more information.

due to their jet layouts. These vehicles should therefore exhibit very little rotational to translational coupling. Gemini, conversely, generates a pure couple only in roll. Pitch and yaw couple significantly into Z and Y-axis translation respectively.

The primary difference between the two cases, Gemini and Bailey simulated vehicle docking, appears to be the radial position tolerance within the docking mechanisms. In the case of Gemini (and Apollo) the mechanism supports up to 1 ft (12 in) of radial position error. By contrast, the Bailey vehicle docking mechanism supports approximately 3 in of radial position error. (This smaller value is characteristic of modern docking mechanisms.)

Now consider a perturbing translational impulse of some specific magnitude in ft/s. Such an impulse would be caused by a vehicle that exhiibits rotational to translational coupling as it fires an RCS jet to remain within its attitude hold deadband. A vehicle accelerated by that translation impulse will reach the radial edge of the docking corridor four times faster in the Bailey vehicle than in Gemini. Alternatively, the Bailey vehicle can be thought of as being four times more sensitive to a perturbing translational impulse.

$$k_{drtc}(1/s) = \frac{PerturbingRadialTranslationImpulse(ft/s)}{RadialPositionTolerance(ft)} \tag{4.9}$$

The author therefore proposes that there is a relationship between the magnitude of the perturbing translational impulse created by a pitch or yaw attitude hold deadband firing and the radial position tolerance of the docking mechanism. This design parameter k_{drtc} (Docking Rotational Translational Coupling) is defined in equation 4.9. This parameter can be thought of as describing how sensitive the docking mechanism is to spacecraft attitude control with regards to radial position. Larger values result in increased sensitivity. There is probably a critical value at which managing the effects of attitude control significantly increase pilot workload and worsen handling. The value for Gemini, using a 0.02 sec pitch or yaw jet firing, is estimated to be 0.004 $1/s$. Unfortunately, insufficient data exists to estimate the critical value for this parameter and determination of it is left as future work.

4.8.2 Design Parameters for Docking

Docking mechanisms will have a tolerance in approach velocity at contact. This is usually bounded on the low end by having enough energy to trigger

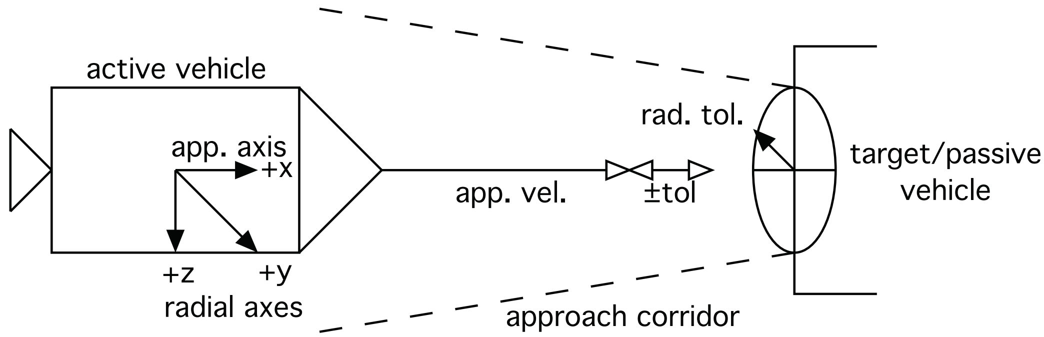

Figure 4.9: Docking Geometry

the capture latches and on the high end by the amount of energy the damping mechanism can absorb without damage. This is illustrated in Figure 4.9.

Thus we define the design parameter k_{dai} (Docking Approach Impulse) to be the minimum translational impulse magnitude along the approach axis divided by the approach velocity tolerance defined previously. If the impulse magnitude is different for approach and braking we use the mean value. This parameter is intended to describe the ease with which the pilot can control the approach velocity to be within the constraint.

$$k_{dai} = \frac{MinimumApproachImpulseMagnitude(ft/s)}{ApproachVelocityTolerance(ft/s)} \tag{4.10}$$

Docking mechanisms must also be able to tolerate some amount of angular misalignment at contact. However, this analysis assumes that both the active and target vehicles are stabilized in attitude and that any angular misalignment due to attitude deadbands is within the tolerance of the docking mechanisms. In other words, for purposes of defining requirements for satisfactory handling docking is assumed to be a three degree of freedom problem.

With regards to the radial axes, docking mechanisms will often have requirements that specify tolerances in radial position and radial velocity. However, a study by Russo and Freeberg [125] noted that failures to dock within radial tolerances were more commonly due to radial position rather than radial velocity. In fact, all such failures were due to position rather than velocity. Therefore, for purposes of analyzing handling, we neglect radial velocity and consider radial position only.

Active Vehicle	Target Vehicle	Req'd Approach Velocity (ft/s)
Gemini	Agena	0.83 ± 0.68
Apollo CSM	Apollo LM	0.55 ± 0.45
Apollo CSM+DM	Soyuz 7K-TM	0.58 ± 0.42
Shuttle	ISS	0.10 ± 0.03

Table 4.16: Historic Docking System Required Approach Velocities at Contact

We define the parameter k_{dri} (Docking Radial Impulse) to be the minimum radial translational impulse magnitude divided by the docking mechanism's radial position tolerance. For vehicles with different minimum translational impulse magnitudes along the two radial axes we use the mean value. This is justified by the fact that both axes must be controlled and that the values are historically similar in magnitude. This parameter is intended to describe the ease with which the pilot can control the radial position within the allowed tolerance.

$$k_{dri}(1/s) = \frac{MinimumRadialImpulseMagnitude(ft/s)}{RadialMisalignmentTolerance(ft)} \tag{4.11}$$

4.8.3 Approach Control Authority

Historic required contact velocities with associated tolerances are shown in Table 4.16. The values for Apollo CSM/LM, and Apollo CSM/Soyuz are as specified in program documentation. The Gemini/Agena docking system has no minimum approach velocity requirement that can be found by the author. That value is assumed to be 10% of the maximum contact velocity to be in character with other docking systems.

Table 4.17 shows historic approach control authorities for a number of vehicles. Little pilot rating data exists concerning this aspect of handling. We therefore estimate that k_{dai} will yield satisfactory handling between 0.02 and 1.0. This is shown in Table 4.18.

Active Vehicle	Target Vehicle	Impulse (ft/s)	Tolerance (ft/s)	k_{dai} (-)
Apollo CSM (Heavy)	Apollo LM (with S-IVB)	0.01	0.45	0.022
Soyuz 7K-TM (ASTP)	Apollo CSM+DM (ASTP)	0.01	0.42	0.024
Apollo CSM (Medium)	Apollo LM (Ascent Only)	0.017	0.45	0.038
Apollo CSM+DM (ASTP)	Soyuz 7K-TM (ASTP)	0.022	0.42	0.052
Gemini	Agena	0.066	0.68	0.097
Apollo LM (Apollo 9)	Apollo CSM (Apollo 9)	0.065	0.45	0.144
Shuttle (Medium)	ISS	0.035	0.03	1.167

Table 4.17: Historic Docking Approach Control Authorities

Control Authority $k_{dai}(unitless)$	Handling Quality (Estimated)
$k_{dai} < 0.02$	Unsatisfactory
$0.02 < k_{dai} < 1.0$	Satisfactory
$1.0 < k_{dai}$	Unsatisfactory

Table 4.18: Docking Approach Estimated Handling

Active Vehicle	Target Vehicle	Radial Tolerance (ft)
Gemini	Agena	1.0
Apollo CSM	Apollo LM	1.0
Apollo CSM+DM	Soyuz 7K-TM	1.0
Shuttle	ISS	0.25

Table 4.19: Historic Docking System Radial Position Tolerances

Active Vehicle	Target Vehicle	Impulse (ft/s)	Tolerance (ft)	k_{dri} ($1/s$)
Apollo CSM (Heavy)	Apollo LM (with S-IVB)	0.01	1.0	0.01
Soyuz 7K-TM (ASTP)	Apollo CSM+DM (ASTP)	0.01	1.0	0.01
Apollo CSM (Medium)	Apollo LM (Ascent Only)	0.017	1.0	0.017
Apollo CSM+DM (ASTP)	Soyuz 7K-TM (ASTP)	0.022	1.0	0.022
Gemini	Agena	0.041	1.0	0.041
Apollo LM (Apollo 9)	Apollo CSM (Apollo 9)	0.065	1.0	0.065
Shuttle (Medium)	ISS	0.017	0.25	0.068
Willman Optimum	Simulation	0.1	1.0	0.1
Willman Sat/Unsat Boundary	Simulation	0.22	1.0	0.22

Table 4.20: Historic Docking Radial Position Control Authorities

4.8.4 Radial Position Control Authority

Radial position tolerances for historic docking systems are shown in Table 4.19.

In Willman's 1963 study [142], docking simulator tests of a preliminary Lunar Module design suggests that optimal radial translational control authority was found at approximately 0.1 $1/s$ and that the transition between satisfactory and unsatisfactory control occurs at approximately 0.22 $1/s$. The radial position tolerance is not stated in the study but is assumed to be 1 ft. This assumption is supported by a description of the docking system selection and development process described in [89]. According to that description, a 1 ft radial tolerance was part of the initial set of assumptions and groundrules for studies and tests that began in 1962. Thus it is reasonable to expect that Williman used the same parameters in his 1963 study.

Another 1963 study, by Hackler et al [74], suggests an optimal radial acceleration of approximately 1.6 ft/s^2. By our usual methodology of estimating minimum manual translational impulse, this equates to an impulse of 0.16 ft/s. The paper is somewhat vague on radial tolerance, stating that pilots were not given guidance with regards to it. However, the paper states that "The significance of a position error of 4 inches is dependent upon the capability of the docking fixture to compensate for misalignments." If this is the assumed tolerance, the stated acceleration would result in a control authority metric of approximately 0.48 $1/s$.

With regards to Apollo CSM active docking, the Apollo 9 crew reported [100] that "[T]he (CSM) docking task was relatively easy as far as the aligning with the standoff cross and doing the actual contact." (See page 304.) The Apollo 10 crew reported [62] that during the initial transposition and docking maneuver the CSM handled "perfectly" and that "It's easy to fly in AUTO [-matic attitude] control. There was nothing to it." (See page 317.) The Apollo 11 crew reported [63] that "Docking [after transposition], as in the simulator, was very easy." (See page 318 in this document.) These three reports indicate agreement that the heavyweight Apollo CSM has very satisfactory handling qualities during docking.

During the LM active docking on Apollo 9, the LM voice transcript [101] quotes the Commander (CDR), flying the LM, as saying "Okay, I can see it now. This thing's really sporty." The Command Module Pilot (CMP) replies, "It sure is. I can tell." After the flight, in the debriefing [100], the CDR states "The light weight of the ascent stage made it so that I never really did stop the translation left/right and the horizontal components with respect to the docking probe and drogue. I had to thrust continually left and right and fore and aft, or whatever that other direction is, to keep myself within the boundaries of where I wanted to be prior to contact." (Note that for LM active docking the CDR had to use left/right and forward/aft THC inputs to control radial position with respect to the docking mechanism.) This indicates that the control authority for radial control during the Apollo 9 docking was very high and near the boundary for satisfactory versus unsatisfactory control. (Note that the Apollo 9 LM ascent stage was significantly more massive at docking than ascent stages used on lunar landing missions.)

Thus we have the following summary results:

0.01 $1/s$ **(Apollo CSM (Heavy) to Apollo LM and Saturn S-IVB)**
Numerous reports agree that this control authority results in satisfactory handling qualities.

Control Authority $k_{dri}(1/s)$	Handling Quality (Estimated)
$k_{dri} < 0.01$	Unsatisfactory
$0.01 < k_{dri} < 0.05$	Satisfactory
$0.05 < k_{dri} < 0.07$	Unsatisfactory but Controllable with Training
$0.007 < k_{dri}$	Unsatisfactory

Table 4.21: Docking Radial Tolerance Estimated Handling

0.017 $1/s$ **(Apollo CSM (Heavy) to Apollo LM Ascent Stage)**
There are no reports of difficulties performing this docking task and therefore this control authority is assumed to have satisfactory handling qualities.

0.04 $1/s$ **(Gemini to Agena)**
Crews reported no difficulties with docking and therefore this control authority is assumed to have satisfactory handling qualities.

0.05 $1/s$ **(Interpolated Value)**
This interpolated value, halfway between 0.04 and 0.065 $1/s$, is the estimated control authority at which handling transitions from being satisfactory to that which requires significant compensatory behavior (Apollo 9) or extensive training (Shuttle).

0.065 $1/s$ **(Apollo 9 LM to CSM)**
The Apollo 9 crew described the handling as "sporty" and noted difficulties with achieving a slow radial rate within the allowable radial tolerance.

0.068 $1/s$ **(Shuttle (Medium) to ISS)**
Achieving a satisfactory Shuttle docking is known to require extensive training.

Summarizing these results, radial control authority k_{dri} between 0.01 and 0.05 $1/s$ is estimated to result in satisfactory handling. Control authority between 0.05 and 0.07 $1/s$ is estimated to yield degraded handling that can be controlled with training. This is summarized in Table 4.21.

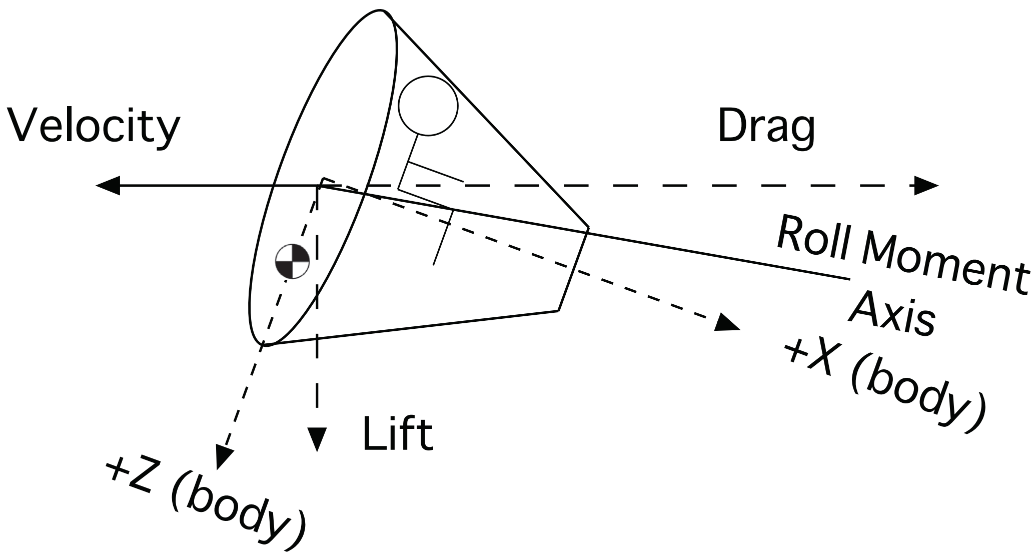

Figure 4.10: Entry vehicle in Aerodynamic Trim

4.9 Atmospheric Entry

This section considers a capsule spacecraft entering the atmosphere as a blunt body. Such a vehicle is typically stable during entry.[7] When the spacecraft has a center of mass offset from the axis of symmetry it will assume a trim position with a non-zero angle of attack, typically on the order of 10 to 20 *deg*, thereby creating lift that can be used to control the trajectory through the atmosphere. This design was used by Gemini, Apollo, and Soyuz, and will be used by the Orion spacecraft.[8]

Figure 4.10 illustrates a typical entry vehicle with the center of mass offset in the +Z direction. Lifting feetwise is common for packaging reasons and because it helps shield the windows, typically on the -Z side, from the plasma flow.

With regards to handling, we consider the attitude control of the space-

[7]The typical capsule shape is normally stable both blunt and apex forward, meaning that it absolutely must enter the atmosphere in the proper attitude lest it capture apex forward. Such an entry is almost certainly unsurvivable. Soyuz, notably, is only stable when blunt end forward and will rotate into that attitude aerodynamically.

[8]Mercury did not perform a lifting, guided entry. It was designed to roll continuously during entry thereby nullifying the effect of the lift vector and entering as a purely ballistic vehicle.

craft during entry. In literature this is sometimes known as the 'short period dynamics' of atmospheric entry. The resulting trajectory through the atmosphere is considered to be the 'long period dynamics' of entry. Most existing research has assumed a specific spacecraft configuration and used it to evaluate aspects of long period dynamics [143] [108] [107] [46] [135]. In contrast, we consider aspects of short period dynamics such as control authority and maximum attitude rate under the assumption that satisfactory handling in attitude is a prerequist for satisfactory trajectory management associated with long period dynamics.

Consider the entry vehicle shown in Figure 4.10. If it executes a rapid 180 *deg* pure roll it will be out of trim in pitch by an amount approximately equal to twice the angle of attack. The preferred maneuver is to instead rotate about the velocity (or 'wind') vector because it keeps the vehicle in aerodynamic trim. In the modern day this is known as banking whereas rotation about the +X axis is rolling. In some older literature this is sometimes known, borrowing terminology from aeronautics, as performing a 'coordinated turn.' The typical implementation for banking will have the pilot command a roll rate using the RHC. The spacecraft does that and also commands a yaw rate equal to the commanded roll rate times the sine of the angle of attack. This combined roll/yaw rotation results in banking. To reduce confusion we typically use the term 'roll' during atmospheric entry with the understanding that yaw is also happening and the end result is bank.

Figure 4.11 illustrates the geometry of the lift vector resulting from the offset center of mass. The vertical component of lift provides down-range control whereas the horizontal component of lift provides cross-range control. Note that for a given vertical component of lift it is possible to steer to the left or right by changing the bank angle.

4.9.1 Piloting Tasks During Entry

To understand the piloting tasks during entry, it is first necessary to have at least an informal understanding of what guidance is trying to accomplish.

First, guidance is attempting to control the gliding range of the vehicle. This is done by controlling drag by flying through less dense (higher altitude) or more dense (lower altitude) air. Altitude is controlled via the sign and magnitude of the vertical component of lift. This control is usually done via gradual changes in bank angle. An exception can occur during a high speed entry, such as a lunar return, in which a large, rapid maneuver is

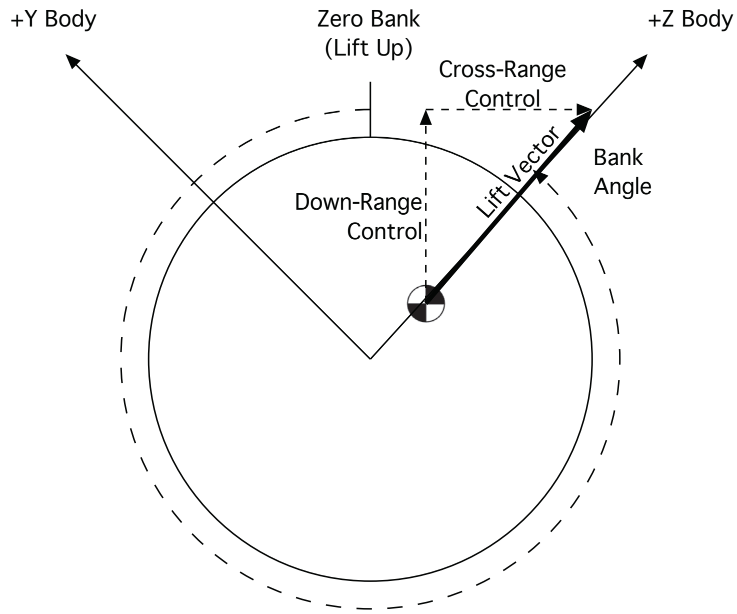

Figure 4.11: Entry Vehicle Bank Geometry (Aft View Looking Forward)

required to arrest the initial descent into the atmosphere and begin climbing. This pull-out maneuver must occur quickly to avoid exceeding acceleration constraints by flying too low into the denser atmosphere. After the pull-out maneuver the lift vector is typically directed down to hold the vehicle within the atmosphere despite traveling at faster than circular orbit velocity. A typical altitude history for a lunar return entry is shown in Figure 4.13.

Second, guidance is attempting to steer to keep the landing site within the remaining cross-range capability of the vehicle. Refer to Figure 4.11 to see that the vehicle is constantly turning unless the lift vector is directed straight up (0 *deg* bank) or down (180 *deg* bank). To do this guidance will periodically call for a change in turning direction, from left to right or vice versa, oscillating bank and forth to keep the landing site ahead of the vehicle. This requires a large, rapid change in bank angle. This maneuver, known as a 'bank reversal' or 'roll reversal,' must be done quickly because the vertical component of lift is being perturbed away from the desired value until the maneuver is complete. In various circumstances it may be desirable to do the reversal by banking in the direction of the smallest angle, always through lift vector up ('over the top'), or always through lift vector down ('under the bottom'). A typical roll angle history is shown in Figure 4.12. It illustrates

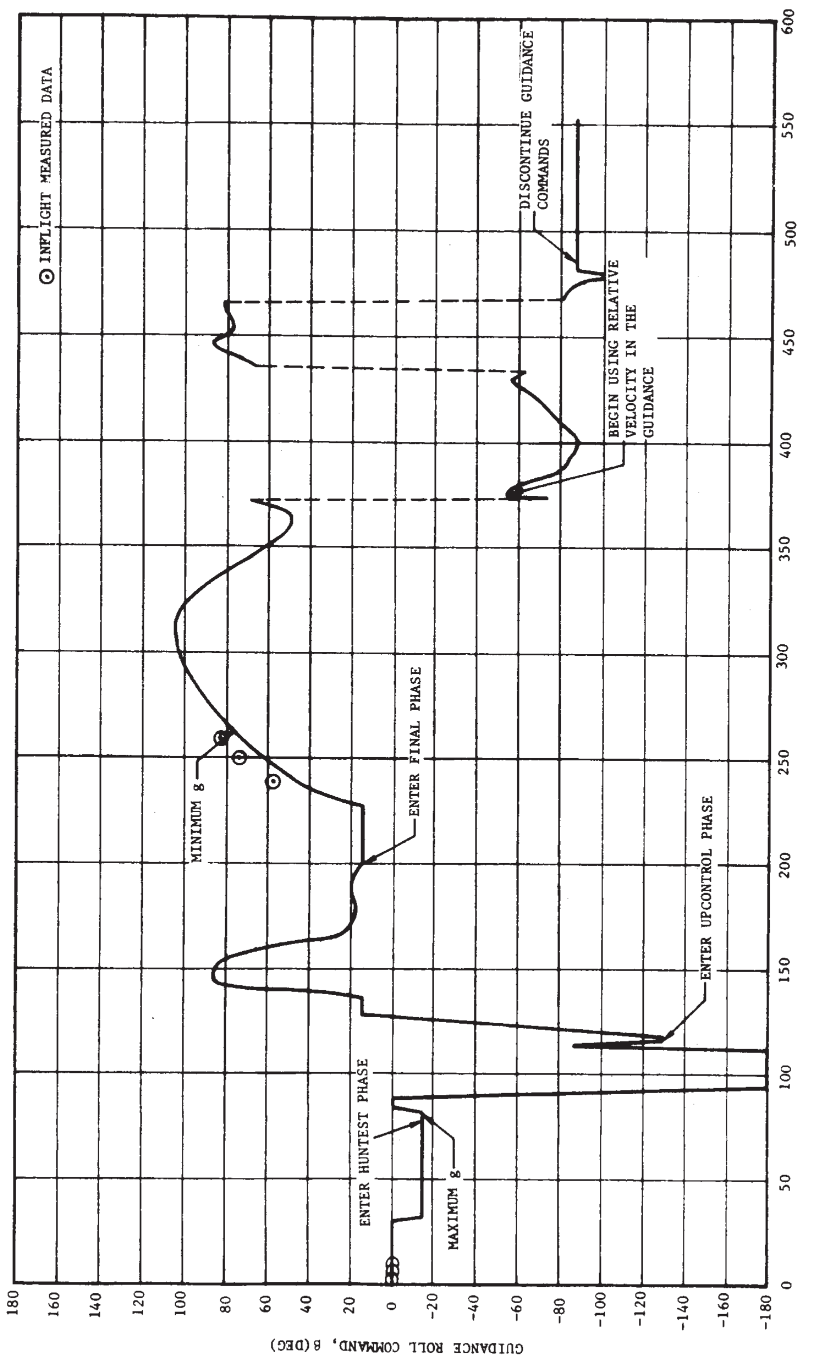

Figure 4.12: Apollo 11 Entry Roll (Short Period Dynamics) [97]

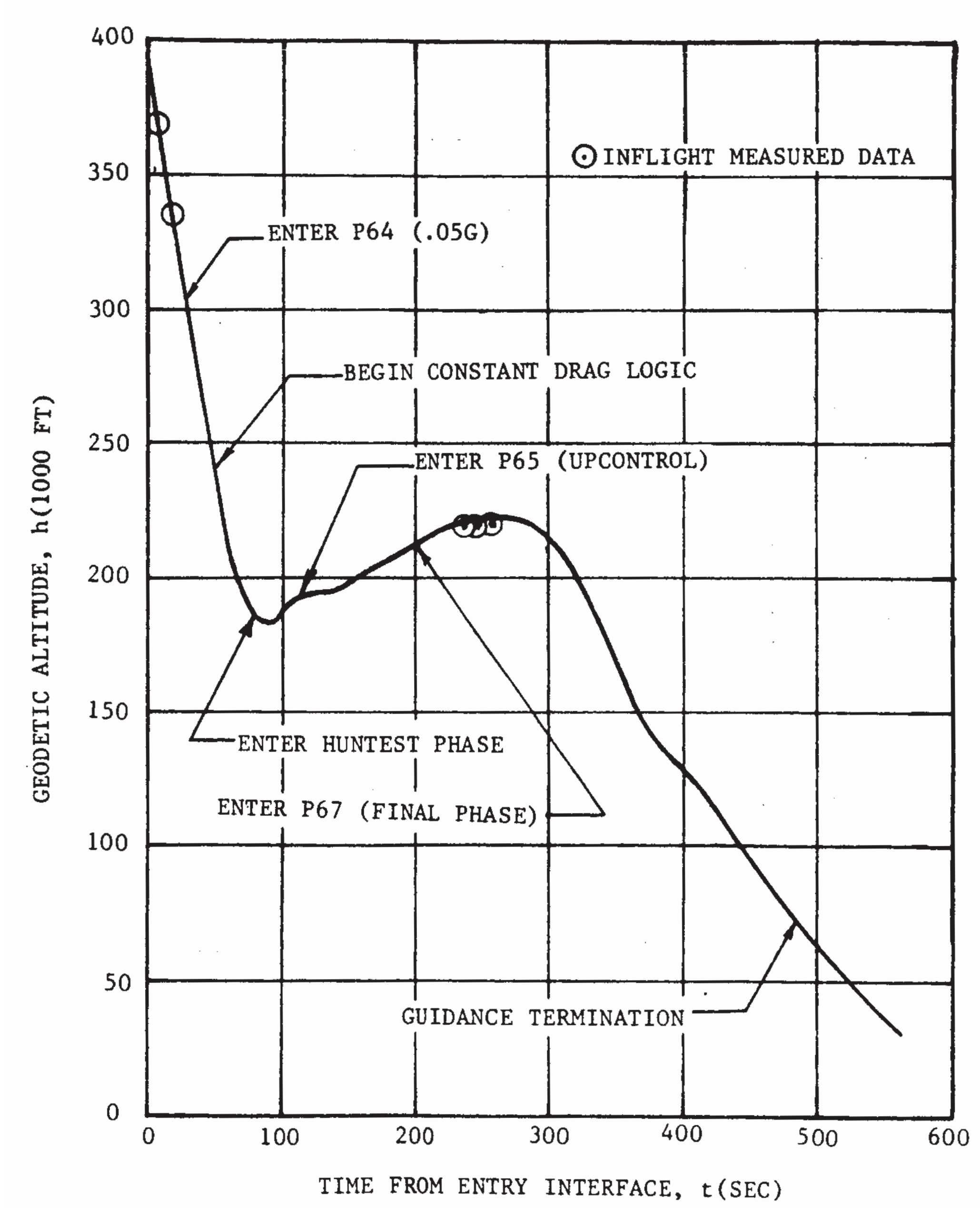

Figure 4.13: Apollo 11 Entry Altitude (Long Period Dynamics) [97]

both small and large roll angle changes for a typical lunar return entry.

Some guidance schemes will sometimes call for continuous banking to nullify the effects of the lift vector. This results in a ballistic drag-only entry. This can also be done as a response to various guidance or control control failures or even by design. Mercury, for example, performed a ballistic entry by design, as did Vostok.

Finally, even though capsules are typically stable when blunt end forward during entry they tend to oscillate in pitch and yaw with increasing magnitude and frequency as dynamic pressure increases. Left unchecked this could result in magnitude growing to the point that the spacecraft could flip to an apex forward attitude. This attitude is usually also stable and, were it to occur, would almost certainly result in loss of vehicle and crew. Thus it is important to damp attitude rates in pitch and yaw. Most spacecraft are designed to rate damp automatically in pitch and yaw when manual rate command is being exercised in bank. When using direct attitude control the pilot is typically required to perform rate damping.

In summary, the pilot is required to perform small, slow bank angle changes with periodic large, fast bank angle changes. In some cases the pilot may also be required to perform constant rate rolling or rate damping in pitch and yaw.

With regards to control modes, it is clear that the need to perform slow, precise maneuvers and fast, large maneuvers is a good match match for proportional rate control in bank. Historically this has been combined with automatic rate damping in pitch and yaw. Direct provides an emergency control mode usable in the event of failures and, historically, has required manual pitch and yaw rate damping.

Two papers provide insight into the piloting task. The first, a 1963 paper by Patterson, et al [114], documents piloting simulations of Gemini spacecraft entries. The second, a 1964 paper by Wingrove, et al [144], documents a similar test of manually flown Apollo spacecraft entries. In both tests the simulated spacecraft could be flown using proportional rate in roll with rate damping in pitch and yaw. Direct in all axes, with no damping, was also available. Both papers agree that manual control using proportional rate yields better handling than direct, arguing that proportional rate is suitable for normal use and direct for emergency use.

Therefore, for purposes of handling analysis we assume either proportional rate or direct control. We also assume that pitch and yaw rate damping is automatic when using proportional rate or, when using direct, is relatively insensitive to control authority. Finally, we also assume that commanding a constant rate roll is also relatively insensitive to control authority. Thus the analysis here focuses on roll control via direct or proportional rate.

Additional studies focused on long period entry dynamics include Wingrove and Coate [143], Moul, et al [108], Moul and Schy [107], Bilimoria [46], Tigges [135].

Summaries of the physics and constraints associated with atmospheric entry can be found in Miller [106], Pritchard [117], Anonymous [13], Tamburro [134], and Steketee [131].

A summary of the development of Apollo mission entry planning can be found in a report by Graves and Harpold [72].

4.9.2 With Direct Roll Control

Direct control during entry is important to evaluate for purposes of surviving a control system failure that renders proportional rate control unusable. However, note that 'satisfactory' in this mode implies that control is satisfactory for emergency use, not necessarily for nominal use.

$$k_{erd}(deg/s^2) = MeanRollAngularAcceleration(deg/s^2) \tag{4.12}$$

We define the critical design parameter k_{erd} (Entry Roll Direct) to be the mean angular acceleration magnitude in roll in deg/s^2. This is shown in Equation 4.12.

Table 4.22 summarizes control authorities for vehicles flown using Direct control systems during atmospheric entry.

0.00 deg/s^2 **(Theoretical Value)**
: This theoretical value of zero control authority would have unsatisfactory handling qualities.

2.86 deg/s^2 **(Interpolated Value)**
: This control authority is halfway between 0.00 and 5.77 deg/s^2 and is the estimated crossover point between unsatisfactory and satisfactory handling qualities.

5.77 deg/s^2 **(Gemini Entry, 1 RCS Ring)**
: The GT-3 crew reported that, "You could do alright on 1 Ring Direct.

Spacecraft Configuration	Roll Acceleration k_{erd} (deg/s^2)
Apollo CM (1 jet)	4.32
Gemini Entry (1 ring)	5.77
Patterson Sim (1 ring)	6.2
Apollo CM (2 jet)	8.64
Wingrove Sim	10.0
Gemini Entry (2 ring)	11.54
Patterson Sim (2 ring)	12.4

Table 4.22: Historic Entry Roll Control Authorities (Direct)

I don't think it would be any problem." The GT-5 crew debriefed that, "Spacecraft control was beautiful. There was no problem at all. I was on single ring Direct and then [went to Rate Command when oscillations grew excessive]." The debriefer then asked, "On the single ring Direct reentry did you have - did you feel like you had all the authority you wanted?" Cooper responded in the affirmative, "Yeah." The GT-7 command pilot, Borman, debriefed that "When we got guidance initiate I went to Direct. I was finding that in order to keep the cross range zeroed, and we had been told that Wally (Schirra) had trouble with his cross range, I was banking back and forth quite frequently maneuvering the spacecraft around the full lift point, from one side to the other and I was overshooting a little bit in Direct." He then went to Rate Command. The GT-7 pilot, Lovell, then asked, "Because you were overshooting in Direct?" Borman answered, "Right. I was not able to get the fine control I wanted. It would not stay in there. It seemed like the spacecraft was picking up a torque in roll also, and I was having to watch it too close." No crew reports that control feel sluggish or that control authority is insufficient. This control authority is therefore considered to be satisfactory.

6.2 deg/s^2 (Patterson Sim, 1 RCS Ring)
According to Patterson [114], this control authority was satisfactory for emergency use but that following guidance was more difficult than with both RCS rings functional.

Control Authority $k_{erd}(deg/s^2)$	Handling Quality (Estimated)
$k_{erd} < 2.86$	Unsatisfactory
$2.86 < k_{erd} < 12.4$	Satisfactory
$12.4 < k_{erd}$	Unsatisfactory

Table 4.23: Entry Roll Control Direct Estimated Handling

10.0 deg/s^2 **(Wingrove Sim, 2 RCS Jets)**
According to Wingrove [144], this control authority was satisfactory for emergency use.

11.54 deg/s^2 **(Gemini Entry, 2 RCS Rings)**
The GT-3 crew reported that, "The selected control mode (Direct, 2 Rings) was perfect for entry. [...] Direct was very good. I had no problem damping out rates. [...] With two rings direct you tend to over control a bit, until you get the hang of it." This control authority is considered to be satisfactory.

12.4 deg/s^2 **(Patterson Sim, 2 RCS Ring)**
According to Patterson [114], this control authority was satisfactory for emergency use. This is the largest control authority known to be satisfactory.

Based upon these comments control authorities from 2.86 to 12.4 deg/s^2 are estimated to yield satisfactory handling qualities. The true upper limit is probably only slightly larger than the one estimated due to the report of an over-control tendency. These results are summarized in Table 4.23.

4.9.3 With Proportional Rate Roll Control

As with analysis of proportional rate control in the coasting flight attitude control regime, we note that there is a relationship between angular acceleration and maximum maneuver rate, and lacking additional information this relationship is assumed to be linear.

We first consider maximum maneuver rate in roll (or bank) as shown in Table 4.24.

Spacecraft Configuration	Maximum Entry Roll Rate (deg/s)
Gemini (Early)	10.0
Gemini (Late)	15.0
Apollo CM	20.0

Table 4.24: Historic Maximum Entry Roll Rates (Proportional Rate)

Evidence, in the form of a 1963 report by Patterson [114], suggests that Gemini was originally conceived as having a 20 deg/s maximum roll rate during entry. However, Gemini first flew in 1965 with a maximum attitude rate in all axes of 10 deg/s. (This is the early configuration.) As described in a McDonnell Astronautics summary report [146], the maximum roll rate for Gemini was changed for Gemini 9 and subsequent from 10 to 15 deg/s. (This is the late configuration.) The stated reason was that "This change was made to increase the roll gain capability during the reentry phase of the spacecraft flight." The strong implication was that 10 deg/s was insufficient for roll control during entry. A 1964 report by Wingrove [144], suggests that the Apollo CM was originally conceived as having a maximum entry roll rate of 20 deg/s. This value did not change for the production vehicle.

A relatively fast roll rate is important for two primary reasons. First, it reduces trajectory (long period dynamics) dispersions by allowing bank reversals to be performed quickly. (Recall that, because horizontal and vertical components of lift are coupled, the vehicle will be either lofting or depressing the trajectory during the reversal.) Second, the pull-out maneuver during a lunar return entry is time critical and must be performed quickly to avoid exceeding vehicle acceleration limits.

Therefore, lacking detailed analysis for a specific spacecraft and mission design, the author's general guideline is for designers to specify between 15 and 20 deg/s maximum roll rate for Earth orbiting capsule vehicles and 20 deg/s for lunar return capsule vehicles.

$$k_{erpr}(1/s) = \frac{RCSRollAngularAcceleration(deg/s^2)}{MaximumRollManeuverRate(deg/s)} \tag{4.13}$$

Proportional rate control authority for entry roll is the design parameter k_{erpr} (Entry Roll Proportional Rate) and is defined to be the angular acceleration in roll divided by the maximum roll rate. This is shown in Equation 4.13.

Spacecraft Configuration	Angular Accel (deg/s^2)	Discrete Mnvr Rate (deg/s)	Control Authority ($1/s$)
Apollo CM (1 Jet)	4.32	20	0.22
Gemini (Late) (1 RCS Ring)	5.77	15.0	0.38
Apollo CM (2 Jet)	8.64	20.0	0.43
Wingrove Sim (2 Jet)	10.0	20.0	0.5
Gemini (Early) (1 RCS Ring)	5.77	10.0	0.58
Patterson Sim (2 RCS Rings)	12.4	20.0	0.62
Gemini (Late) (2 RCS Rings)	11.54	15.0	0.77
Gemini (Early) (2 RCS Rings)	11.54	10.0	1.15

Table 4.25: Historic Entry Control Authorities (Proportional Rate)

Control Authority $k_{erpr}(deg/s^2)$	Handling Quality (Estimated)
$k_{erpr} < 0.22$	Unsatisfactory
$0.22 < k_{erpr}$	Satisfactory

Table 4.26: Entry Roll Control Proportional Rate Estimated Handling

Historic values for entry proportional rate control authority (k_{erpr}) are shown in Table 4.25.

0.22 $1/s$ **(Apollo CM, 1 Jet)**
The Apollo 7 crew manually flew the early part of their entry in 1 Jet Proportional Rate and did not report any control problems. They later switched to 2 Jet control after a suspected RCS jet failure. This control authority is considered to be satisfactory.

0.5 $1/s$ **(Wingrove Simulated Apollo CM, 2 jet)**
Wingrove [144] reported that pilots found flying with rate command to be satisfactory, noting that "This task was simple and required very little learning."

0.58 $1/s$ **(Gemini Early, 1 RCS Ring)**
The GT-5 crew reported in their mission debrief that they switched from Direct to Rate Command (Proportional Rate) when oscillations became excessive and did not report any control problems. The GT-6 crew reported that used proportional rate for entry and did not report any control problems. The GT-7 crew (Borman) reported that, "I was also starting to pick up some pitch and yaw oscillations, so then I went to single ring Rate Command (Proportional Rate). And boy, this was a really great control mode, it was steady as a rock. You could put it right where you wanted and it stayed there." This control authority is considered to be satisfactory.

0.62 $1/s$ **(Patterson Simulated Gemini, 2 RCS Rings)**
According to Patterson [114], pilots found this level of authority to be "acceptable for pilot control." This control authority is considered to be satisfactory.

Based upon published research and crew debriefing comments, entry roll control authority using proportional rate, k_{erpr}, of 0.22 $1/s$ or greater is estimated to yield satisfactory handling assuming that the maximum roll rate is sufficient for trajectory management. This is summarized in Table 4.26.

4.10 Powered Lift Landing

This section addresses handling associated with the powered lift landing spaceflight regime. To understand it we first briefly review the flight dynamics of powered descent as performed by the Apollo Lunar Module (LM). A more detailed description is provided by Bennett [42].

It should be noted that even though the LM descent engine can gimbal to control attitude using the thrust vector it does not do so during landing. Instead, flight software gimbals the engine to keep the thrust vector pointed through the vehicle center of mass. Attitude control is performed using RCS jets only.

Descent from lunar orbit to the surface occurs in three phases. The first, braking, is a long retrograde burn started from orbit that slows the vehicle from approximately 5560 to 500 ft/s. At this point, known as 'High Gate,' the spacecraft pitches forward and brings the landing site into view in the pilot's forward window. This maneuver is known as pitchover and it signals the start the second phase, approach.

At pitchover the spacecraft is at approximately 7500 ft altitude, 500 ft/s velocity, and descending at 145 ft/s. During the approach phase the pilot uses angles determined by guidance and reference lines scribed onto the window to see the actual point on the surface being targeted.[9] During this phase the pilot is able to change the landing site by incremental angles ($\pm 1 deg$) by displacing the RHC in pitch (down-range) or roll (cross-range). This is known as the Landing Point Designator (LPD) system. This can be done to correct for a navigation error or to change the landing site to a more desirable location. At this point the vehicle is still normally under automatic control, save for landing point redesignation, and, if manual control is not invoked, will continue approaching the landing site before nulling horizontal

[9] With current technology this would probably be accomplished using a Heads Up Display (HUD).

velocity and performing a 3 ft/s descent to touchdown. The approach phase lasts about 90 *seconds*.

However, manual control is normally taken at approximately 500 ft altitude at a point known as 'Low Gate.' This marks the beginning of the landing phase. During this phase the pilot must commit to a landing site, fly to a point above it, null horizontal velocity, and touch down within the dynamic constraints imposed by the landing gear design.

For purposes of analyzing handling, we are concerned only with the landing phase, Low Gate to touchdown. Extensive research work has been done in this area and designers are urged to consult the original source material. The author's intent here is to guide the reader through that material and provide some conclusions based upon it and the author's personal experience. No attempt is made to derive new requirements for satisfactory handling in this regime.

4.10.1 Horizontal Control

Horizontal control is performed by rotating the lifting thrust vector away from vertical. This conceptually similar to a helicopter but, due to the lower lunar gravity, the angle must be much larger. Figure 4.14 illustrates the difference in pitch attitudes to achieve 2 ft/s^2 horizontal acceleration in Earth and lunar gravity. The pitch attitude for Earth, as might be used by a helicopter, is only 3.6 deg. Conversely, achieving the same horizontal acceleration on the moon requires pitching at 20.6 deg.

A number of studies exist in which attitude control of the LM during landing is investigated. Cheatham and Hackler [54] report on a fixed base simulator study that determined satisfactory handling exists for a system with maximum attitude rate of 20 deg/s when angular acceleration was at least 5 deg/s^2. A similar result was found by Jarvis [84] using the Lunar Landing Research Vehicle (LLRV) experimental aircraft. Both of these studies utilized proportional rate control with a rate deadband but no attitude hold. (Additional information about the LLRV can be found in the official narrative history by Matranga, et al [98].)

A subsequent report by Hackler, et al [73], provides a good overview of the near final LM design and briefly discusses the addition of attitude hold to the rate command system to improve handling at lower control authorities.

A comprehensive paper by Stengel [132] documents subsequent work to improve handling near touchdown. Briefly stated, significant work was done

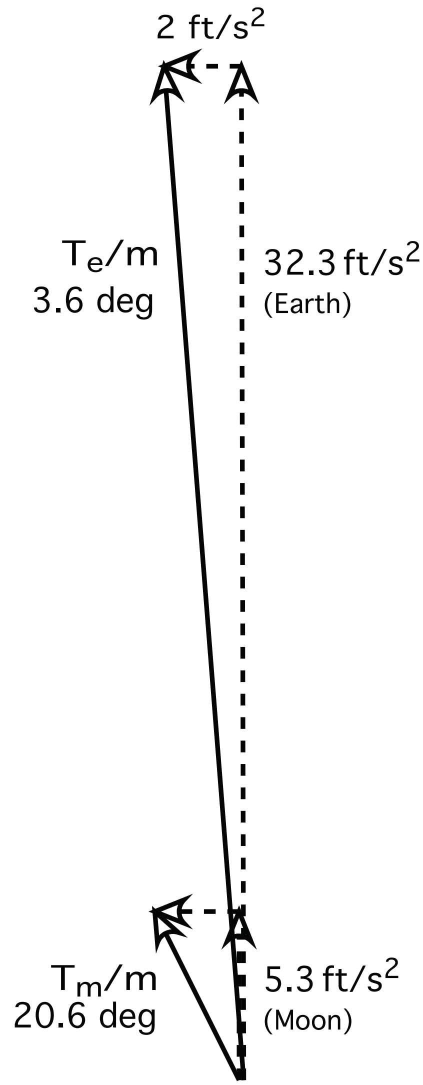

Figure 4.14: Earth and Moon Pitch Comparison

within flight software to allow more precise attitude control at low rates despite the hard requirement imposed by flight crews that the maximum attitude rate of 20 deg/s be retained. A major part of the solution was the incorporation of non-linear proportional rate control. In other words, the RHC was deliberately made less senstive (deg/s of attitude rate per deg of RHC displacement) at the beginning of travel and more sensitive near the end of travel. This allows for more precise control at low rates, as would be normally used near touchdown, at the expense of less precise control at high rates.

As documented in a memo by Tindall [138], a change was made in LM flight software for Apollo 13 and subsequent. Intended for use in the last 100 ft of descent, the change provides the crew with the option of having the vehicle automatically null horizontal velocity to allow a strictly vertical descent to touchdown. According to the memo, the Apollo 13 crew was, in training, enthusiastic about the feature. As documented in [20], horizontal velocity nulling was enabled by placing the MODE CONTROL PGNS switch in AUTO, disabled by returning the switch to ATT HOLD.

4.10.2 Vertical Control

Vertical control of the LM descent was accomplished by throttling the LM descent engine. This was directed via two methods.

First, the LM's THC, which was actually known as the Thrust/Translation Controller Assembly (TTCA), had a mode lever that changed the function of the controller from three-axis translation to descent engine thrust. In thrust mode moving the handle up and down commanded engine throttle from minimum (fully down) to maximum (fully up). Spring return to center was disabled when in throttle mode.

As described by Hackler, et al [73], work was done to evaluate the sensitivity of the throttle control to allow for satisfactory vertical rate control near touchdown. As with the RHC sensitivity, the final design was non-linear to allow for fine control at low thrust levels at the expense of more coarse control at high thrust levels.

However, the normal method of descent rate control was via the Rate Of Descent (ROD) switch. The crew used the ROD switch to incrementally change the commanded descent rate by $\pm 1 ft/s$. Flight software would then automatically control the descent engine throttle accordingly.

As documented extensively by Zupp [148], a recognized hazard was the possibility of damaging the descent engine nozzle at touchdown, perhaps catastrophically. To manage this risk the LM was equipped with touchdown sensing probes extending downward several feet from the landing pads. Probe contact with the surface would cause them to buckle and illuminate the blue CONTACT light in the cockpit. This alerted the crew to command engine shutdown and allow the vehicle to fall the remaining distance to the surface.

4.10.3 Piloting Technique, Potential Enhancements, and Other Information

Implementation of the LM Dightal Autopilot (DAP) is detailed in [16].

It is clear, from reviewing the post-flight debriefings, that Apollo flight crews found the Landing Point Designator (LPD) system efficient and easy to use. The obvious enhancement for a modern vehicle would be to use a HUD to show the targeted landing site location. The Space Shuttle HUD was designed to draw a runway outline on top of the actual runway. Operationally this was used to confirm navigation accuracy and then removed from view with the declutter switch. A similar capability, using a few prominent craters, would allow for the same navigation check for a lunar landing. A navigation state update could potentially be made by allowing the crew to move the crater outlines onto the actual craters in view.

As described previously the automatic horizontal velocity nulling feature was incorporated into flight software for Apollo 13 and subsequent. Although the Apollo 13 crew was reportedly enthusiastic about using it they did not, of course, get the opportunity to land. No mention of it being used is made in the Apollo 14 through 17 debriefings, suggesting that crews found fine control of horizontal velocity to not be a problem. In fact, there is general praise for LM handling qualities during landing.

Stengel [132] discusses potential improvements to the flight control system to reduce pilot workload. The first of these is essentially automatic yaw control to, by default, keep the forward (out the window) axis aligned to the velocity vector. This largely removes an axis of control from the pilot workload by allowing airplane-like coordinated turns.

Recall that, as designed, the LM pilot controlled down-range position using fourth-order control. The pilot directly controlled pitch attitude rate, which is integrated to yield pitch attitude, which is proportional to down-range acceleration, which is integrated to yield down-range velocity, which is integrated to yield down-range position. The equivalent control is happening for cross-range control. Stengel proposes a control mode he calls ‘attitude command’ in which pitch and roll attitude is proportional to RHC displacement. (This system would more properly be called ‘proportional attitude’ using the terminology of this document.) Returning to our example, the pilot now controls second order systems for down-range and cross-range because RHC displacement is now proportional to horizontal acceleration. Such a system is likely to be much less challenging to fly than proportional rate.

More recent research into lunar lander display and control enhancements is presented by Mueller, et al [109].

LM pilots discuss several visual phenomena of note. First, the fractal nature of lunar surface features, combined with the total lack of man-made objects, makes visual determination of range, including altitude, very difficult. However, pilots reported that the LM shadow, once it came into view near the surface, made determination of altitude and altitude rate relatively easy. (Recall that Apollo landings were always made with the sun behind the LM and at a moderate elevation.) Second, blowing dust can obscure the surface during landing. The Apollo 15 crew reported that the outside view was totally obscured below about 50 to 60 ft altitude and that the landing was made using cockpit instruments only. Future vehicles must be designed to allow a safe landing in non-visual conditions. Finally, because dust is blowing radially outward from the vehicle it can give the pilot the illusion of moving backwards.

Finally, several crews noted their preference to land with a small forward velocity. This was done to ensure that, having overflown an obstacle such as a boulder or crater, they did not accidentially back into it again. An excellent discussion of LM landing constraints and touchdown dynamics can be found in Zupp [148].

The author expects that, as with docking systems, there will be programmatic pressure exerted on designers to make future landing systems increasingly less robust in terms of tolerating vertical descent rate, horizontal velocity, angular rate, slope, and so on, in the name of reducing weight or some other goal. Apollo experience suggests that this should resisted due to the highly variable nature of the lunar surface at the scale of interest and variations in piloting technique. The author’s experience is that advantage gained by reducing design robustness is usually lost due to the resulting subsequent complexity in analysis, supporting systems (especially software), training, and operations.

Chapter 5

Biomechanical Interfaces

This chapter derives a set of proposed requirements for cockpit displays and hand controllers, the biomechanical interface between pilot and spacecraft, based upon history and personal experience with Mercury, Gemini, Apollo, and Space Shuttle spacecraft. The approach is narrative, focusing on rationale for implementations and changes moving forward in time from Mercury to Shuttle. This chapter is intended to be relatively concise but additional design information is available in the appendices.

Parameter	Value
Breakout Torque ($in * lb$)	N/A
Switch Deflections (deg)	Low Thrust @ 3.3 (R,P), 2.5 (Y)
	High Thrust @ 9.8 (R,P), 7.5 (Y)
Max Nominal Deflection (deg)	13 (R, P), 10 (Y)
Torque at Max Nominal Deflection ($in * lb$)	N/A
Roll Pivot (in below Pitch Pivot)	N/A

Table 5.1: Mercury RHC Characteristics

Parameter	Value
Breakout Torque ($in * lb$)	3.0 (R), 10.3 (P), 4.0 (Y)
Switch Deflections (deg)	Direct @ 3 (All)
	Impulse @ 4 (All)
Max Nominal Deflection (deg)	10
Torque at Max Nominal Deflection ($in * lb$)	6.45 (R), 29 (P), 12.7 (Y)
Roll Pivot (in below Pitch Pivot)	4.2

Table 5.2: Gemini RHC Characteristics

5.1 Hand Controllers

5.1.1 Rotational Hand Controller (RHC) Physical Characteristics

Characteristics of the Mercury RHC are presented in Table 5.1. As described in [4] and [102], the RHC was positioned for the pilot's right hand. The wrist pivot for pitch design was unique to Mercury. The RHC was spring-loaded for feel but no specific requirements for torque appear to exist. Maximum displacement was 13 *deg* in roll and pitch, 10 *deg* in yaw. The roll pivot location is not available in known documentation.

Characteristics of the Gemini RHC are presented in Table 5.2. Design information concerning the Gemini hand controllers is available in Barnes [40]. A narrative description of development is given in Wolfers and Motchan [146].

In comparison to Mercury, Gemini changed the location of pitch pivot from the wrist to the center of the palm. This change was made, according to Wolfers, because "The center of the human wrist was not the best place for the handle pivot point because of mechanical differences between the wrist and the controller." The yaw pivot remained the long axis of the grip and the roll pivot below the palm. Wolfers notes that "This provided a clear distinction of pitch, yaw, and roll to prevent inadvertent cross coupling." All subsequent RHC designs adopted this approach.

Wolfers also notes that crews found the torque required to displace the RHC was undesirably high. Starting with Gemini 9, the top of the controller was modified to include a T-shaped handle for overhead grip that improved yaw control with a pressurized suit.

Parameter	Value
Breakout Torque ($in * lb$)	5.3 (R), 7.2 (P), 5.0 (Y)
Switch Deflections (deg)	Direct, Impulse @ 1.75 (All)
Max Nominal Deflection (deg)	10
Torque at Max Nominal Deflection ($in * lb$)	14.2 (R), 23.5 (P), 12.9 (Y)
Soft Stop Step ($in * lb$)	11.1 (R), 14.7 (P), 5.5 (Y)
Stop Stop to Hard Stop (deg)	1.5 (All)
Roll Pivot (in below Pitch Pivot)	4.0

Table 5.3: Apollo CM RHC Characteristics

With regards to sensitivity for proportional rate control, Wolfers notes that "a non-linear potentiometer in place of the linear one used would have given the astronaut finer control at low rate levels." The maximum attitude rate was initially 10 deg/s in all axes (Gemini 3 through 8) changing to 15 deg/s in roll only for Gemini 9 and subsequent. Assuming 10 deg/s maximum rate, this implies a sensitivity of 1 $(deg/s)/deg$ is near the upper limit for satisfactory handling when performing general purpose orbital attitude control.

As discused in earlier when addressing atmospheric entry, the maximum attitude rate in roll was increased from 10 to 15 deg/s "to increase the roll gain capability during the reentry phase of the spacecraft flight." [146]

Characteristics of the Apollo CM RHC are presented in Table 5.3. A detailed history of the development of Apollo hand controllers, including requirements, is provided by Wittler [145].

As with Gemini, the controller had a nominal operating range of approximately 10 deg in all axes but added a soft stop and small extended range. The soft stop is a torque step that the pilot must push through in order to command a secondary function such as emergency jet firing.

Operationally, switches at approximately 1.75 deg of displacement closed to command, if the spacecraft was configured that those modes, either impulsive or direct (continuous) jet firing. Switches beyond the soft stop in the extended range commanded direct (continuous) jet firing regardless of control system configuration. In other words, the soft stop provided a physical cue to the pilot that the controller was at the end of nominal travel and that emergency jet firing was instantly available by pushing past it.

Parameter	Value
Breakout Torque ($in * lb$)	7.6 (R), N/A (P), 3 (Y)
Switch Deflections (deg)	Impulse @ 4.3 (R,P), 2.5 (Y)
Max Nominal Deflection (deg)	19.5 (R,P), 10 (Y)
Torque at Max Nominal Deflection ($in * lb$)	40.95 (R), 28.28 (P), 7 (Y)
Soft Stop Step ($in * lb$)	17 (R), 12 (P), 8 (Y)
Stop Stop to Hard Stop (deg)	4.8 (R,P), 4.3 (Y)
Roll Pivot (in below Pitch Pivot)	4.5

Table 5.4: Space Shuttle RHC Characteristics

Characteristics of the Space Shuttle RHC are presented in Table 5.4. The breakout torque for pitch is missing from program documentation but is probably about 3 to 4 $in*lb$. Shuttle continued the Apollo practice of having a soft stop with emergency direct (continuous) jet firing beyond, regardless of control system configuration. This capability was utilized in certain contingency procedures requiring faster than normal attitude control.

Development of the Shuttle RHC is described by Gilbert [70]:

> The Orbiter uses the same Apollo-type hand controller for both aero control and onorbit reaction control system (RCS) attitude control. The latter is essentially an on/off control function. Ideally it should have a different type of feel than that required for good aero control. We optimized as much as possible for good aero control and accepted the result for RCS control. As a result, it is impossible to tell by the feel force exactly when the jets fired. Consequently, there is a tendency to make sure the control input is big enough. There has been some concern, but this is apparently acceptable, although some of the more demanding tasks like docking have not been done yet.[1] The alternative is more mechanical complexity, such as having two controllers or adjustable feel. Although this area could be developed further, it doesn't appear necessary.
>
> [...][2]

[1]The first Shuttle docking would not occur until 1995, ten years after this was written, on mission STS-71.

[2]Source text not relevant has been deleted for clarity.

> Controller location was also of some concern. It is in the center (not side stick) and canted some 19 degrees left to be comfortable for right-hand use. It provides better access and room for displays and switches. However, there was concern about the possibility of control cross-coupling since it is not aligned mechanically with the vehicle axes. To keep it in the center and aligned with vehicle axes would make it misaligned with natural arm motion. Either way some cross-coupling is likely. It does occur at times but not to a large degree and apparently has not been objectionable.

This optimization for aerodynamic flight resulted in several design differences as compared to Apollo. First, nominal maximum displacement was changed from 10 to 19.5 *deg* in pitch and roll, yaw remained at 10 *deg*[3]. This change allows for finer control throughout the full range of displacement in pitch and roll. Second, switches for discrete functions, such as impulse jet firing, were removed to provide a very smooth torque gradient. Instead, triple redundant continuous position sensors are read and interpreted by flight software. Impulse jet firings occured at approximately 4.3 *deg* of displacement in pitch and roll, 2.5 *deg* in roll.

Proposed RHC requirements for satisfactory handling are summarized in Table 5.5, although this is would be more accurately described as a design experience envelope. Gemini and Apollo experience suggest that 10 *deg* maximum deflection in all axes is satisfactory for orbital flight, Shuttle experience is that 20 *deg* maximum deflection in pitch and roll is acceptable. 10 *deg* is probably about the limit for yaw based upon human wrist capability. The author's experience and opinion regarding the Shuttle RHC is that the torque gradient feels appropriate for aerodynamic flight but steeper than ideal for orbital flight. As Gilbert [70] notes, the tendency is to displace the RHC to near the soft stop to ensure that the RCS jets fire, emphasizing the steepness of the gradient. At the forward flight stations Shuttle provides RCS activity lights that indicate when jets are firing as a visual cue.

Parameter	Value
Breakout Torque ($in * lb$)	3.0 - 7.6 (R) 7.2 - 10.3 (P) 3.0 - 5.0 (Y)
Switch Deflections (% of Max)	Impulse @ 18 - 30 (All Axes)
Max Nominal Deflection (deg)	10-19.5 (R,P), 10 (Y)
Torque at Max Nom Deflection ($in * lb$)	6.45 - 40.95 (R) 23.5 - 29.0 (P) 7.0 - 12.9 (Y)
Soft Stop Step ($in * lb$)	11.1 - 17.0 (R) 12.0 - 14.7 (P) 5.5 - 8.0 (Y)
Stop Stop to Hard Stop (deg)	1.5 - 4.8 (R,P), 1.5 - 4.3 (Y)
Roll Pivot (in below Pitch Pivot)	4.0 - 4.5

Table 5.5: Proposed RHC Requirements

Parameter	Value
Breakout Force (lb)	4 (X), 5.5 (Y), 4 (Z)
Max Nominal Deflection (in)	0.5
Force at Max Nom Deflection (lb)	5.75 (X), 7.0 (Y), 5.75 (Z)

Table 5.6: Gemini THC Characteristics

Parameter	Value
Breakout Force (*lb*)	N/A
Max Nominal Deflection (*in*)	0.5
Force at Max Nominal Deflection (*lb*)	N/A

Table 5.7: Apollo CM THC Characteristics

5.1.2 Translational Hand Controller (THC) Physical Characteristics

Physical charactoristics of the Gemini THC are presented in Table 5.6. As with the RHC, design information is available in Barnes [40] and a narrative description of development is given in Wolfers and Motchan [146]. A unique characteristic of the Gemini THC is that it was designed to stow by being rotated under the forward instrument panel. This was probably done to provide clearance for the crew ejection seats. The THC grip was a ball approximately 1 1/8 *in* (1.125 *in*) in diameter, chosen to be suitable for both unpressurized and pressurized suit operations.

Physical characteristics of the Apollo CM THC are presented in Table 5.7. A detailed history of the development of Apollo hand controllers, including requirements, is provided by Wittler [145]. Breakout force and force at maximum deflection are unknown.

The Apollo CM THC handle was T-shaped. This allowed an additional feature in which the handle could be rotated about the X-axis to command an abort, engine shutdown, or backup control system takeover.

The Apollo LM THC had a separate operating mode for descent engine throttling. In throttle mode the up/down axis spring centering mechanism was disabled and the range of motion corresponded to engine throttle command: up for increased thrust, down for decreased thrust.

Physical characteristics of the Space Shuttle THC are presented in Table 5.8. The THC handle is a cube, approximately 1 *inch* in size. Hall effect sensors are used instead of physical switches.

Proposed THC requirements for satisfactory handling are presented in Table 5.9. As with the proposed RHC requirements, this is arguably more of an envelope of design known to be satisfactory. The Shuttle THC breakout

[3] RHC yaw is disabled during Shuttle aerodynamic flight, control via standard transport aircraft pedals.

Parameter	Value
Breakout Force (*lb*)	1.7 (X), 1.5 (Y,Z)
Max Nominal Deflection (*in*)	0.45
Force at Max Nominal Deflection (*lb*)	2.4 (X), 2.2 (Y,Z)

Table 5.8: Shuttle THC Characteristics

Parameter	Value
Breakout Force (*lb*)	1.5 - 5.5
Max Nominal Deflection (*in*)	0.45 - 0.5
Force at Max Nominal Deflection (*lb*)	2.2 - 7.0

Table 5.9: Proposed THC Requirements

and max deflection forces are significantly lighter than Gemini and the author's experience is that it feels very light to push or pull in a very satisfactory way.

5.1.3 RHC Sensitivity

Here we address the mapping of RHC displacement to commanded attitude rate, commonly known as 'shaping.'

Figure 5.1 illustrates linear shaping. Beyond the small deadband at neutral commanded rate is a linear function of RHC displacement. Most proportional rate systems implement linear shaping including Mercury, Gemini, Apollo CSM, Shuttle Ascent, Shuttle OMS, and Shuttle Entry. Linear shaping is straightforward to implement but becomes problematic when a control system must support both fine attitude control and large attitude rates.

$$RHC sensitivity(1/s) = \frac{Change in Angular Rate(deg/s)}{Change in RHC Displacement(deg)} \tag{5.1}$$

Equation 5.1 defines the concept of RHC sensitivity. It is the slope of the of the shaping function and describes how sensitive the commanded attitude rate is to the displacement of the RHC. Since it there is a limit as to how accurately the pilot can physically control the RHC it makes intuitive sense

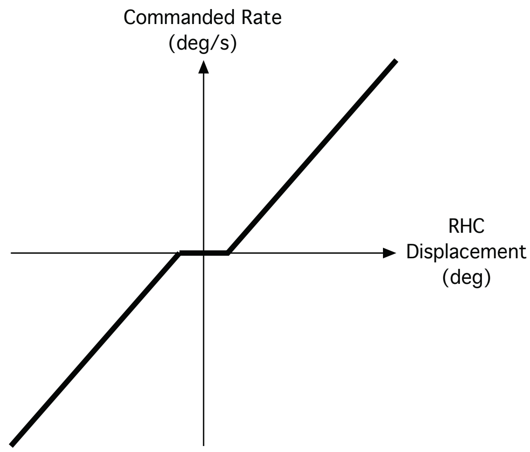

Figure 5.1: RHC Linear Shaping

that there is also a limit to sensitivity beyond which fine control of attitude rate becomes too difficult and handling becomes unsatisfactory.

This condition was first addressed by Wolfers and Motchan [146] while discussing the design and operational experience of the Gemini RHC. As noted previously, Gemini used a linear potentiometer to sense RHC displacement for proportional rate control. Wolfers states “A non-linear potentiometer in place of the linear one used would give the astronaut finer control at low rate levels.”

Figure 5.2 illustrates conceptual non-linear shaping. Note the decreased sensitivty at lower attitude rates while the ability to command a large rate is retained. The trade off, decreased capability for fine rate control at high rates, is normally much less important than fine control at low rates.

The first known implementation of non-linear RHC shaping is illustrated in Figure 5.3 taken from a paper by Stengel [132] describing the development of the Apollo LM attitude control system. The non-linear shape was found through simulator testing of lunar landings and significantly improved handling. The ‘NORMAL SCALING’ line, with a maximum rate of 20 deg/s, is used for landing. The ‘FINE SCALING’ line, with a maximum rate of 4 deg/s, is used for orbital flight.

Subsequently, non-linear RHC shaping was used on the Space Shuttle during approach and landing to provide for finer attitude contro during those critical phases. The author’s experience is that non-linear shaping would have also improved manual control during Shuttle ascent. The maximum

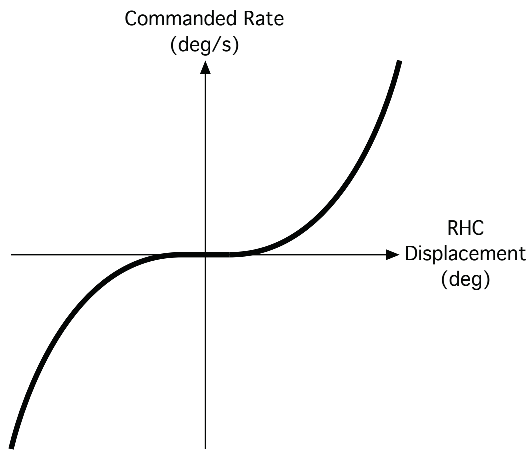

Figure 5.2: RHC Non-Linear Shaping

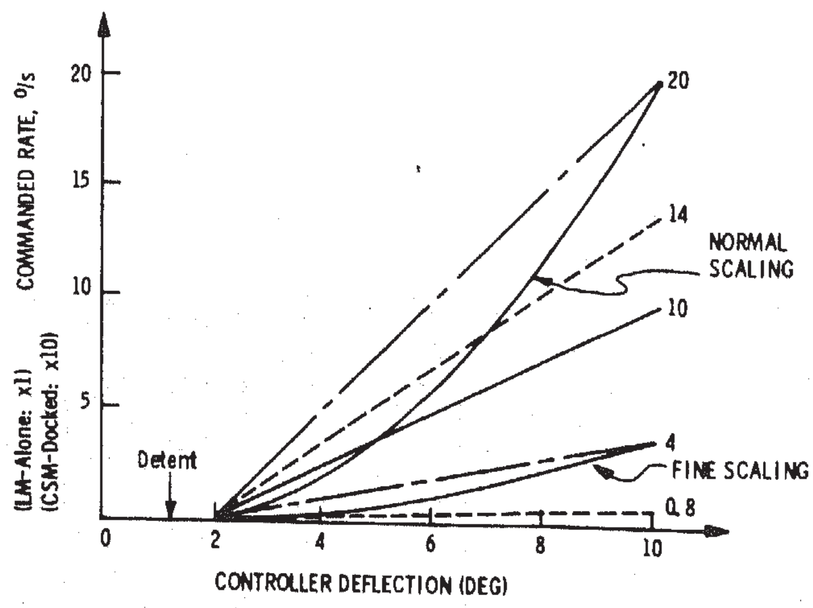

Figure 5.3: Apollo LM RHC Shaping [132]

attitude rates during ascent were 11.5 deg/s in pitch and roll, 6.7 deg/s in yaw. Fine pitch control was significantly harder during ascent than during an OMS burn in orbit in which the maximum rate was only 2.0 deg/s.

The author's recommendation is that future vehicle flight software be designed to support a second-order polynomial for the RHC shape function. The coefficients can be set initially for linear shaping but also provide the ability for handling optimization once a simulator is available for human-in-the-loop testing.

5.1.4 Hand Controller Sampling Rates

A common characteristic of digitial flight control systems is that hand controllers are periodically sampled for control inputs. The Apollo and Space Shuttle programs can provide some insight into minimally acceptable sampling rates.

The Apollo RHC was sampled at 10 Hz and that rate was satisfactory for lunar landing, probably the most demanding piloting task for Apollo era spacecraft.

Pilot impressions of an early Space Shuttle entry simulation are documented in an astronaut office memo by Hartsfield and McCandless [75]. In it they report flying a simulator with variable RHC sampling rates of 12.5 Hz (80 ms), 6.25 Hz (160 ms), and 3.125 Hz (320 ms). They report a "jerky response" at 3.125 Hz, that the effect is "barely noticable" at 6.25 Hz, and that the effect "cannot be seen" at 12.5 Hz. They recommend, for entry simulations, that "a stick sample rate of no lower than 6.25 Hz should be used for entry."

Shuttle was initially designed with a sampling rate of 12.5 Hz for all phases of flight. However, during Approach and Landing Test 5 (ALT-5), the vehicle entered a Pilot Induced Oscillation (PIO) during final flare and touchdown. This resulted in a number of software design changes including changing the sampling rate during approach and landing to 25 Hz with the goal of reducing overall control system delay. This sampling rate was used during the entire operational life of the Shuttle program without any known problems.

We therefore conclude that the minimum acceptable RHC sampling rate for all spaceflight regimes is 10 Hz, with the caveat that high gain tasks like powered lift landing may require a faster rate depending upon the overall characteristics of the vehicle.

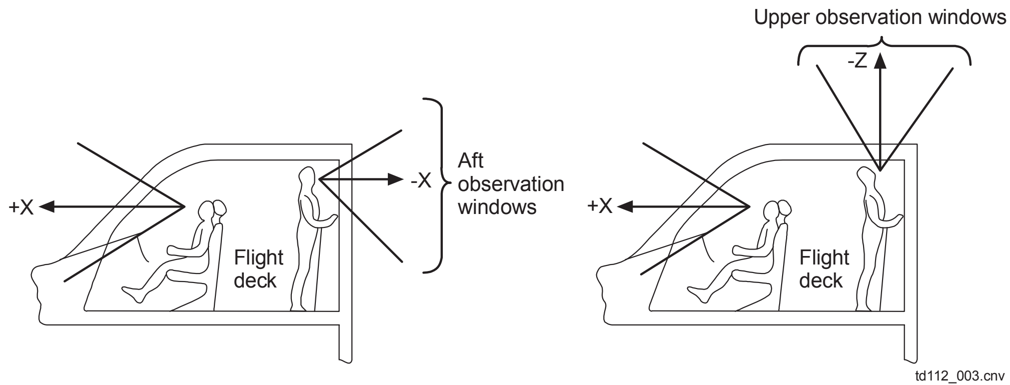

Figure 5.4: Shuttle Flight Stations [139]

As discussed on page 52, the Space Shuttle was originally designed to sample the THC every 160 ms (0.16 s, 6.25 Hz). This resulted in several known instances of crew inputs being missed by flight software. After increasing the sampling rate to once every 80 ms (0.08 s, 12.5 Hz) no further instances of missed inputs are known.

This suggests that the minimum THC sampling rate for satisfactory handling is approximately 10 Hz.

5.1.5 Bi-Modal Hand Controllers

A bi-modal hand controller is one in which the same physical input will result in two different outputs depending upon the selected mode. Two examples of this are the Space Shuttle aft flight station and the Simplified Aid for EVA Rescue (SAFER).

As shown in Figure 5.4, the Shuttle aft flight station is designed up support flying with a forward sense in either the -X (aft into the payload bay) or -Z (up through the overhead window) directions.[4] The RHC and THC are mounted at an intermediate angle approximately 45 deg above horizontal. A switch, shown in Figure 5.5, changes the sense of the hand controllers between -X and -Z. For example, pushing the aft THC in will result in -X or -Z translation depending upon the switch setting. In practice this capability was not used and all flying from the aft station was performed in -Z

[4] The forward flight station is said to have +X sense although it is not reconfigurable.

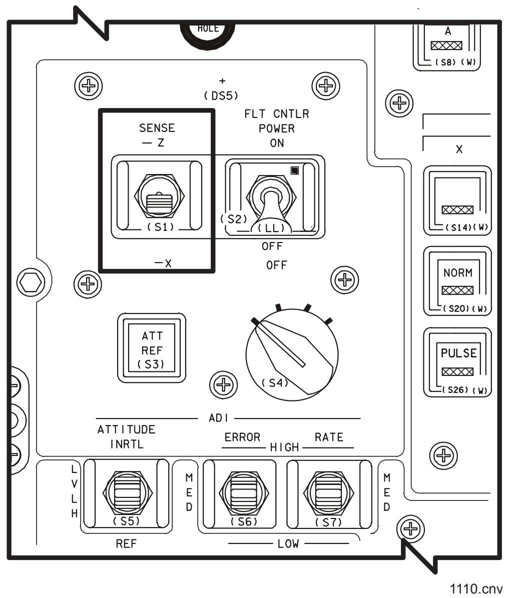

Figure 5.5: Shuttle Sense Switch [34]

sense.[5] Interviews with Shuttle instructors indicate that astronauts would periodically attempt to switch to -X sense, attempting to take advantage of the capability, but would invariably make incorrect control inputs.

Astronauts performing spacewalks at the International Space Station (ISS) using United States spacesuits have available a device known as the Simplified Aid for EVA Rescue (SAFER). SAFER is conceptually similar to the Manned Maneuvering Unit (MMU) in that it attaches to the backpack of the Extravehicular Mobility Unit (EMU) spacesuit and provides a propulsive capability using compressed nitrogen jet thrusters. However, it is much smaller than the MMU and intended for emergency use only. If an astronaut becomes physically separated from the ISS she can activate and use SAFER to arrest the separation and translate back to a handhold. The SAFER is controlled with a bi-modal hand controller used for both rotational and translational control via a mode switch. In practice, people flying a simulated self rescue using SAFER regularly make incorrect inputs due to

[5]Shuttle rendezvous sensors, including a crew optical sight, generally point in the -Z direction. Proximity operations with and docking to the ISS were therefore performed through the overhead window.

being in the wrong mode. Extensive training is required in order to be able to fly SAFER reliably.

This common tendency to make incorrect control inputs strongly suggest that bi-modal hand controllers should generally be avoided.

5.2 Flight Instruments and Displays

Flight instruments and displays, in addition to out the window views and kinesthetic sense, are the way the spacecraft communicates to the pilot. The pilot requires this information to exercise closed loop control. It therefore makes sense to design flight instruments and displays to minimize the pilot's mental workload when designing a spacecraft to have satisfactory handling qualities.

5.2.1 Attitude Director Indicator (ADI)

The Attitude Director Indicator (ADI) is the primary source of attitude information available to the pilot. Although Mercury used individual roll, pitch, and yaw attitude indicators all subsequent spacecraft have used an ADI to show combined three axis attitude information. A diagram of the final version of the Space Shuttle ADI, implemented as a software graphic, is shown in Figure 5.6.

The basic ADI consists of a ball, either physical or virtual, upon which are lines depicting angles of roll, pitch, and yaw with respect to the current reference frame. The bottom hemisphere is usually darker to represent the ground and the top lighter to represent the sky. Three attitude error needles are used to depict the difference between the current and reference attitude. Three additional indicators provide attitude rate information.

The Gemini ADI was a lightly modified F-4 aircraft flight instrument with only a single set of needles that could display attitude error, attitude rate, or a combination. During the program it became apparent that having two scale factors for needle displacement allowed for better insight and control for both fine and coarse attitude control. Apollo added a third scale factor and separate indicators for attitude error and attitude rate. The early Shuttle ADI, which was mechanical, was very similar to the Apollo unit but added separate scale selection for both attitude error and rate. The late Shuttle ADI, a software display, added a digital attitude display and numeric indica-

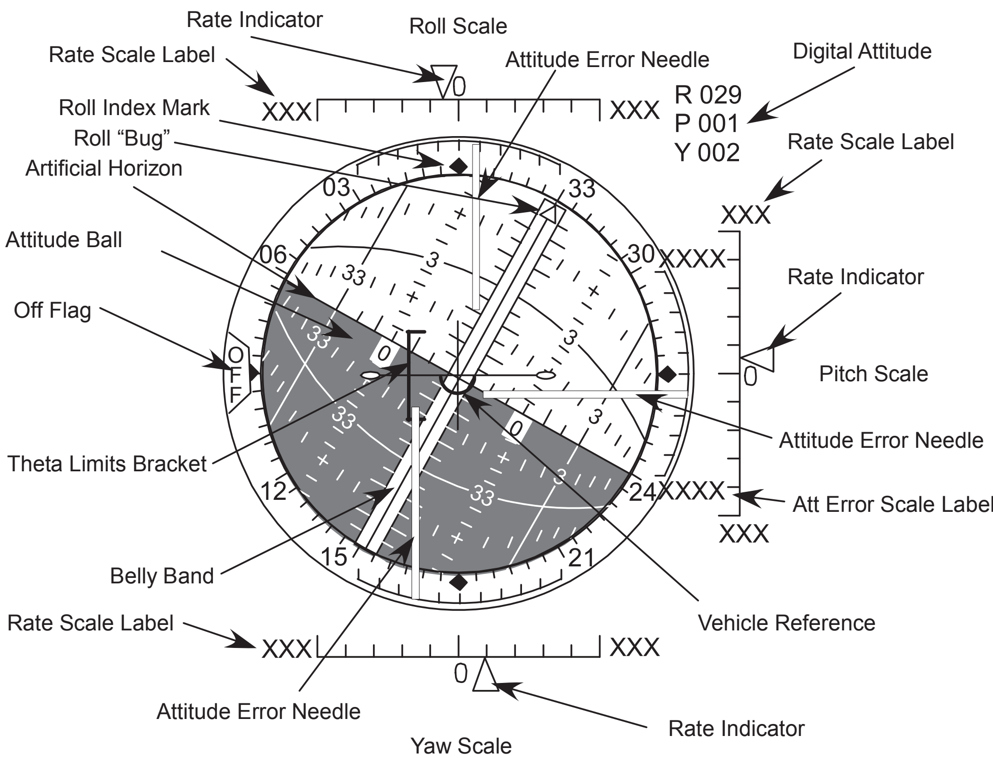

Figure 5.6: Shuttle ADI [34]

Vehicle	Axis	Low ($\pm deg$)	Medium ($\pm deg$)	High ($\pm deg$)
Gemini	Roll	5	N/A	15
	Pitch, Yaw	5	N/A	10
Apollo CM	Roll	5	N/A	50
	Pitch, Yaw	5	N/A	15
Apollo LM	All	5	5	5
Shuttle (Ascent, Orbit)	All	1	5	10
Shuttle (Entry)	Roll	10	25	25
	Pitch	1	2	5
	Yaw	2.5	2.5	2.5

Table 5.10: Historic ADI Attitude Error Ranges

Vehicle	Axis	Low ($\pm deg/s$)	Medium ($\pm deg/s$)	High ($\pm deg/s$)
Gemini	Roll	5	N/A	15
	Pitch, Yaw	5	N/A	10
Apollo CM	Roll	1	5	50
	Pitch, Yaw	1	5	10
Apollo LM	All	5	N/A	25
Shuttle (Ascent, Entry)	All	1	5	10
Shuttle (Orbit)	All	0.2	1	5

Table 5.11: Historic ADI Attitude Rate Ranges

tors to show rate scale information. Scaling information for Gemini, Apollo, and Shuttle are presented in Tables 5.10 and 5.11.

For purposes of handling, scaling should be determined from mission requirements. Note, for example, the very large scaling in roll for Gemini and Apollo. This is to support large, fast maneuvers in roll during atmospheric entry. Shuttle maneuvers much more slowly during entry and has a corresponding smaller high rate scaling.

Attitude Reference Frames

The ADI shows attitude, attitude error, and attitude rate with respect to a reference frame. Apollo was designed to show this information with respect to an inertial reference frame only, although that frame could be offset from M1950 via a fixed transformation matrix. Late in development the capability of displaying a pseudo Local Vertical Local Horizontal (LVLH) frame was added using a known as Orbital Rate Display Earth And Lunar (ORDEAL) to precess the inertial attitude at a rate determined from circular orbit altitude.[6]

[6]The LVLH frame is defined such that +Z (Local Vertical) is parallel to the radius vector and positive toward the central body, +Y is towards the negative angular momentum vector, and +X completes the right hand system. In a circular orbit +X is along the velocity vector. The primary idea is that the LVLH rotates as the vehicle orbits the central body.

Shuttle revised this system to provide three pilot selectable reference frames. The first, Inertial, displayed attitude with respect the M1950 inertial frame. The second, Reference, displayed inertial attitude based upon the Shuttle vehicle attitude when the pilot last pressed the Attitude Reference (ATT REF) pushbutton. In other words, the pilot could maneuver to an attitude, by pushing the ATT REF button, reset the ADI ball to 0,0,0 (pitch, roll, yaw). This allowed subsequent maneuvers to be easily referenced to that referenced attitude. This process was normally done prior to performing a large translational burn so that attitude excursions could be easily identified. The third frame, LVLH, was determined in software using the Shuttle's state vector. The majority of time in orbit the Shuttle was flown in an LVLH attitude, payload bay to Earth, so this mode was used extensively.

For purposes of handling, experience has shown the utility of all three reference frames: M1950 or J2000 Inertial, User Reference Inertial, and LVLH. Future vehicles should be designed to support all three.

Attitude Rate Sign Convention

Apollo and early Shuttle used a sign convention such that attitude rate indicators were displaced in the direction the pilot must thrust in order to arrest attitude rates and come to a stop. In other words, if the pitch rate needle was displaced upward on the scale the pilot must thrust upward in pitch by pulling back on the RHC in order to stop the pitch rotation. This may have been design chosen in response to an incident during Gemini 8 in which the pilot struggled to control a vehicle rotating at very high rates due to a malfunction.

A Shuttle flight software change in 2001 changed the implementation such that the sign of the rate indicator pointer now illustrated the sign of the attitude rate. With this change the ADI in Figure 5.6 indicates that the vehicle is rotating away from the desired attitude in all axes. As reported in [127], the following reasons were cited for the change:

> The current movement of the rate pointers is counter-intuitive because they move opposite to the direction of spacecraft rotation when rates are being established. From a piloting perspective, the display of rate information in the direction of attitude error needle deflection is superior to the opposite direction of today. Interpretation of current rate indication runs counter to previous

pilot training and conditioning. The current direction of travel is inconsistent with a similar instrument with which pilots are very familar, the turn rate indicator.

The author's experience is that the revised rate indicator logic was superior because it felt more intuitive. For example, if the pitch rate indicator was above the neutral line the vehicle was pitching up. This history suggests that future ADI implementations should use the revised rate indicator pointer logic for satisfactory handling.

ADI Euler Sequence

The ADI ball is generally driven by converting an attitude quaternion into a specific Euler sequence. This process can introduce problems and the choice of sequence is usually driven by which problem the designer wishes to solve.

Aircraft with three axis ADIs generally use the Yaw, Pitch, Roll (YPR) Euler sequence. This solves a problem best illustrated by example. Suppose an airplane is at the 0,0,0 attitude, typically heading north, nose on the horizon, and no roll. The ball is centered. If the pilot then pitches up 45 degrees and yaws right until the nose is on the horizon, a typical aircraft maneuver, the ball will show two different attitudes depending upon the Euler sequence. If the ball is driven using the aircraft typical YPR sequence it will correctly show the aircraft rolled with respect to the horizon. (In other words, the attitude becomes a yaw and roll maneuver.) However, if the ball uses the Pitch, Yaw, Roll (PYR) sequence, typical for historic spacecraft, the attitude will be encoded as a pitch and yaw maneuver, no roll, and the ADI ball roll indication will disagree with the visible horizon. Thus, YPR initially appears to be more desirable than PYR.

However, Euler sequences introduce the problem of an attitude singularly. The YPR singularity is at Pitch $= \pm 90$ *deg*, the PYR singularity is at Yaw $= \pm 90$ *deg*. Exposure to the pitch singular is more likely during launch, particularly during liftoff and aborts. The spacecraft is unlikely to yaw 90 *deg* during during these maneuvers. Also, if the spacecraft lands via parachute, exposure to the pitch singularity is possible in the time frame between parachute deploy and landing. These issues are an argument for the PYR sequence. Conversely, if the spacecraft lands aerodynamically, like the Space Shuttle, exposure to the yaw singularity is possible as the vehicle maneuvers near the runway, arguing for the YPR sequence. During orbital

ΔV_x	98.3
ΔV_y	-23.1
ΔV_z	8.6
ΔV_{total}	101.3

Table 5.12: Conceptual Incremental Velocity Indicator (IVI)

flight the spacecraft is exposed to both singularities during arbitrary maneuvers and to the yaw singularity during translational burns perpendicular to the orbital plane.

Euler sequence selection is a case of "pick your poison" and should be considered carefully. One advantage of a software generated ADI is the possibility of having different Euler sequences during different phases of flight. Modern spacecraft typically maintain attitude with a quaternion that is not subject to singularities, the exposure comes from conversion of that quaternion to Euler angles.

5.2.2 Incremental Velocity Indicator (IVI)

The Incremental Velocity Indicator (IVI) is a flight instrument that indicates velocity to be gained for a translational maneuver as mapped onto the spacecraft coordinate frame. In other words, the total velocity to be gained is mapped into X, Y, and Z components. To perform the burn the pilot pushes the THC in the directions specified by the IVI until the components of velocity to gained reach zero. Although Gemini had a mechanical IVI, subsequent spacecraft implement the IVI in software.

Table 5.12 illustrates a conceptual IVI as it would be shown on a cockpit display. Based on these indications the pilot would displace the THC forward (+X), left (-Y), and down (+Z) to drive the velocities to be gained to zero and complete the burn.

For satisfactory handing, two factors are important. First, the mapping of the total velocity to be gained onto the spacecraft coordinate frame must be dynamic and updated continuously as the spacecraft changes attitude. If not, velocity errors can occur if the spacecraft changes attitude during the burn. Second, the IVI must indicate velocity to be gained, not velocity that has been gained. In other words the pilot should use the THC to burn the IVI indications to zero, as opposed to starting from zero and burning up to a specific value. This design reduces workload and error frequency by allowing the pilot to always burn to zero. The other convention requires the pilot to keep three target velocity numbers in mind and continuously compare them to the numbers displayed on the IVI to determine when to stop the burn.

Chapter 6

Human-in-the-Loop Testing

6.1 Introduction

This chapter summarizes the results of a human-in-the-loop test performed in 2011 in support of NASA research into spacecraft design and interprets those results in the context of generic requirements for satisfactory handling qualities. The test informally investigated manual control of a degraded Space Shuttle Orbital Maneuvering System (OMS) burn. The OMS consists of two 6000 *lb* thrust gimbaling engines used for large translational maneuvers including orbital insertion, rendezvous, and deorbit. The nominal OMS gimbal rate is 5.0 deg/s. The author served as the pilot for the test.

6.2 Equipment and Scenario

The Shuttle Mission Simulator (SMS) was a high fidelity simulator used for astronaut and flight controller training. It had two cockpits, one equipped with a hexapod motion base, and one with a fixed base. Both cockpits were used for this study but motion was always disabled.

For training purposes the SMS supported the insertion of spacecraft malfunctions. For this study two malfunctions were used in combination to degrade the spacecraft's handling qualities. The first reduced the engine thrust below normal thereby limiting the maximum angular acceleration the system was capable of generating. The second slowed the thrust vector control (TVC) system actuators thereby slowing the response time of the system. The attitude control mode was proportional rate and the maximum commandable angular rate was fixed at 2.0 deg/s.

Closed-loop guidance was operating and computing the desired thrust direction in order to enter the atmosphere at a specific location and specific angle. This was used to compute attitude error to be displayed on the ADI attitude error needles.

6.3 Test Procedure

Each simulation run began approximately one minute before the deorbit burn with the spacecraft out of desired ignition attitude by about 45 deg in pitch and configured for manual control. At ignition the pilot was required to pitch to intercept the attitude requested by closed-loop guidance and then, for the duration of the burn, perform three-axis attitude control to keep the ADI attitude error needles centered within ± 1 deg. The initial attitude capture was flown with the goal of intercepting the guidance attitude as quickly as possible without overshoot or undershoot. The burn terminated automatically when guidance determined that the burn target had been achieved. This scenario is characteristic of a routine piloting task for a shuttle pilot during training. If the pilot felt capable, a small distracting task involving computer keyboard inputs was also performed in the cockpit.

After each run the pilot verbally stepped through the Cooper-Harper flowchart, a copy of which was available in the cockpit, to assign a handling rating. Paper was also provided to record additional commentary. Due to facility constraints, and to avoid pilot fatigue, the test took place over a number of days.

The result of each run was used to determine the subsequent run's engine thrust and TVC actuator speed with the intent of determining boundaries for satisfactory handling as quickly as possible due to the limited availability of the simulator.

6.4 Results

Simulation results are summarized in Table 6.1.[1] The mean pitch acceleration is the mean magnitude of pitch angular acceleration at full TVC actuation.

[1]Run IDs do not start at 1 due to simulator technical characteristics.

Run ID	Thrust (%)	Thrust (lb_f)	Mean Pitch Accel (deg/s^2)	Gimbal Rate (deg/s)	Cooper-Harper Rating
52	100	12000	0.330	5.00	2
53	70	8400	0.231	5.00	3
54	60	7200	0.198	5.00	3
55	50	6000	0.165	5.00	4
56	40	4800	0.132	5.00	5
57	70	8400	0.231	3.00	2
58	60	7200	0.198	2.50	3
59	50	6000	0.165	2.20	4
60	40	4800	0.132	1.20	5
61	38	4560	0.125	0.67	6
62	70	8400	0.231	0.60	6
63	70	8400	0.231	1.20	4
64	70	8400	0.231	1.65	3
65	60	7200	0.198	1.65	3

Table 6.1: Shuttle Thrust Vector Control Man-in-the-Loop Test Results

Plots of human (and simulated) pilot performance for these runs start on Page 239. Pilot notes after each run were as follows:

Run 52 [2] No malfunctions, sluggish but easy to fly, Cooper-Harper 2 because you have to slow down to avoid overshoot, very stable after attitude capture

Run 53 70% thrust, nominal TVC, significantly more sluggish, some overshoot on capture (approx. 3 deg) but damped within two to three oscillations, very easy once attitude is captured, Cooper-Harper 3

Run 54 60% thrust, nominal TVC, more sluggish, significant overshoot even coming off RHC approx. 8 deg before intercepting pitch attitude, Cooper-Harper 3

Run 55 50% thrust, nominal TVC, still more sluggish, accidental significant undershoot, had to correct to capture pitch, some long period approx.

[2]Run IDs do not start at 1 due to simulator technical characteristics.

2 deg. oscillation in pitch and yaw, distraction had to be done stepwise, rate feels like it takes a long time to build up, Cooper-Harper 4

Run 56 40% thrust, nominal TVC, feels like it took forever to get the initial pitch rate, significant overshoot that took a long time to correct via lightly damped oscillations, would not want to do a distraction during that period, did a small distraction near end of burn and lost track of time remaining, came back after burn completed, Cooper-Harper 5

Run 57 70% thrust, TVC Mal = 0.00075 = 3.0 deg/s, significantly less sluggish than last run, no overshoot at all on pitch capture, reasonably responsive, distraction was fairly easy, Cooper-Harper 2

Run 58 60% thrust, TVC Mal = 0.001 = 2.5 deg/s, more sluggish than run 57, feel like it takes forever to get the initial pitch rate but nailed the pitch attitude probably due to learning (did a slow backoff), some small amplitude long period oscillations in pitch and yaw after settling into attitude, Cooper-Harper 3

Run 59 50% thrust, TVC Mal = 0.0012 = 2.2 deg/s, more sluggish than run 58, still takes forever to get initial rate, overshoot with lightly damped oscillations in pitch, same pitch and yaw stuff after settling, Cooper-Harper 4 due to poor damping during corrections

Run 60 40% thrust, TVC Mal = 0.0015 = 1.2 deg/s, very sluggish, the usual oscillation, overshoot, and correction, Cooper-Harper 5

Run 61 38% thrust, TVC Mal = 0.00175 = 0.67 deg/s, took a very long time to get moving, lots of oscillation during pitch capture, went hands off for fear that I was in PIO, after capture occasional small amplitude oscillations, again poorly damped, Cooper-Harper 6

Run 62 70% thrust, TVC Mal = 0.002 = 0.60 deg/s, took a very long time to get moving, stopped just short of pitch attitude then required pitch jumped further down, went to capture it and got into a very large amplitude (approx ±10 deg) poorly damped oscillation, not too terrible once in attitude and settled down but small errors still resulted in oscillation, some hesitancy to acknowledge the TVC fail caution and warning message on CRT 1, Cooper-Harper 6

Run 63 70% thrust, TVC Mal = 0.012 = 1.2 deg/s, sluggish but better, nailed the pitch attitude, generally sluggish but not too terrible, Cooper-Harper 4

Run 64 70% thrust, TVC Mal = 0.00135 = 1.65 deg/s, captured attitude pretty easily using backoff technique, sluggish but easy to control, Cooper-Harper 3

Run 65 60% thrust, TVC Mal = 0.00135 = 1.65 deg/s, more sluggish but not much worse, captured and maintained attitude without much trouble, marginal overshoot, failed an engine late in the burn (Left OME) and had a satisfactory maneuver to single engine attitude, held new attitude okay, Cooper-Harper 3

6.5 Application to Generic Requirements

Figure 6.1 depicts the test results graphically. Cooper-Harper ratings are plotted at associated values of mean maximum pitch acceleration at full TVC deflection versus TVC gimbal rate. The nominal configuration (no decrease in thrust or actuator speed) is in the upper right corner and, as expected, the general trend is that handling gets worse towards the lower left as angular acceleration gets smaller and gimbal rate decreases. This is reflected in the numerically larger Cooper-Harper ratings in those directions. Run 57, with a rating of 2, appears to be an outlier but is representative of some uncertainty in subjectively assigned ratings.

The boxed area of the plot is set by the mid-points between clustered Cooper-Harper ratings of 3 and 4. This boundary represents a theoretical rating of 3.5 as the transition between satisfactory and unsatisfactory handling.

As noted previously (page 80), these results indicate that real world thrust vector control systems are unlikely to gimbal at a rate sufficiently slow to cause unsatisfactory handling.

Using the definition of design parameter k_{tvc} (Equation 4.8, Page 81), and the Shuttle OMS maximum commandable attitude rate of 2 deg/s, we see that the vertical boundary shown in Figure 6.1 corresponds to $k_{tvc} = 0.091$ $1/s$. We conservatively round up slightly and estimate that for powered flight with thrust vector control we require that $k_{tvc} > 0.1$ $1/s$.

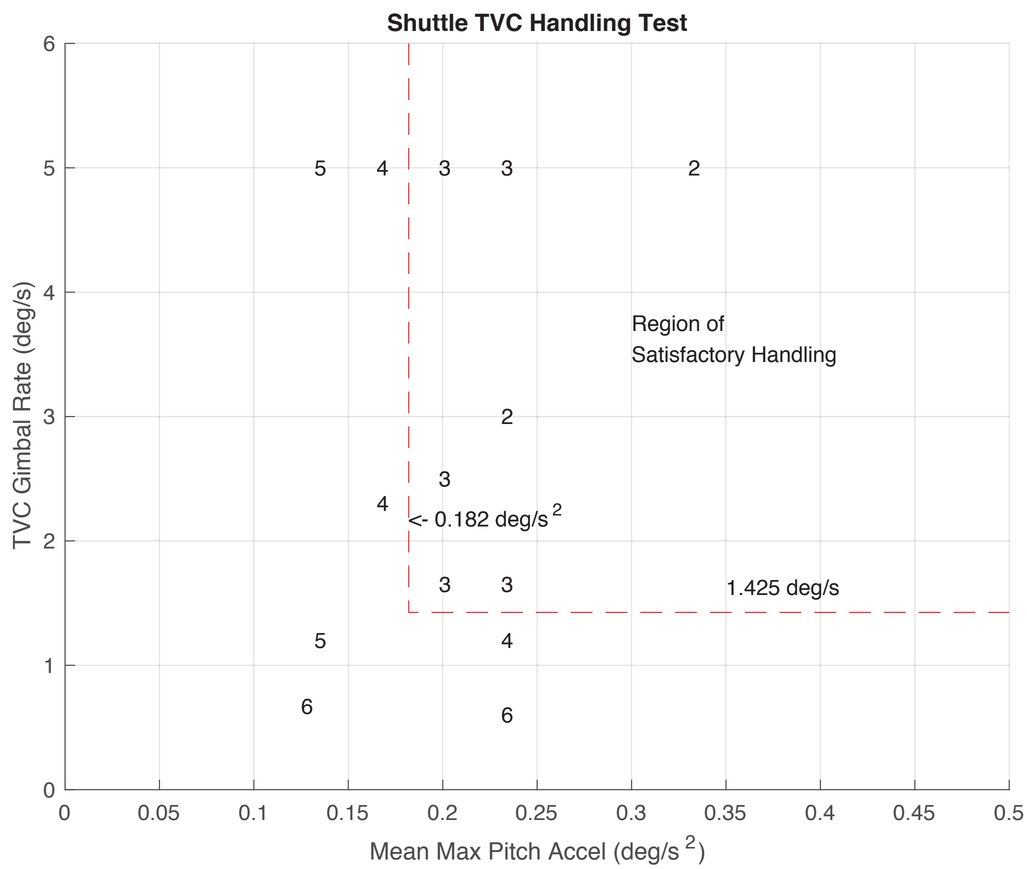

Figure 6.1: Shuttle SMS TVC Test Results

Chapter 7

Simulation of Human Pilot Performance

To review, we have now defined a set of requirements for satisfactory handling consisting of design parameters and estimated critical values at which handling transitions between satisfactory and unsatisfactory. The next step would normally be to verify that the estimated critical values are correct. Unfortunately, this requires a highly reconfigurable spacecraft simulator as well as a cadre of qualified pilots to fly test cases and assign ratings. Those resources are, unfortunately, not presently available.

As a substitute, this chapter adopted the process illustrated in Figure 7.1. Data from human-in-the-loop testing is used to create a model of a human pilot. The simulated pilot is shown to have human-like performance and limitations by comparing cases with the same initial conditions. Having demonstrated suitability, the simulated pilot is then used to evaluate handling in two additional spaceflight regimes: coasting flight attitude control and powered flight with reaction control.

7.1 Human Pilot Characteristics

We first note that, as documented by Miall, Weir, and Stein [105], human manual tracking behaves like an intermittent, as opposed to continuous, controller. In other words, we assume that the pilot periodically samples sources of input, such as flight instruments, and then, after a delay, generates an output to the hand controller.

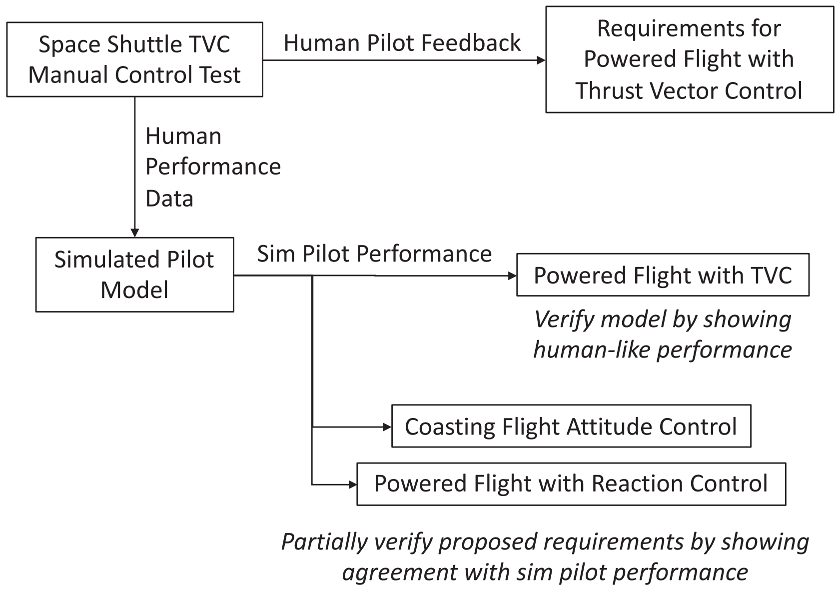

Figure 7.1: Simulated Pilot Partial Verification Concept

We define pilot delay time (t_{pd}) to be the time between human sensory input, such as an update on a flight instrument, and controlling output, such as moving a hand controller. Using data from Privoznik and Berry [118] we estimate pilot delay time as a linear function of the vehicle's Guidance, Navigation, and Control (GNC) delay time (t_{gd}) normally distributed as follows:

$$\mu_{pd}(sec) = 0.264t_{gd} + 0.196 \tag{7.1}$$

$$\sigma_{pd}(sec) = 0.025 \tag{7.2}$$

In other words, we first note the characteristic GNC delay time t_{gd} for a spacecraft. Typical values are 0.08 *sec* (Shuttle) and 0.10 *sec* (Apollo). This is the time between GNC cycles in which the hand controller is sampled, computations are performed, flight instruments are updated, and control effectors (such as TVC actuators or RCS jets) are commanded.[1] This is used

[1] The GNC delay time for Shuttle aerodynamic flight is significantly longer, on the order of 0.7 *sec*, due to the long chain of avionics and hydraulic actuators for aerodynamic control surfaces. Times for RCS and OMS TVC control should be significantly faster.

to compute the mean pilot delay time μ_{pd}. The total pilot delay time t_{pd} is computed by dispersing μ_{pd} with σ_{pd}.

For the Space Shuttle ($t_{gd} = 0.08sec$) this equates to a pilot delay time of $\mu_{pd} = 0.217$, $\sigma_{pd} = 0.025$ *sec*. This is consistent with the value given by Smith [56], describing the sum of neurological and neuromuscular delay as normally being between 0.2 and 0.3 *sec*. A report by Edwards [64], in which pilot delay time is analyzed for several manual control tasks during the Gemini-10 mission, notes that pilot delay time will tend to increase as the difficulty of the piloting task decreases. No attempt to model that phenomenon is made here.

The piloting task being modeled is to read the attitude error shown on the Attitude Direction Indicator (ADI), determine the appropriate attitude rate to null the error, and move the hand controller accordingly. Data from human-in-the-loop testing is used to create the pilot model. However, a limitation of this analysis is that the attitude error is not directly available and must be computed via the telemetered position of the ADI attitude error needle. Because of this, only attitude errors smaller than 5 *deg*, the maximum needle deflection, are known exactly. Larger attitude errors are off-scale large and always indicate 5 *deg*. In other words, for this analysis only pilot behavior within ± 5 *deg* of the desired attitude is known. However, this range is large enough to still yield useful results as will be shown.

As shown in Figure 7.2, the pilot function can be modeled as a symmetric linear segmented line constrained to pass through the origin. The number of segments and segment endpoints were found with a numeric least-squares fit to minimize the miss distance to all data points. A model incorporating attitude error rate was evaluated but not improve simulation performance and was subsequently discarded.

The required pilot performance for Shuttle manual control is to capture and maintain the desired attitude within ± 1 *deg*. As a result, the pilot need not attempt to maintain zero attitude error. To account for this, pilot data was analyzed to determine the probability of commanding zero attitude rate as a function of attitude error. The result is shown in Figure 7.3 and can be seen to be nearly symmetric and with increasing probability near zero attitude error.

Details of the pilot rate function and zero rate probability function are provided in the appendices starting on page 239.

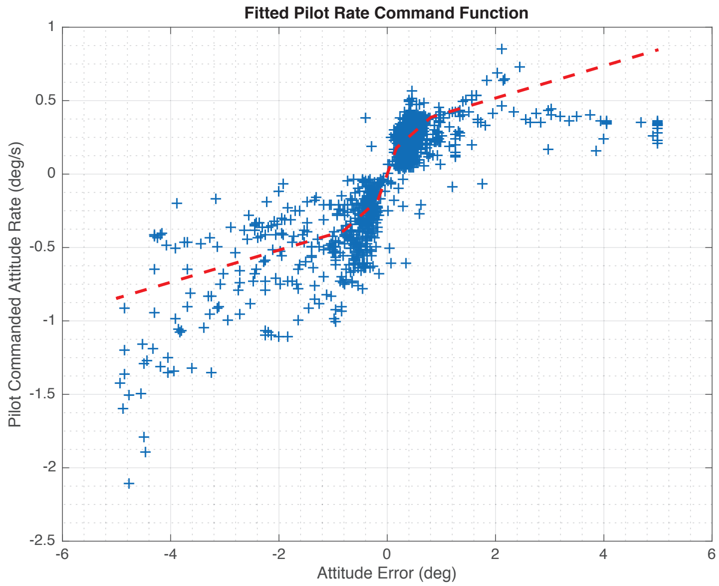

Figure 7.2: Fitted Pilot Rate Command Function

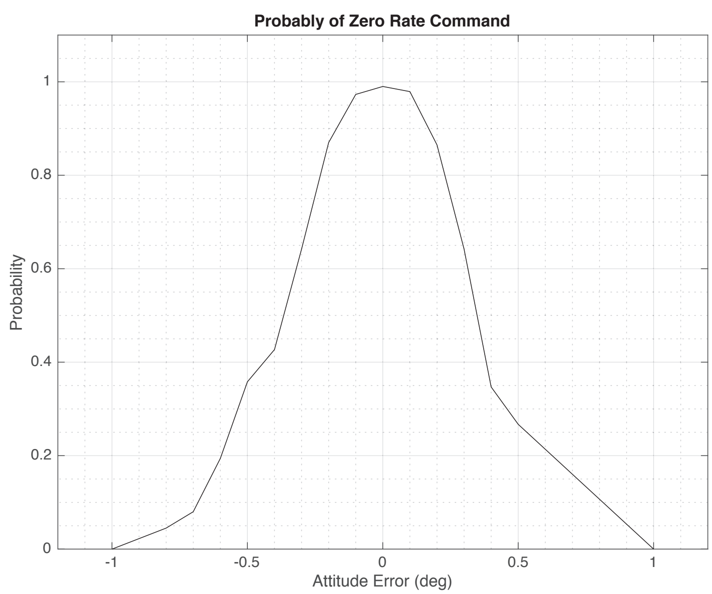

Figure 7.3: Zero Commanded Rate Probability Function

7.2 Spacecraft Characteristics

The simulated spacecraft incorporates a simplified version of the Shuttle Orbital Maneuvering System (OMS). Whereas the actual spacecraft has two 6000 lb_f OMS engines with pitch and yaw actuators, the simplied model has a single nominal 12000 lb_f engine located at the midpoint with a pitch actuator only to support the one degree of freedom simulation. As with the real vehicle, the TVC actuator has a range of ± 6 deg. The hysteresis characteristics are also shared in that movement will not occur until actuator position error exceeds 0.4 deg and movement will cease when error is reduced to less than 0.06 deg. The nominal actuator rate is 5.0 deg/s. Spacecraft center of mass and moment of inertia in pitch are shared with the human-in-the-loop simulation.[2]

The spacecraft control system operates on a 0.08 sec cycle. Every cycle the RHC is sampled to determine the desired pitch rate, the pitch rate error is computed, and the TVC actuator command is computed as function of pitch rate error (P-Controller). In addition, the pitch attitude error is determined to update the ADI error needle. Independently in the simulation, logic determines if the TVC actuator position error exceeds the the hysteresis tolerance and, if so, it is driven at the specified rate (which may be degraded). Closed loop control of the TVC actuator on the actual vehicle is via circuitry, independent of flight software. Therefore no delay is incorporated in the simulation.

$$OrbitalRate = \frac{360deg}{5400s} = 0.067\frac{deg}{s} \tag{7.3}$$

In the human-in-the-loop simulation the desired attitude is a function of closed-loop guidance attempting to achieve specific atmospheric entry conditions. This results in a gradual change in desired pitch attitude over the course of the burn. To approximate this, the desired pitch attitude in the simulation is changed at orbital rate (0.067 deg/s). As shown in Equation 7.3, this is the inertial attitude rate required to maintain a fixed LVLH attitude in an orbit with an assumed 90 minute period.[3]

[2]TVC actuators typically extend and retract linearly to cause the engine to rotate at the gimbal bearing. Although actuator position can be described linearly it is common practice to cite position in terms of the angular deflection of the engine. Thus, actuator rate and gimbal position (or rate) are often used interchangably to describe engine angular motion.

[3]A fixed Local Vertical, Local Horiztonal (LVLH) attitude can be thought of as the

7.3 Simulation Design

In summary, there are three control loops (pilot, spacecraft GNC, TVC actuator) operating at three different periods. One of those periods, the pilot, being normally dispersed. The pilot function is non-linear with a zero-rate probabilistically invoked override. The TVC actuator has limited travel and hysteresis. Finally, the target attitude is continuously changing. All of these factors suggest that a linearized classic control theory model is likely to yield misleading results.

The pilot-spacecraft simulation is therefore implemented in software as a numeric model. The model consists of states (pitch target, pitch attitude, pitch rate, TVC actuator position) that are integrated continuously and a time-ordered event queue to account for delays. For example, the pilot component periodically reads the current attitude error, computes the corresponding pitch rate command, and places the command forward in time in the event queue to account for the pilot delay. Similarly, at every GNC task event the model updates the current attitude error, uses the latest attitude rate command to compute the TVC actuator position command, and enqueues another GNC task event to occur 0.08 *sec* in the future.

7.4 Powered Flight with Thrust Vector Control

Runs were performed with the same TVC configuration (total thrust, gimbal rate) and initial conditions (attitude error, attitude rate, actuator position) as those performed by a human pilot in the Space Shuttle simulator. The simulated pilot runs arbitrarily end at 200 *sec*.

The agreed upon standard for pilot performance among the Space Shuttle flight operations community for a manually flown maneuver such as this is to capture and maintain attitude to within 1 *deg* of error without overshoot. Using this critereon, simulated pilot results were judged to be satisfactory (they achieved the desired performance) or unsatisfactory (they did not achieve the desired results). Handling with a human pilot is considered satisfactory for Cooper-Harper ratings of 1, 2, or 3. Higher ratings indicate unsatisfactory

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spacecraft flying like an airplane in cruise, fixed in attitude relative to the surface below, as opposed to inertially fixed relative to the Sun and stars.

Run ID	Ang Accel deg/s^2	TVC Gimbal Rate deg/s	Human Result (Cooper-Harper Rating)	Simulation Result
52	0.330	5.00	Satisfactory (2)	Satisfactory
53	0.231	5.00	Satisfactory (3)	Satisfactory
54	0.198	5.00	Satisfactory (3)	Satisfactory
55	0.165	5.00	Unsatisfactory (4)	Satisfactory
56	0.132	5.00	Unsatisfactory (5)	Satisfactory
57	0.231	3.00	Satisfactory (2)	Satisfactory
58	0.198	2.50	Satisfactory (3)	Satisfactory
59	0.165	2.20	Unsatisfactory (4)	Unsatisfactory
60	0.132	1.20	Unsatisfactory (5)	Unsatisfactory
61	0.125	0.67	Unsatisfactory (6)	Unsatisfactory
62	0.231	0.60	Unsatisfactory (6)	Unsatisfactory
63	0.231	1.20	Unsatisfactory (4)	Unsatisfactory
64	0.231	1.65	Satisfactory (3)	Unsatisfactory
65	0.198	1.65	Satisfactory (3)	Unsatisfactory

Table 7.1: Shuttle Thrust Vector Control Human and Simulated Pilot Results

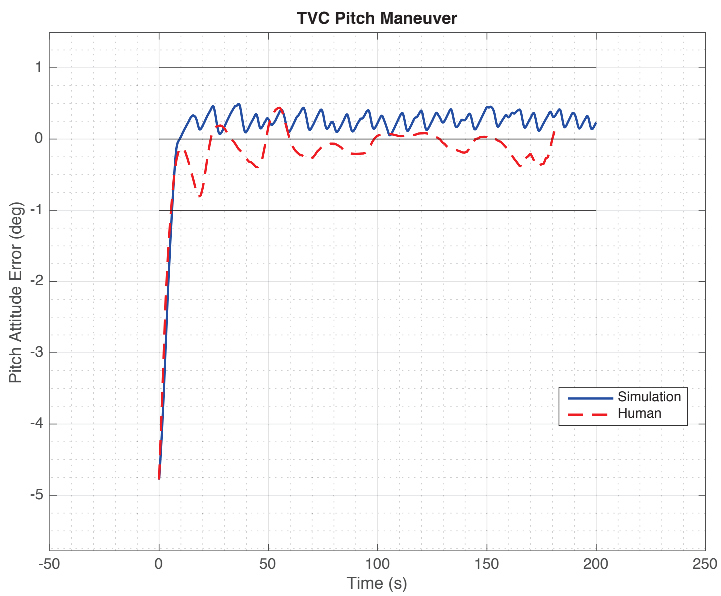

Figure 7.4: Space Shuttle TVC Pilot Performance Run 52 (Satisfactory)

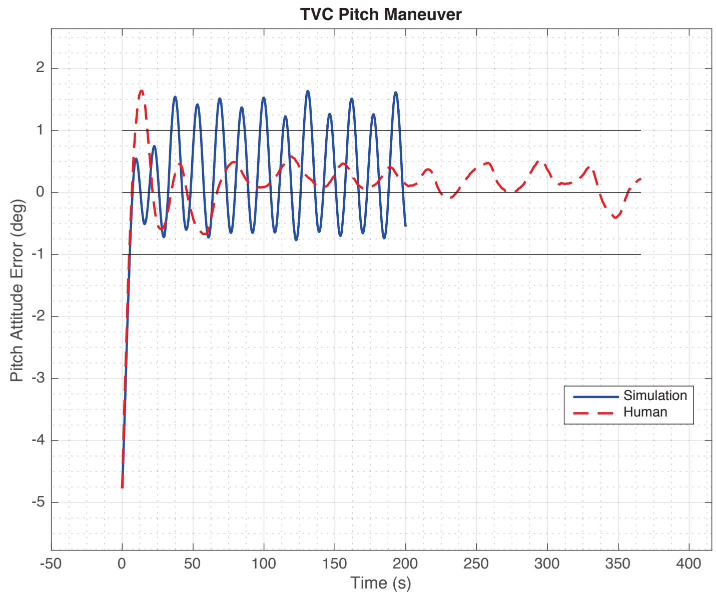

Figure 7.5: Space Shuttle TVC Pilot Performance Run 59 (Unsatisfactory)

handling. Results are summarized in Table 7.1.

Human and simulated pilot data were plotted together for comparison and are presenting in the appendices starting on page 239. Two representative plots are shown in Figure 7.4 and 7.5 to illustrate satisfactory and unsatisfactory handling as determined by the simulated pilot. Run 59 is unsatisfactory in that it fails to settle within the tolerance band.

In general we see good agreement between the human and simulated pilot for high angular acceleration and fast TVC gimbal rates in which handling is satisfactory, and with low angular acceleration and slow gimbal rates in which handling is unsatisfactory. There is some disagreement at intermediate levels, such as in runs 55 and 56, in which the human pilot rated the handling as unsatisfactory but the simulated pilot satisfied the performance criteria.

Having shown good agreement for these particular cases, a number of runs were performed to determine boundaries for satisfactory handling. Figure 7.6 illustrates a run at the minimum level of angular acceleration and TVC gimbal rate that yields satisfactory handling: 0.171 deg/s^2 and 2.5 deg/s respectively.

Figure 7.7 repeats Figure 6.1 on page 135 with the red dashed line indicating the human boundary for satisfactory handling but adds the simulated

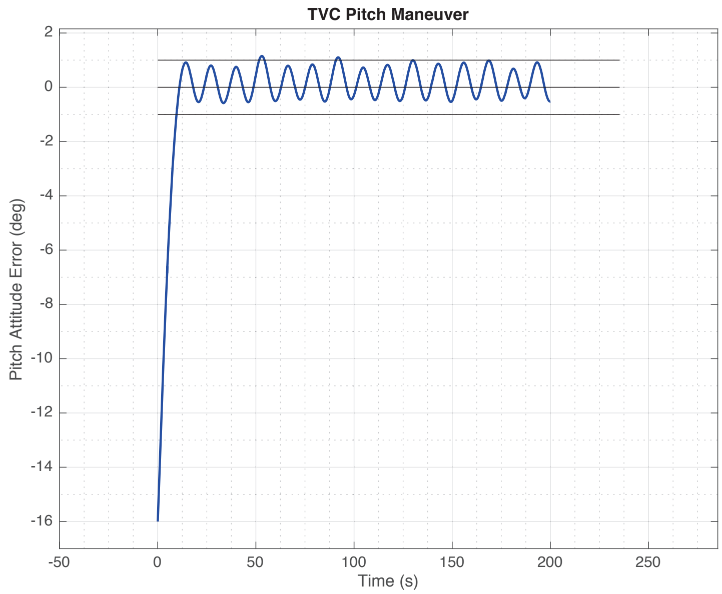

Figure 7.6: Simulated Pilot TVC Minimum Control Authority Performance

pilot boundary shown with the solid blue line. As can be seen, the minimum acceptable values of angular acceleration are in very close agreement. The boundary for TVC gimbal rate is somewhat higher for the simulated pilot, 2.5 versus 1.425 deg/s. As has been noted previously, this parameter is less important because actual thrust vector control systems are unlikely to move this slowly.

Recalling the defition of TVC control authority k_{tvc} (Equation 4.8, Page 81), and noting the maximum attitude rate of 2.0 deg/s, the human and simulated pilots require 0.091 and 0.086 $1/s$ respectively for satisfactory handling. Both values round up to the proposed requirement value of 0.1 $1/s$.

7.5 Coasting Flight Attitude Control

Having demonstrated that the software pilot provides a good match for human performance, the spacecraft model was modified to simulate coasting flight attitude control using a proportional rate control system. The maximum attitude rate remained at 2.0 deg/s and the attitude rate deadband was set to 0.1 deg/s.

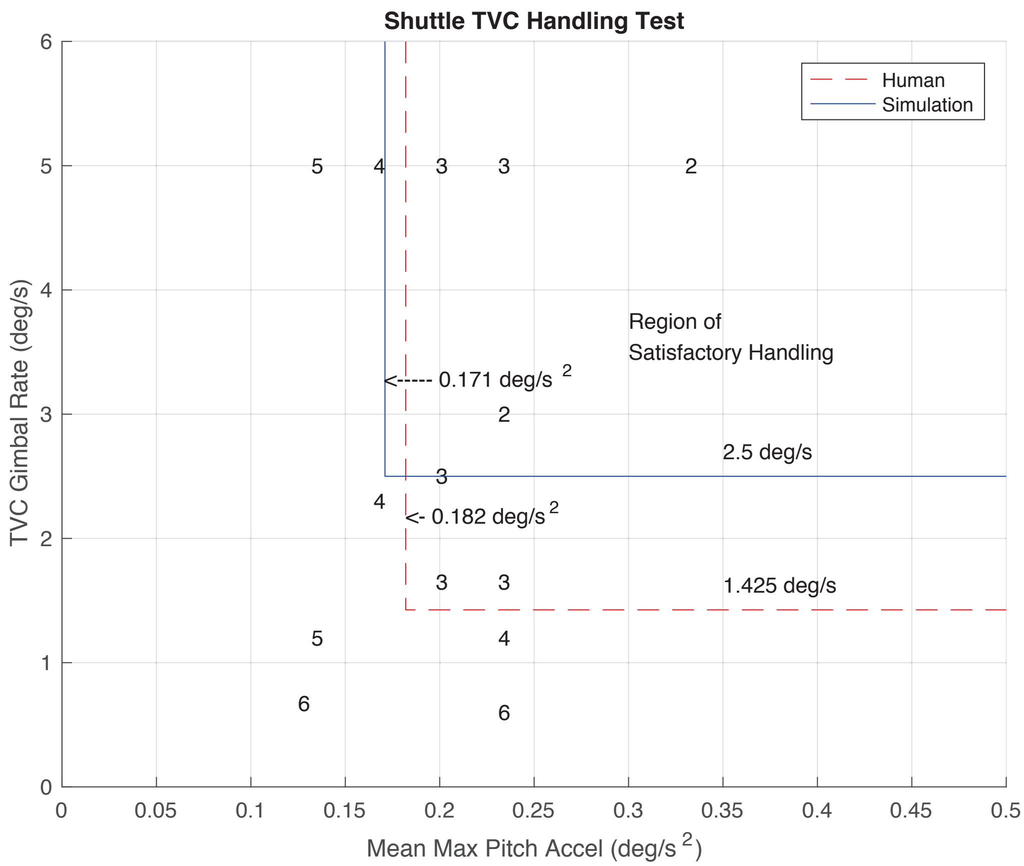

Figure 7.7: Boundaries for Satisfactory Handling Including Simulation

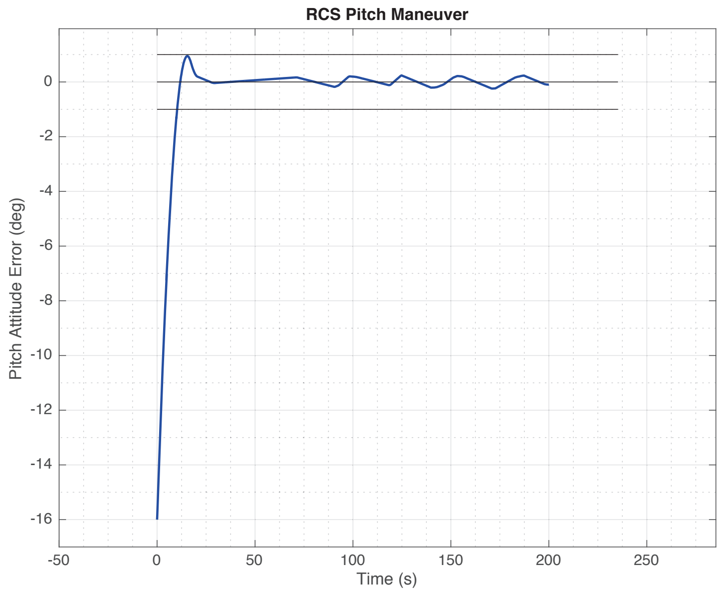

Figure 7.8: Simulated Pilot RCS Minimum Control Authority Performance

Figure 7.8 illustrates performance of the simulated pilot with the minimum satisfactory control authority. The angular acceleration at this control authority is 0.144 deg/s^2, corresponding to the design parameter k_{acpr}=0.072 $1/s$ as defined in Equation 4.5 on page 66. This compares well to the estimated critical value of 0.1 $1/s$.

7.6 Powered Flight with Reaction Control

To investigate the spaceflight regime of powered flight with reaction control, the spacecraft model was modified to incorporate a continuous perturbing moment as would be applied by a translation thrust vector not passing through the spacecraft center of mass.

Figure 7.9 illustrates an attitude maneuver during powered flight with reaction control with the minimum satisfactory control authority. A perturbing moment equivalent to 0.1 deg/s pitch up has been applied, simulating the translational thrust vector passing below the center of mass. To achieve the desired performance, no more than 1 deg overshoot, the angular acceleration has been increased to 0.25 deg/s^2. The maximum attitude rate remains 2.0

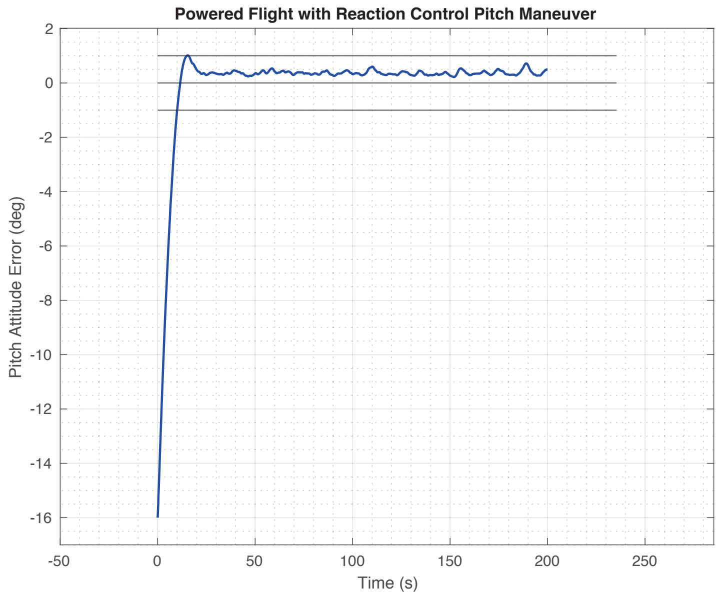

Figure 7.9: Simulated Pilot Powered Flight with Reaction Control Minimum Control Authority Performance

deg/s.

Using the usual definition of proportional rate control authority, the effective control authority therefore becomes 0.175 $1/s$ when pitching up, 0.075 $1/s$ when pitching down. For the critical case, pitch down, this value is very close to the value previously found for coasting flight attitude control (0.072 $1/s$). This tends to support the handling qualities assumption for this flight regime given on page 74, namely that handling will be satisfactory if control authority still meets the requirement for coasting flight attitude control despite the perturbing moment created during translation.

7.7 Conclusions

Table 7.2 summarizes design parameter critical values for satisfactory handling during powered flight with thrust vector control. As can be seen, there is good agreement between the human and simulated pilots. This data, as well as the good agreement with specific cases also flown by a human pilot, suggests that the model, although limited in application, is sufficiently

Parameter	Human Pilot	Simulated Pilot
Angular Accel (deg/s^2)	>0.182	>0.171
Cntl Auth k_{tvc} ($1/s$)	>0.091	>0.086
Gimbal Rate (deg/s)	>1.425	>2.5

Table 7.2: Comparison of Powered Flight with Thrust Vector Control Parameters

Parameter	Estimated	Simulated Pilot
Cntl Auth k_{acpr} ($1/s$)	>0.1	>0.072

Table 7.3: Comparison of Coasting Flight Attitude Control Parameters

human-like to provide partial verification of requirements for other spaceflight regimes.

Table 7.3 summarizes critical values for the control authority parameter associated with coasting flight attitude control when using a proportional rate control system. The estimated value is via analysis of historic spacecraft. The value found via simulated pilot and spacecraft is sufficiently close to the estimated value, and notably rounds up to it, that the author considers the estimated value to be partially validated.

Table 7.4 summarizes the estimated requirement for minimum satisfactory control authority during powered flight with reaction control and the value found using a simulated pilot and spacecraft. The central assumption for the regime is that handling will be satisfactory if the coasting flight attitude control requirement is met despite the presence of the perturbing moment resulting from translational thrust. The critical value found, 0.075 $1/s$, is virtually identical to the value found by the simulated pilot performing coasting flight attitude control (0.072 $1/s$). We therefore conclude that the assumption is partially verified.

Parameter	Estimated	Simulated Pilot
Cntl Auth (Critical Direction) k_{acpr} ($1/s$)	>0.1	>0.075

Table 7.4: Comparison of Powered Flight with Reaction Control Parameters

In conclusion, this chapter presented a technique to model human pilot and spacecraft interaction using human performance data. The model was shown to similar have performance and limitations as the human pilot when performing powered flight with thrust vector control. The model was then used to perform successful partial verification of proposed requirements for the regimes of coasting flight attitude control and powered flight with reaction control, both using proportional rate control systems with a maximum attitude rate of 2.0 deg/s. Although human-in-the-loop testing is required for full verification of the proposed requirements, this partial verification suggests that the proposed critical values are approximately correct.

Chapter 8

Conceptual Design of a Compliant Spacecraft

Having now defined a set of design parameters and estimated critical values at which handling transitions between satisfactory and unsatisfactory, and having performed partial verification of those values using a simulated pilot, we now seek to perform a partial validation. This is accomplished by showing that the set of requirements is not self-contradictory. In other words, we prove by example that designing a spacecraft to comply with one requirement does not prohibit compliance with any other requirement. The example is a conceptual vehicle design that is fully compliant with all relevant requirements. In doing so we also demonstrate a methodology for design of a spacecraft with satisfactory handling.

The conceptual spacecraft is a four person taxi designed to ferry personnel to and from the International Space Station (ISS). The spacecraft, known as the *Fireball*, launches on an expendable launch vehicle, performs a rendezvous with the ISS, docks, remains attached for an extended period of time, undocks, performs a deorbit burn, reenters the atmosphere, and lands via parachute. It therefore operates in all spaceflight regimes except powered lift landing. The nature of spacecraft engineering is that designing a single vehicle capable of both powered lift landing and atmospheric entry is very difficult and no attempt to do so is made here. As a result, the Fireball will be shown to be compliant with all proposed requirements except those for powered lift landing.

Fireball superfically resembles the Apollo or Orion spacecraft in that it consists of a conical Command Module (CM) attached to a cylindrical Service Module (SM). The CM contains the habital pressurized volume, guidance systems, and a propulsion system (SM RCS) for atmospheric entry. The SM contains propellant tanks, batteries, solar arrays, and the orbital propulsion system consisting of propellant tanks, a Reaction Control System (SM RCS), and a gimbaling Orbital Maneuvering System (OMS) engine. For the majority of the mission the two components operate together as a combined Command and Service Module (CSM). After the deorbit burn the two components separate and the CM performs a brief period of exoatmospheric flight followed by atmospheric entry and landing. The SM, lacking thermal protection, breaks up during entry and is not recovered.

As with Apollo, the docking mechanism is at the apex of the CM. Unlike Apollo, which used fuel cells, Fireball is powered with solar arrays and batteries to remain powered indefinitely while docked to the ISS.

8.1 Design Process

The design process for the conceptual vehicle is illustrated in Figure 8.1.

Box 1: We first define the mission concept and requirements. In this case the concept is an ISS taxi vehicle and, broadly speaking, the requirements are to carry four people and to be capable of remaining docked to the ISS for the extended period of time.

Box 2: System requirements are a function of mission requirements. Here, for example, the mission requirement to travel to and from the ISS implies a system requirement of approximately 800 ft/s velocity change capability. Definition of system requirements is discussed in Sections 8.2, 8.3, 8.4, and 8.5.

Box 3: Layout of the vehicle is performed in a way that is conscious of the eventual impact on handling. For example, the center of mass is positioned as close as possible to the centerline of the vehicle to minimize coupling. Layout is discussed in Sections 8.6, 8.7, and 8.8. The resulting mass properties are then estimated in Section 8.9. Finally, design requirements are used to determine allowable ranges of RCS thrust for satisfactory handing. This process is extensively documented in Sections 8.10, 8.11, 8.12, 8.13, and 8.14. Analysis of Powered Flight with Thrust Vector Control is discussed in Section 8.15.

Box 4: A summary of the vehicle's compliance with requirements for satisfactory handling is given in Section 8.16. The conceptual vehicle designed

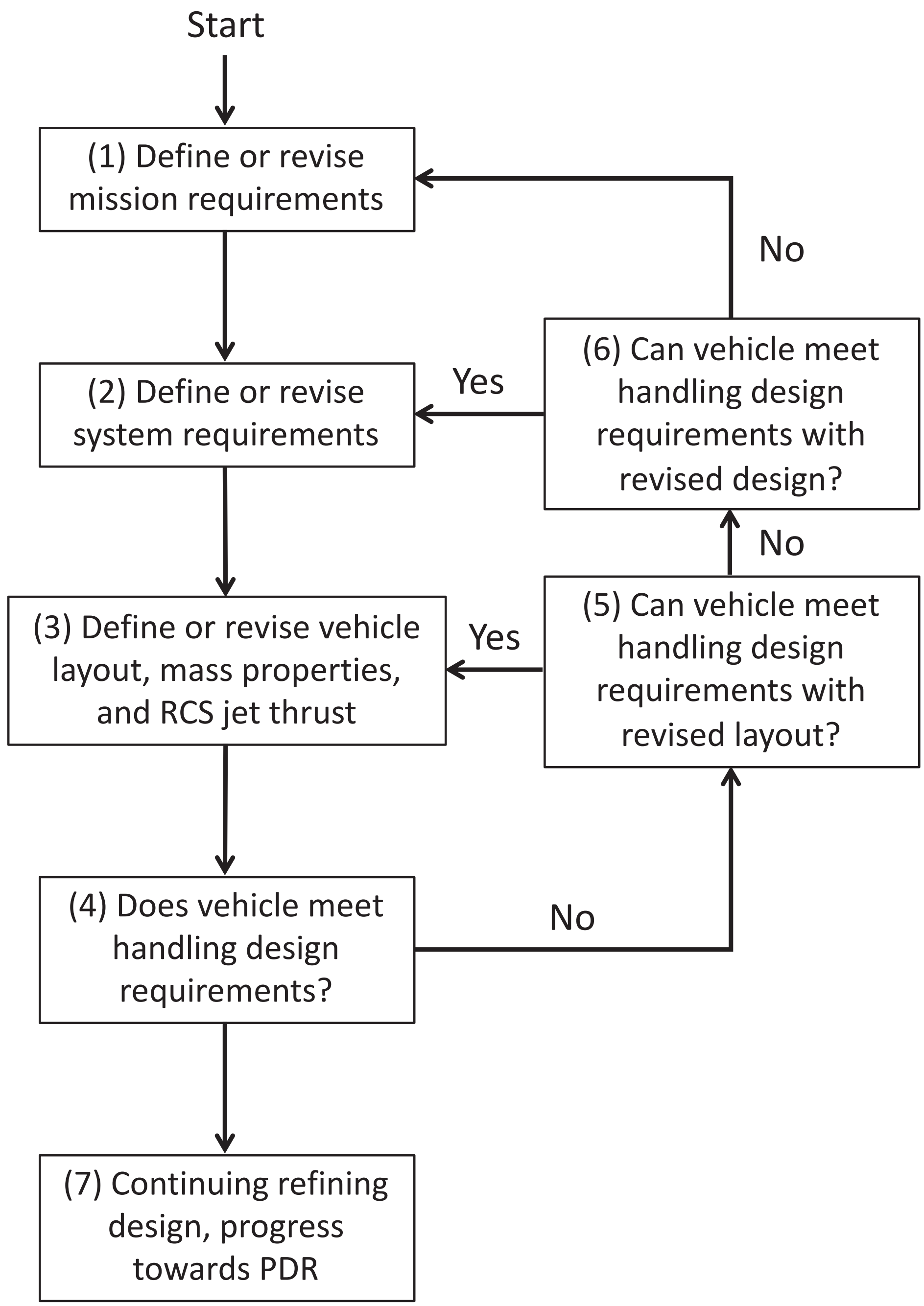

Figure 8.1: Design Process Flowchart

here is fully compliant and flow should continue to Box 7. If the vehicle had not been compliant flow would continue to Box 5.

Box 5: In some cases it may be possible to revise the vehicle layout in a way that it will subsequently meet handling design requirements. For example, RCS thrust directions may be adjusted slightly to minimize coupling. The example vehicle provides an example of this by canting translational jets to aim the thrust vectors through the estimated center of mass location at docking.

Box 6: If adjusting vehicle layout fails to allow for satisfactory handling the next corrective action is to revise system requirements. Potential candidates include a more complex reaction control system design with both small and large thrust jets, as was used on the Space Shuttle, or a docking mechanism with larger tolerances for approach velocity and radial position. Extreme caution should be exercised when reduction of safety margin is proposed to solve a handling or other performance problem. If these approaches fail it becomes necessary to revise mission requirements to those which can be achieved safely. For example, changing the mission requirement to carry fewer people allows the spacecraft to become significantly lighter and may result in the ability to meet all other mission requirements without compromising safety.

Box 7: Design is an iterative process. As the design matures mass properties will changes and compliance with performance requirements, including handling, must be checked regularly.

8.2 Command Module Sizing

The Fireball CM, shown in Figure 8.2, has the same shape as an Apollo CM, roughly conical with sides depressed 33 degrees from vertical, because this is a shape known to be stable and suitable for atmospheric entry. Because it must carry four people, as opposed to Apollo's three person capability, the cone radius is increased from 77 to 88 inches. The relative location and direction of CM RCS jets are the same as Apollo, again because this is a configuration that is known to work well. CM RCS jet thrust is determined as part of the handling analysis. RCS jet numbers have been added to the original illustration from [17].

Comparison of an Apollo CM and Orion CM shows that for this type of vehicle mass scales most closely with surface area. By linear extrapolation

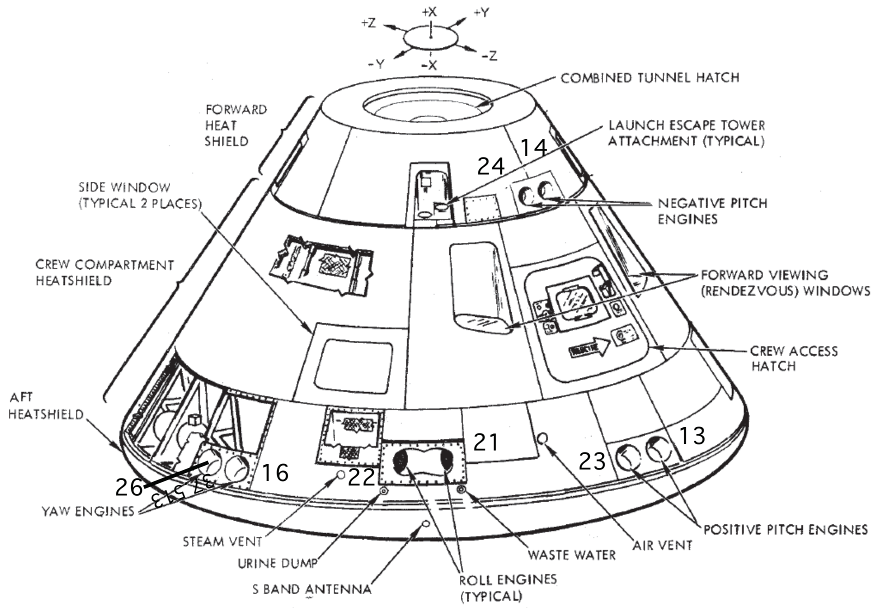

Figure 8.2: Fireball CM Layout (Based on Apollo CM) [17]

of weight as a function of surface area using two known vehicles, the Fireball CM is estimated to weigh 17885 lb.

Moments and products of inertia of the Fireball CM are assumed to scale linearly with weight from the Apollo CM. The locations of points on the Fireball CM, including jets and center of mass, are scaled by fractional increase in radius. CM mass property data are shown in Table 8.8. CM RCS jet information is shown in Table 8.2 and Table 8.3.

8.3 Propulsion Sizing

The Design Reference Mission (DRM) for the Fireball begins with being placed into a 24 x 226 nautical mile orbit by the launch vehicle. This orbit has an atmospheric perigee for disposal of the launch vehicle upper stage. Translational burn #1, normally not performed, is used to make up for a launch vehicle underspeed.

Burn #2 occurs approximately 40 minutes after launch at the first apogee and is used to raise perigee out of the atmosphere to achieve a stable orbit. A 138 ft/s burn is used to achieve a 100 x 226 nmi orbit.

A series of posigrade burns are then used to gradually raise perigee and slow the closing rate to the ISS. This is modeled as a single 220 ft/s burn (#3) to achieve a 226 x 226 nmi orbit to match the orbit of the ISS.

Burn #4 is the deorbit burn. A single 358 ft/s retrograde burn is used to lower perigee into the atmosphere for entry and landing. This results in a 24 x 226 nmi orbit.

The design reference mission therefore requires a total of delta-V capability of 716 ft/s. We add 10% to account for attitude control requirements resulting in a total requirement of 788 ft/s. This number is then rounded up to 800 ft/s to account for additional uncertainties.

8.4 Service Module Sizing

The Apollo SM, without fuel cells and cryogenic reactant storage and distribution systems, is estimated to weigh approximately 7500 lb. Because the SM must support the weight of the CM during launch acceleration, we assume that the mass of the SM will scale linearly with CM weight. The core dry Fireball SM is therefore estimated to weigh 10361 lb.

$$\frac{FireballCM}{ApolloCM} = \frac{17885lb}{12946lb} * 7500lb = 10361lb \tag{8.1}$$

The Fireball uses two SM-mounted solar arrays for power generation. We assume an electrical load slightly smaller than Apollo to account for technology improvements, 1400 W, for sizing the arrays. Using techniques documented in [90] we estimate that the GaAs arrays must total approximately 160 ft^2 in size divided into two 80 ft^2 panels mounted to the Fireball SM. With support structure these arrays are estimated to weight 100 lb each (200 lb total). Battery weight is assumed to be included with SM core weight estimated previously.

The total dry weight of the Fireball SM is therefore estimated to be 10561 lb.

$$SMstructure + SolarArrays = 10361lb + 200lb = 10561lb \tag{8.2}$$

The dry weight for the entire Fireball CSM spacecraft is therefore estimated to be 28446 lb.

$$CMweight + SMweight = 17885lb + 10561lb = 28446lb \tag{8.3}$$

8.5 Propellant Quantity Sizing

The Fireball SM has both a gimbaling Orbital Maneuvering System (OMS) Engine and a Reaction Control System (RCS). They share a common hypergolic propellant supply using Monomethyl Hydrazine (MMH) as fuel and Nitrogen Tetroxide (N_2O_4) as oxidizer. The OMS engine is assumed to have a specific impulse (I_{sp}) of 315 *sec* and the RCS of 280 *sec*. This is consistant with current production engine performance. In order to be able to tolerate failure of the OME, we size the propellant quantity assuming that the entire mission must be performed using the RCS with associated lower specific impulse.

Using the ideal rocket equation with a spacecraft dry weight of 28446 lb, a specific impulse of 280 *sec*, and required delta-V capability of 800 ft/s, the required propellant weight is 2418 lb yielding a spacecraft wet weight of 28446 lb + 2814 lb = 30864 lb. Using a stoichiometric mixture ratio of 1.66 (oxidizer mass to fuel mass) the propellant is divided into 1509 lb of oxizider and 909 lb of fuel.

The oxidizer, N_2O_4, has a volumetric density of 89.272 lb/ft^3. This results in an oxidizer tank volume of 16.903 ft^3. The fuel, MMH, has a volumetric density of 53.688 lb/ft^3. This results in a fuel tank volume of 16.931 ft^3. The fact that both propellants require almost exactly the same size tank is a particular convenience of this oxidizer and fuel combination because it allows for identical tanks. In this case we round slightly and assume one oxidizer and one fuel tank each of 16.9 ft^3 capacity. This results in a spherical tank with a radius of 1.59 ft (19.1 *in*) or diameter of 3.18 ft (38.2 *in*).

8.6 Service Module Layout

The Service Module is assumed to be a cylinder of the same 88 *inch* radius as the Command Module. The length is set by several factors including the radius of the Command Module heat shield hemisphere, propellant tank volume, and solar array size.

The coordinate system is typical for modern spacecraft in that the X-axis

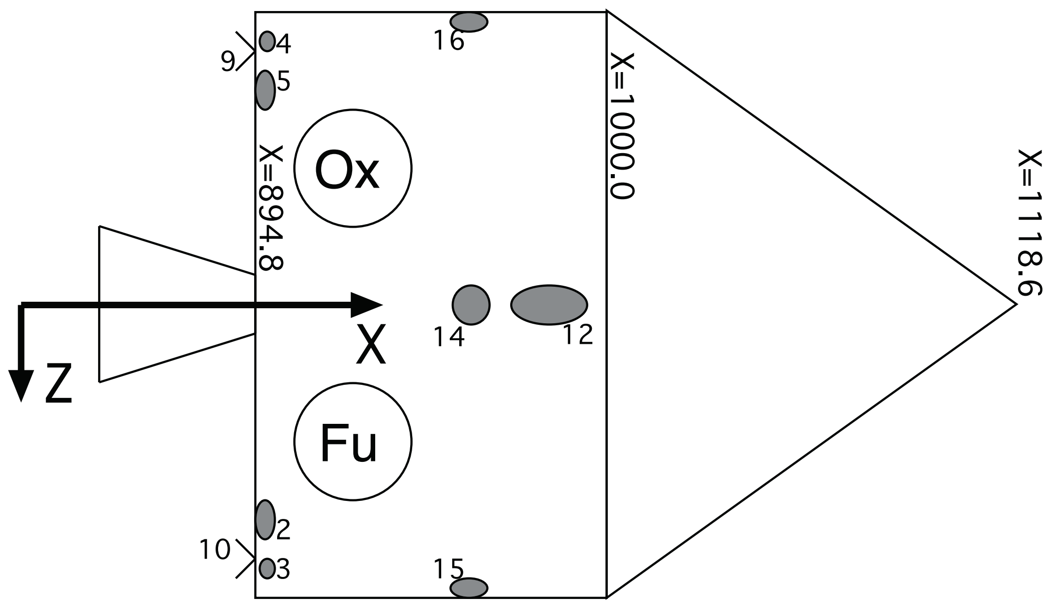

Figure 8.3: Fireball Layout (Side View)

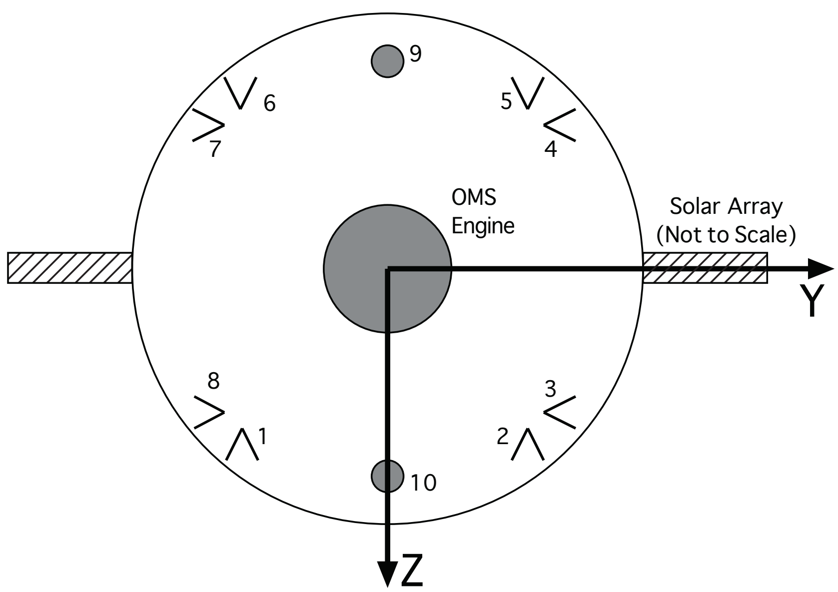

Figure 8.4: Fireball Layout (Aft View)

Parameter	Value
Thrust Point (in)	894.0, 0.0, 0.0
Thrust (lb)	6000
Specific Impulse (sec)	315
Gimbal Rate (deg/s)	5
Maximum Gimbal Deflection (deg)	±6

Table 8.1: Fireball OMS Engine Parameters

points forward, the Y-axis points to starboard, and the Z-axis points to nadir to complete the right hand system. The origin is defined to be 1000 inches aft of the SM to CM interface line.

It is desirable that the CSM center of mass be located approximately in the plane of RCS thrusters used for Y and Z axis translation. This minimizes the coupling of radial translation during docking into rotation. In order to achieve this, the propellant tanks are located in the aft of the Service Module and lighter weight equipment, including some RCS jets, are located forward. Solar arrays are also mounted aft to assist in placing the center of mass.

It is also desirable to have the CSM center of mass located as near as possible to the vehicle centerline. This minimizes X axis translation coupling into rotation when performing approach rate control during docking. Since the Crew Module center of mass is displaced in the +Z direction to generate lift during atmospheric entry, the heavier oxidizer tank is placed in the -Z direction away from centerline and the lighter weight fuel tank is placed in the +Z direction away from centerline. This placement helps but does not totally eliminate the +Z axis center of mass offset while in orbit.

The Solar Arrays are located near the aft of the Service Module and extend along the ±Y axes. Each 80 ft^2 panel is 240 by 48 inches in size.

The overall SM layout is shown in Figures 8.3 and 8.4.

8.7 Orbital Maneuvering System Engine

For orbital maneuvering an engine equivalent to the Shuttle Orbital Maneuvering System (OMS) engine is located at the aft of the Service Module. A summary of engine parameters is presented in Table 8.1.

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
11	1010.85	59.41	-57.54
12	1010.85	59.41	-57.54
13	1005.57	5.05	-82.61
14	1071.21	4.49	-40.65
15	1005.57	82.61	-5.05
16	1005.57	-82.61	5.05
21	1010.85	-59.41	-57.54
22	1010.85	-59.41	-57.54
23	1005.57	-5.05	-82.61
24	1071.21	-4.49	-40.65
25	1005.57	82.61	5.05
26	1005.57	-82.61	-5.05

Table 8.2: Fireball CM RCS Jet Locations (*inches*)

8.8 RCS Jet Layout

RCS jet layout is an important contributor to satisfactory handling. As a general philosophy the designer should first seek to minimize coupling and maximize control authority. In other words, the jet layout should generally create moments about the primary axes (X, Y, Z) because those are the axes about which the pilot is controlling using the RHC. This is less of a consideration for fully automated vehicles in which rotation is typically performed about a single arbitrary axis.

Fireball RCS CM and SM RCS jet locations are in Tables 8.2 and 8.4 respectively. Fireball CM and SM RCS command responses are in Tables 8.6 and 8.7 respectively.

Fireball CM RCS jet locations are scaled up from the Apollo Command Module so that they are in the same relative position. Jet thrust directions are the same as the Apollo CM. Locations of the CM RCS jets are illustrated in Figure 8.2.

Fireball SM RCS jets use a layout similar to the Gemini OAMS with separate groups of jets dedicated for rotation (jets 1 through 8) and translation (9 through 16). Rotation jets are located in the aft of the vehicle and fire in pairs to produce pitch, roll, and yaw moments. +X translation jets fire as a

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
11	-0.0769	0.0609	0.9952
12	-0.0539	-0.9976	0.0443
13	-0.7198	-0.0424	0.6929
14	-0.0396	-0.1097	0.9932
15	-0.7225	0.6901	0.0422
16	-0.7225	0.6901	-0.0422
21	-0.0539	0.9976	0.0443
22	-0.0769	-0.0609	0.9952
23	-0.7198	0.0424	0.6929
24	-0.0396	0.1097	0.9932
25	-0.7225	-0.6901	-0.0422
26	-0.7225	0.6901	0.0422

Table 8.3: Fireball CM RCS Thrust Force Vector Directions (*unitless*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
1	900	-60	60
2	900	60	60
3	900	60	60
4	900	60	-60
5	900	60	-60
6	900	-60	-60
7	900	-60	-60
8	900	-60	60
9	895	0	-82
10	895	0	82
11	965	-88	0
12	965	88	0
13	980	-88	0
14	980	88	0
15	980	0	88
16	980	0	-88

Table 8.4: Fireball SM RCS Jet Locations (*inches*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
1	0	0	-1
2	0	0	-1
3	0	-1	0
4	0	-1	0
5	0	0	1
6	0	0	1
7	0	1	0
8	0	1	0
9	1	0	0
10	1	0	0
11	-0.9397	0.3420	0
12	-0.9397	-0.3420	0
13	0.1045	0.9945	0
14	0.1045	-0.9945	0
15	0.1045	0	-0.9945
16	0.1045	0	0.9945

Table 8.5: Fireball SM RCS Thrust Force Vector Directions (*unitless*)

Command	Jet Response
+Pitch	13, 23, or (13+23)
-Pitch	14, 24, or (14+24)
+Yaw	15, 25, or (15+25)
-Yaw	16, 26, or (16+26)
+Roll	11, 21, or (11+21)
-Roll	12, 22, or (12+22)

Table 8.6: Fireball CM RCS Command Responses

Command	Jet Response
+Pitch	5 and 6
-Pitch	1 and 2
+Yaw	3 and 4
-Yaw	7 and 8
+Roll	(3 and 7) or (1 and 5)
-Roll	(4 and 8) or (2 and 6)
+X	9 and 10
-X	11 and 12
+Y	13
-Y	14
+Z	16
-Z	15

Table 8.7: Fireball SM RCS Command Responses

pair and are located in the aft of the SM near the top and bottom of structure. -X translation jets also fire as a pair and are located on the side of the SM, towards the front of the module. They are canted outward 20 degrees to allow the exhaust plume to clear structure. Y and Z translation jets are located near the forward part of the SM and fire as single jets directly outward (up, down, left, or right) away from structure. The Y translation jets fire laterally, the Z translation jets fire vertically. The Y and Z jets are located aft of the overall center of mass for the 50% propellant quantity configuration, the expected configuration for docking. To minimize Y,Z translation coupling into rotation during docking, the Y and Z jets are canted such that the thrust vector points 6 degrees forward. This causes the thrust vector to pass through the approximate X-location of the 50% quantity center of mass to minimize rotational coupling at the cost of a slight coupling into +X translation. Locations of the SM RCS jets are illustrated in Figures 8.3 and 8.4.

8.9 Mass Property Estimation

To estimate CSM mass properties, several assumptions are made. The Service Module, which in real life will be densely packed with equipment, is

Parameter	100% Prop (Heavy)	50% Prop (Medium) (Docking)	0% Prop (Light)	CM Only
Weight (*pounds*)	30864	29655	28446	17885
c.m. Location (î) (*inches*)	986.40	988.86	991.54	1018.61
c.m. Location (ĵ) (*inches*)	0.06	0.07	0.07	0.11
c.m. Location (k̂) (*inches*)	2.92	3.48	4.09	6.51
Moment of Inertia (I_{xx}) ($slug * ft^2$)	19873	19361	17743	8196
Moment of Inertia (I_{yy}) ($slug * ft^2$)	23554	23058	21295	7304
Moment of Inertia (I_{zz}) ($slug * ft^2$)	25822	23798	21536	6560
Product of Inertia (I_{xy}) ($slug * ft^2$)	442	97	392	84
Product of Inertia (I_{xz}) ($slug * ft^2$)	796	913	661	-536
Product of Inertia (I_{yz}) ($slug * ft^2$)	-518	-535	-516	-14

Table 8.8: Fireball Mass Properties

modeled as a cylinder of uniform mass. The Solar Arrays are modeled as thin plates. The OMS engine, which is mass concentrated at the power head, is modeled as a point mass. Spherical propellant tanks are assumed to be massless. Propellant quantities less than 100% are modeled as hollow spheres attached to the inside surface of the tank due to surface tension. The hollow area is assumed to be massless pressurant gas (helium).

Under +X acceleration any propellant in a tank will shift to the aft of the vehicle. A calculation was performed with a 50% propellant load forming hemispherical shapes in the tanks and mass properties were very close to the microgravity (hollow sphere) configuration. Thus, for simplicity, we assume that propellant does not shift during acceleration and only compute mass properties for the microgravity configuration.

Moments and products of inertia for each Service Module component were calculated using standard equations from [41]. For each propellant quantity configuration an overall vehicle center of mass was calculated. Moments and products of inertia with respect to that overall center of mass location were then computing using the parallel-axis theorem. The results are shown in Table 8.8.

8.10 Minimum Thrust Impulse

A critical factor in RCS control is the minimum thrust impulse. This is a function of steady state thrust, minimum firing signal duration, and thrust rise and decay times. Gemini and Apollo had dedicated hardware to generate very short duration firing signals, 0.014 *sec* in the case of Apollo, but modern spacecraft, such as the Space Shuttle, generate firing signals as a function of GNC flight software cycle time. Thus, the shortest firing signal for Shuttle is 0.08 *sec*. Thrust rise and decay result in approximately 70% to 90% efficiency. In other words, the minimum thrust impulse is thrust (T) times minimum firing signal duration (t) times efficiency (e, 0.7 to 0.9), as shown in Equation 8.4. This can be modeled as full step function thrust for a shorter duration.

$$MinImpulse(lb * sec) = T(lb) * t(sec) * e \tag{8.4}$$

For this conceptual design, the GNC cycle time is assumed to be 0.05 *sec*, which is a modest improvement over Shuttle and easily within the capabilities of modern avionics systems. Minimum impulse efficiency is assumed to be 0.8. Thus the equivalent full step function thrust minimum firing time is 0.04 *sec*. Thrust is to be determined as a function of handling requirements.

8.11 Thrust Gain

Many proposed design requirements incorporate calcuations such as mean angular acceleration magnitude about all axes. When determining RCS thrust level this calcuation can be tedious. A useful shortcut is to calculate this value once for a reasonable thrust level and then compute a thrust gain for rotation, as shown in Equation 8.5.

$$k_r(deg/lb * s^2) = \frac{\alpha(deg/s^2)}{T(lb)} \tag{8.5}$$

Once the desired thrust is known it is a simple matter to compute the resulting angular acceleration as shown in Equation 8.6.

$$\alpha(deg/s^2) = k_r(deg/lb * s^2) * T(lb) \tag{8.6}$$

Fireball thrust gains for rotation are given in Table 8.9. A similar technique can be used for translation.

Vehicle	Thrust Gain (Rotation) k_r $deg/(lb * s^2)$
Fireball CM (1 jet)	0.04131
Fireball CM (2 jet)	0.08265
Fireball CSM (Heavy)	0.032
Fireball CSM (Medium)	0.03407
Fireball CSM (Light)	0.038

Table 8.9: Fireball Thrust Gains for Rotation

8.12 Thrust Selection Assumptions

A small number of assumptions are useful in the design process.

First, when considering impulse control we assume no lower limit on thrust. While this is not strictly true in the extreme, we make the assumption that the firing time of any realistically sized jet can be increased to meet a minimum impulse requirement. In contrast there is a hard lower limit on firing time, as discussed previously, and a thrust that cannot be exceeded while still meeting a maximum impulse requirement.

Second, when considering a spacecraft with redundant RCS jets, we assume that handling requirements must be met with redundant RCS jets disabled. For example, the Fireball CM, like the Apollo CM, can be operated with 1 jet or 2 jet control. This provides failure tolerance and grows the satisfactory design envelope by assuming that redundant jets can be disabled to avoid excessive control authority.

8.13 CM RCS Jet Thrust Selection

The Fireball CM is assumed to operate in two regimes: coasting flight attitude control (from CM/SM separation until entry) and atmospheric entry. The available control modes for coasting flight are direct, impulse, and proportional rate. For atmospheric entry the available control modes are direct and proportional rate.

Table 8.10 lists minimum and maximum thrust constraints in order to meet control authority requirements for coasting flight attitude control. The assumed maximum for proportional rate control is 2.0 deg/s.

Mode	Min Thrust (lb)	Max Thrust (lb)
Direct (1 jet)	7.26	307.43
Impulse (1 jet)		114.98
Prop Rate (1 jet)	4.84	

Table 8.10: Fireball CM Coasting Flight Attitude Control Thrust Constraints

Mode	Min Thrust (lb)	Max Thrust (lb)
Direct (1 jet)	78.25	339.26
Prop Rate (1 jet)	90.29	

Table 8.11: Fireball CM Atmospheric Entry Thrust Constraints

Table 8.11 lists minimum and maximum thrust constraints in order to meet control authority requirements for atmospheric entry. For proportional rate control the assumed maximum rate is 15 deg/s.

The overall thrust constraint is set by the largest minimum (90.29 lb) and smallest maximum (114.98 lb) that meet all requirements. We conservatively choose an intermediate thrust level of 100 lb for CM RCS jets.

8.14 SM RCS Jet Thrust Selection

Table 8.12 lists Fireball CSM thrust constraints for docking. The docking mechanism is assumed to have the same constaints as Shuttle to ISS: 0.03 ft/s approach velocity tolerance and 0.25 ft radial position tolerance. The control mode is impulse. The vehicle is assumed to be in the medium weight configuration for docking.

Note that a feature of the Fireball SM RCS design is that specific jets are dedicated to translation or rotation. As a result, the capability exists to

Axis	Min Thrust (lb)	Max Thrust (lb)
Approach		356.29
Radial		289.35

Table 8.12: Fireball CSM Docking Thrust Constraints

Mode	Min Thrust (lb)	Max Thrust (lb)
Direct (Heavy)	9.38	
Direct (Light)		334.21
Impulse (Light)		125.00
Prop Rate (Heavy)	6.25	
Disc Rate (Heavy)	6.25	

Table 8.13: Fireball CSM Coasting Flight Attitude Control Thrust Constraints

Mode	Min Thrust (lb)	Max Thrust (lb)
Direct (Heavy)	13.09	393.16
Direct (Medium)	13.03	368.54
Direct (Light)	12.74	329.37
Direct (Light, TAR)	14.52	
Prop Rate (Heavy)	9.97	

Table 8.14: Fireball CSM Powered Flight with Reaction Control Thrust Constraints

select a different thrust level for each if required. We conservatively select a translation thrust level of 100 lb, significantly below the maximum.

Table 8.13 presents Fireball CSM thrust constraints for coasting flight attitude control. Note that, in constrast to the Fireball CM, discrete rate control has been added as an available mode. Heavy and light weight mass properties are used for worst case configurations.

Table 8.14 lists attitude control thrust constraints for powered flight with reaction control. This table assumes 100 lb thrust translation jets. When so equipped, the spacecraft will pitch down due to the offset center of mass at 0.119, 0.144, and 0.184 deg/s^2 for the heavy, medium, and light configurations respectively. As a result, the spacecraft must have sufficient control authority to still pitch up with the minimum satisfactory angular acceleration but, for direct control, not so much thrust that it exceeds the control authority limit for pitching down. This is reflected in tighter thrust constraints than for pure attitude control shown in Table 8.13. The minimum thrust to meet the torque advantage ratio requirement is computed for the worst case light weight configuration. The maximum attitude rate for proportional rate control is the same as for coasting flight, 2.0 deg/s.

Again using the technique of selecting the largest minimum thrust and the smallest maximum thrust it can be determined that requirements for satisfactory handling can be met for SM attitude control thrust between 14.52 and 125.00 lb. Recall that CM RCS and SM Translational RCS thrust were both set at 100 lb. For commonality, SM Rotational RCS thrust is also set at 100 lb.

8.15 Powered Flight with Thrust Vector Control

The conceptual vehicle, in worst case (heavy) configuration, meets the control authority requirement for powered flight with thrust vector control ($k_{tvc} > 0.1$ $(1/s)$) for OMS engine thrust of 146 lb or greater. The specified engine has 6000 lb of thrust and therefore this requirement is easily satisfied. Note that because the center of mass is offset in the +Z direction there is less control authority when pitching up than when pitching down. Although not done here this can be cured by biasing the neutral position of the thrust vector through the expected center of mass location.

8.16 Requirements Compliance Summary

Table 8.15 summarizes the Fireball conceptual design's full compliance with the proposed requirements for satisfactory handling. Listed configurations are generally worst case. For powered flight with reaction control (direct), two values are given to represent pitch up and pitch down cases. In other words, Fireball is predicted to have satisfactory handling in all applicable spaceflight regimes and control modes. The most sensitive part of the design appears to be the Command Module (CM) thrust sizing which is approaching the maximum allowable value for coasting flight attitude control using impulse but is also approaching the minimum value for atmospheric entry roll control using proportional rate (with 15 deg/s maximum rate).

Full compliance is proof by example that the proposed set of requirements is internally consistent in that satisfying one requirement does not strictly

Vehicle Config	Regime (Mode)	Requirement	Fireball	Sat?
CSM Heavy	Att Cntl (Direct)	0.3< k_{acd} <12.7 deg/s^2	3.2	Yes
CSM Light	Att Cntl (Direct)	0.3< k_{acd} <12.7 deg/s^2	3.8	Yes
CSM Light	Att Cntl (Direct)	k_{ard} <14.3 deg	1.83	Yes
CSM Heavy	Att Cntl (Impulse)	0.01< k_{aci} <0.19 deg/s	0.128	Yes
CSM Light	Att Cntl (Impulse)	0.01< k_{aci} <0.19 deg/s	0.152	Yes
CSM Light	Att Cntl (Impulse)	k_{ari} < 15.5 deg	1.83	Yes
CSM Heavy	Att Cntl (Disc Rate)	$0.1(1/s) < k_{acdr}$	1.6	Yes
CSM Heavy	Pwr RCS (Direct)	0.3< k_{acd} <12.7 deg/s^2	3.4, 3.6	Yes
CSM Medium	Pwr RCS (Direct)	0.3< k_{acd} <12.7 deg/s^2	3.5, 3.8	Yes
CSM Light	Pwr RCS (Direct)	0.3< k_{acd} <12.7 deg/s^2	3.9, 4.3	Yes
CSM Light	Pwr RCS (Direct)	3< k_{tar}	22.3	Yes
CSM Heavy	Pwr RCS (Prop Rate)	$0.1(1/s) < k_{acpr}$	1.7	Yes
CSM Heavy	Pwr TVC (Prop Rate)	$0.1(1/s) < k_{tvc}$	4.1	Yes
CSM Medium	Docking (Impulse)	0.02< k_{dai} <1.0	0.28	Yes
CSM Medium	Docking (Impulse)	0.01 < k_{dri} <0.05 $(1/s)$	0.02	Yes
CM Only (1 jet)	Att Cntl (Direct)	0.3< k_{acd} <12.7 deg/s^2	4.13	Yes
CM Only (1 jet)	Att Cntl (Impulse)	0.01< k_{aci} <0.19 deg/s	0.165	Yes
CM Only (1 jet)	Att Cntl (Prop Rate)	$0.1(1/s) < k_{acpr}$	2.07	Yes
CM Only (1 jet)	Entry (Direct)	2.86< k_{erd} <12.4 (deg/s^2)	4.13	Yes
CM Only (1 jet)	Entry (Prop Rate)	$0.22(1/s) < k_{erpr}$	0.28	Yes

Table 8.15: Fireball Compliance with Handling Requirements

prohibit satisfying any other requirement. This provides partial validation of the proposed requirement set.

Chapter 9

Conclusions

> I wish to have no connection with any ship that does not sail fast; for I intend to go in harm's way.
>
> *John Paul Jones, 1778*

This work was motivated by the lack of guidance for spacecraft designers with regards to making vehicles compatible with human operation. The author has personally attended meetings in which designers have dismissed the possibility of manual control as impossible and meetings in which manual control of a vehicle was described as trivial, both claims completely free from supporting data. As the age of commercial manned spacecraft opens this situation is increasingly unacceptable.

The primary goal, therefore, of this dissertation research was to propose a set of design requirements to yield satisfactory handling of manned spacecraft. The primary challenge was the lack of large scale institutional support required to perform dedicated human-in-the-loop testing of various spacecraft configurations using qualified pilots. This required that the work be done using extremely limited existing data. Had support been available for extensive human-in-the-loop testing the resulting design requirements would likely be described as conclusive rather than estimated.

The approach taken was to model historic spacecraft in simulation and contemporaneous commentary with associated dynamic characteristics. In this way sufficient data was available to estimate critical design parameter values at which handling transitions between satisfactory and unsatisfactory. It should be recognized that this data are extremely thin for such a study, often relying on a single comment from a single pilot, and that the proposed requirements are estimates only. That said, the result is the first such set ever proposed.

Historic data was also used to provide design guidance for biomechanical interfaces: flight instruments and hand controllers.

To gain confidence in the proposed set of requirements a software model of a human pilot was constructed using existing data from a human-in-the-loop test in one spaceflight regime, powered flight with thrust vector control, and used to evaluate handling in two other regimes, coasting flight attitude control and powered flight with reaction control. The simulated pilot was shown to have human-like limitations via direct comparison to human performance using identical test cases and initial conditions. When used to evaluate other flight regimes the simulated pilot failed to achieve required performance at approximately the points predicted by historic vehicle analysis. This provided partial verification of the associated requirements.

Finally, partial validation of the proposed requirements was performed by proving that the requirement set is not self-contradictory. The proof was by example in which the conceptual design of a spacecraft fully compliant with requirements was performed. The design example also served to illustrate techniques useful for designing a spacecraft with satisfactory handling qualities.

In summary, this work accomplished the following:

1. Creation of a new taxonomy for analysis of spacecraft handling qualities
2. Proposal of a complete set of design requirements for satisfactory handling via analysis of historic spacecraft
3. Documentation of design guidance for biomechanical interfaces (flight instruments and hand controllers)
4. Creation of a software pilot with capabilities and performance limitations similar to a human pilot
5. Partial verification of proposed requirements using a simulated pilot
6. Partial validation of proposed requirements via proof that the set is non-self contradictory
7. Demonstration of techniques useful for design of a spacecraft with satisfactory handling

Future work in this domain should emphasize human-in-the-loop testing of the proposed requirements using a cadre of qualified test pilots and a high fidelity spacecraft simulator. This work should lead to the creation of requirements in which sufficient confidence exists that they can be incorporated into formal requirements for new spacecraft development.

Alternatively, recognize that this work was intended to span all spaceflight regimes and, as a result, only the factors that in the author's opinion most influence handling in each regime are considered. In other words the work here is prioritized to be broad and, as a result, is limited in depth. As a result there is considerable opportunity for deeper research in each area. Proximity operations and docking in particular appears to be a prime opportunity for additional investigation given the ever tightening contact condition tolerances in new docking mechanisms.

Appendix A

Mercury Spacecraft Data

A.1 Overview

Mercury, shown in Figure A.1, was a small, single-occupant spacecraft operated by the United States from 1961 to 1963. It was designed to demonstrate basic human spaceflight capabilities and, as such, performed the very simple mission of being inserted into orbit by a launch vehicle, coasting, and then deorbiting.

Mercury program documentation uses an obsolete coordinate system in which the X-axis is to startboard, Y-axis is to zenith, and Z-axis is foward to complete the left handed system. Data has been converted here to use the modern system in which the X-axis points forward, Y-axis to starboard, and Z-axis down to complete the right handed system. The origin is an abitrary station within the launch vehicle.

A.2 Propulsion System

Mercury had very limited translational capability. A small strap-on pack fitted behind the heat shield had three small solid rocket motors for separation from the launch vehicle and three larger solid rocket motors for deorbiting. The pack was normally jettisoned after the deorbit burn to fully expose the heat shield.

For rotation the spacecraft had two independent mono-propellant reaction control systems utilizing H_2O_2 jets for attitude control.

RCS System A consists of twelve jets configured in high and low thrust

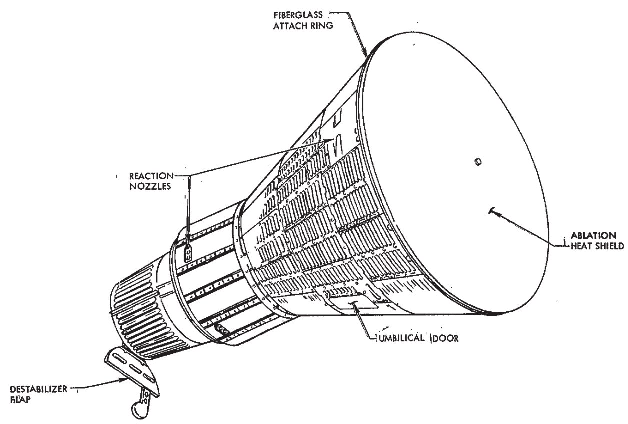

Figure A.1: Mercury Spacecraft External View [102]

pairs in six locations. Thrust is 24 *lb* (pitch and yaw high thrust), 6 *lb* (roll high thrust), and 1 *lb* (all low thrust). System A jets are fired electronically via solenoid operated fuel valves. Control of RCS System A is via the Automatic Stabilization Control System (ASCS).

RCS System B consists of six jets in six locations. Jet thrust is a maximum of 24 lb (pitch and yaw) and 6 lb (roll). System B jets can be fired either via electronic signal, which results in maximum thrust (24 *lb* pitch and yaw, 6 *lb* roll), or via mechanical linkage between the rotational hand controller and associated propellant flow control valve. In the latter case, jet thrust is proportional to hand controller displacement. Control of RCS System B is via the Rate Stabilization Control System (RSCS).

The estimated locations and thrust force directions of both RCS systems are specified in Tables A.1 and A.2 respectively.

Although this work uses Reaction Control System (RCS) System A and B terminology, no standard nomenclature appears to exist to consisely refer to specific jets. The nomenclature used here is based upon that used in [13] with corrections but should not be considered official Project Mercury usage. The initial letter, A or B, refers to the RCS System and a trailing letter 'a' denotes a low thrust jet.

Similarly, no standard reference exists that documents exact RCS jet location. X-axis location of the roll jets is estimated by combining the roll moment arm cited in [81] with the spacecraft angular shape documented in (Mercury Fam). Y and Z-axis locations of the roll jets are estimated using

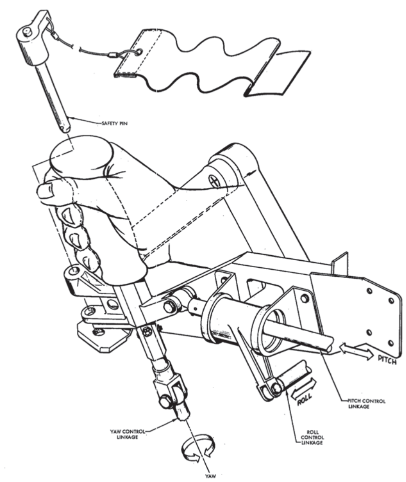

Figure A.2: Mercury Rotational Hand Controller [102]

photographs and engineering judgement. X-axis location of the pitch and yaw jets is determined by using the moment arm cited in [81] and assuming that, at the time that document was written, pitch and yaw jets were planned to have 6 lb of thrust. The resulting answer is consistent with estimates made by analyzing unlabeled figures illustrating the external appearance of the spacecraft in [102] and is therefore assumed to be correct. Y and Z-axis locations of pitch and yaw jets are estimated using photographs and engineering judgement.

A.3 Control System

The nominal attitude during orbital flight is also the deorbit burn attitude – tail-first (blunt end forward) and slightly nose down. After the deorbit burn the retro-rocket package is jettisoned to fully expose the heat shield. Attitude is held until acceleration due to atmospheric drag reaches 0.05g, at which point a continuous roll is performed until the end of atmospheric entry to reduce landing point dispersions.

The pilot exercises manual attitude control using a three-axis Rotational Hand Controller (RHC) positioned for the right hand. Maximum RHC displacement is ± 13 *deg* in pitch and roll and ± 10 *deg* in yaw.

Attitude control on the Mercury spacecraft is performed using two independent systems. Each system has a control component and associated Reaction Control System

RCS System A is controlled by the Automatic Stabilization Control System (ASCS). The ASCS has three operating modes controled by the ASCS switch. *Norm* provides automatic control of the spacecraft. *Aux Damp* provides three axis rate damping only, no ASCS manual control. *Fly By Wire* disables rate damping and allows for manual control of the System A jets. Moving the hand controller 3.9 *deg* or more will close microswitches causing the associated low thrust jet to fire continuously. Moving the hand controller 9.8 *deg* or more will close additional microswitches causing the associated high thrust jet to also fire.

Three handles labelled ROLL, PITCH, and YAW can be pulled to close valves blocking the flow of propellant to the associated RCS System A jets, both high and low thrust.

Confusingly, power to the ASCS is controlled via the two position "RSCS Switch." (Note, this terminology is from the pilot's checklist.) *AUTO* provides power to the ASCS, while *RATE COMD* provides power to the RSCS.

RCS System B is controlled by the Rate Stabilization and Control System (RSCS). The RSCS has two operating modes controlled by the "Manual Handle." Selecting *DIRECT* by pulling the handle operates a selector valve that allows propellant flow to proportioning valves. Moving the hand controller causes mechanical linkages to open those valves proportionate to the amount of hand controller displacement, thereby creating thrust and hence angular acceleration proportionate to hand controller displacement. The system, sometimes called "manual proportional," does not need electrical power to operate. Selecting *RATE COMD* by pushing the Manual Handle in operates the selector valve to flow propellant to electrically operated solenoid valves.

The *RATE COMD* mode allows the pilot to command attitude rate proportionate to the amount of hand controller displacement. A sensor reads the hand controller position and converts that to a commanded rate up to 12 deg/s at full displacement. Rate sensing gyroscopes are used to determine rate error and RCS System B jets are fired, at full thrust, to drive the error to zero. With the hand controller in neutral the rate deadband is 3 deg/s. This mode, if active, will also command a 7 deg/s roll during entry to cancel lift while rate damping in pitch and yaw.

To disable RCS System B jets the Manual Handle must be in *RATE COMD* (pushed), thereby blocking propellant to the proportioning valves.

RSCS Switch must also be in *AUTO*, thereby removing power from the RSCS rate command system and providing power to the ASCS.

The two systems can be operated simultaneously in certain combinations. For example, ASCS can be powered (RSCS Switch - AUTO) and providing rate damping (ASCS Switch - AUX DAMP) while the RSCS is in direct (Manual Handle - DIRECT (Pull)). Alternatively, the ASCS can be in fly by wire (ASCS Switch - FLY BY WIRE) while the RSCS is in direct in order to provide more control authority.

A.4 Mass Properties

Spacecraft mass properties, with the exception of the products of inertia, specified in Table A.4 are from the MA-6 flight report [49] and are assumed to representative of typical Mercury missions. No values of the products of inertia are supplied in Mercury program documents. Therefore, estimates of the products of inertia were computed using a simplified geometric model. The model assumes uniform mass distribution with various spacecraft sections and therefore almost certainly underestimates the actual values, although by how much is unknown. Note that the products of inertia are computed using the positive integal system.

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
A1	181.3	0	-15.8
A1a	181.3	-1.5	-15.8
A2	181.3	-15.8	0
A2a	181.3	-15.8	1.5
A3	181.3	0	15.8
A3a	181.3	1.5	15.8
A4	181.3	15.8	0
A4a	181.3	15.8	-1.5
A5	120.3	-31.7	1
A5a	119.3	-31.7	1
A6	120.3	-31.7	-1
A6a	119.3	-31.7	-1
B1	181.3	1.5	-15.8
B2	181.3	-15.8	-1.5
B3	181.3	-1.5	15.8
B4	181.3	15.8	1.5
B5	119.8	31.7	-1
B6	119.8	31.7	1

Table A.1: Mercury RCS Jet Locations (*inches*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
A1	0	0	24
A1a	0	0	1
A2	0	24	0
A2a	0	1	0
A3	0	0	-24
A3a	0	0	-1
A4	0	-24	0
A4a	0	-1	0
A5	0	0	-6
A5a	0	0	-1
A6	0	0	6
A6a	0	0	1
B1	0	0	24
B2	0	24	0
B3	0	0	-24
B4	0	-24	0
B5	0	0	6
B6	0	0	-6

Table A.2: Mercury RCS Thrust Force Vectors (*pounds*)

Command	Jet Response
+Pitch	A3, A3a, B3
-Pitch	A1, A1a, B1
+Yaw	A2, A2a, B2
-Yaw	A4, A4a, B4
+Roll	A5, A5a, B5
-Roll	A6, A6a, B6

Table A.3: Mercury RCS Jet Command Responses

Parameter	Orbit Configuration	Entry Configuration
Weight (*pounds*)	2986.78	2698.98
c.m. Location ($\hat{\imath}$) (*inches*)	121.18	124.62
c.m. Location ($\hat{\jmath}$) (*inches*)	-0.04	-0.07
c.m. Location ($\hat{k}$) (*inches*)	-0.07	-0.01
Moment of Inertia (I_{xx}) ($slug * ft^2$)	281.6	271.0
Moment of Inertia (I_{yy}) ($slug * ft^2$)	621.6	544.6
Moment of Inertia (I_{zz}) ($slug * ft^2$)	629.3	552.2
Product of Inertia (I_{xy}) ($slug * ft^2$)	0.03	0.05
Product of Inertia (I_{xz}) ($slug * ft^2$)	0.05	0.01
Product of Inertia (I_{yz}) ($slug * ft^2$)	0.00	0.00

Table A.4: Mercury Mass Properties

Appendix B

Gemini Spacecraft Data

B.1 Overview

Project Gemini was an intermediate step between Mercury and Apollo and was intended to bridge the technological and operational gap between those two programs. The spacecraft held two crewmembers designated 'Command Pilot' and 'Pilot'. The Gemini spacecraft could remain in orbit up to two weeks and, while there, had significant translational capability. Gemini was capable of rendezvous and was equipped with radar and a docking mechanism. The rendezvous target for most missions was an unmanned propulsion stage known as Agena. Once docked the Agena could be used to perform attitutde control and large translational maneuvers. Gemini was also equipped with a computer used for rendezvous calculations and entry guidance. Gemini was originally intended to land on a runway using a deployable fabric Rogallo wing known as a 'paraglider' but that system had major development difficulties and was never used operationally. Occasional references to the system can be found in various Gemini documents.

Gemini program documentation uses an obsolete coordinate system in which the X-axis is to startboard, Y-axis is to zenith, and Z-axis is foward to complete the left handed system. Data has been converted here to use the modern system in which the X-axis points forward, Y-axis to starboard, and Z-axis down to complete the right handed system. The origin is within the launch vehicle, 13.44 inches aft of the launch vehicle to spacecraft mating plane.

Note that Gemini documentation uses an obsolete system for body frame

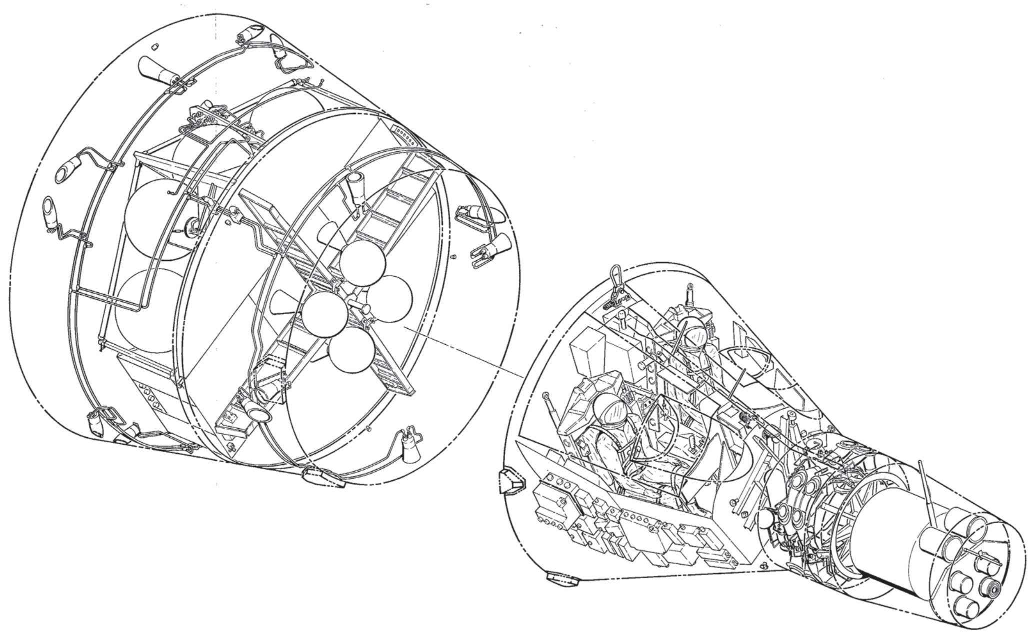

Figure B.1: Gemini Interior Arrangement [5]

axes and references here have been normalized to modern practice: +X is forward, +Y is to starboard, and +Z is in the nadir direction.

B.2 Propulsion System

Gemini had four separate propulsion systems. Orbital attitude control and translation was performed using the Orbit Attitude and Maneuvering System (OAMS), a hypergolic bi-propellant reaction control system. The OAMS was contained within the two-piece Service Module (SM) and had separate jets for rotation and translation. Attitude control from SM jettison through entry was performed using the Reentry Control System (RCS) in the nose of the spacecraft consisting of two independent 'rings' with propellant tanks and jets. The deorbit burn was performed using four solid rocket motors contained within the Service Module. The SM is in two sections; the aft section is jettisoned to expose the solid rocket motors and, following their use, the forward section is also jettisoned. Attitude control must be performed using the RCS once the aft section is jettisoned. This nomenclature is confusing

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
1	188.77	14.9	-12.31
2	188.77	-14.9	-12.31
3	188.77	-12.31	-14.9
4	188.77	-12.31	14.9
5	188.77	-14.9	12.31
6	188.77	14.9	12.31
7	188.77	12.31	14.9
8	188.77	12.31	-14.9

Table B.1: Gemini RCS Jet Locations (Ring A) (*inches*)

because in modern usage RCS is assumed to mean the more generic Reaction Control System, not the specific Gemini usage.

B.2.1 Reentry Control System

The Gemini Reentry Control System (RCS) consists of two redundant rings of jets, A and B, located in the nose of the spacecraft. Ring A is in the forward position and ring B is immediately aft of it. The rings are otherwise identical and equivalently numbered jets point in the same direction. The rings are for attitude control only; no translation capability is provided.

Location and jet firing direction information presented here is from a Gemini propulsion system specification document [3] and is therefore considered accurate.

B.2.2 Orbit Attitude Maneuvering System

The Orbit Attitude Maneuvering System (OAMS) consists of 16 jets arranged within the jettisonable Equipment and Retro sections. Jets 1 through 8 are used for attitude control and generate 25 pounds of thrust. Jets 9 through 16 are used for translation and generate 100 pounds of thrust with the exception of jets 11 and 12, used for -X translation, which are derated to 85 pounds of thrust.

OAMS jet location and thrust vector estimates are aided by a report from Jaquet [82]. The simulated spacecraft properties documented in that report

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
1	183.17	14.9	-12.31
2	183.17	-14.9	-12.31
3	183.17	-12.31	-14.9
4	183.17	-12.31	14.9
5	183.17	-14.9	12.31
6	183.17	14.9	12.31
7	183.17	12.31	14.9
8	183.17	12.31	-14.9

Table B.2: Gemini RCS Jet Locations (Ring B) (*inches*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
1	0	-2.865	24.835
2	0	2.865	24.835
3	0	24.835	2.865
4	0	24.835	-2.865
5	0	2.865	-24.835
6	0	-2.865	-24.835
7	0	-24.835	-2.865
8	0	-24.835	2.865

Table B.3: Gemini RCS Thrust Force Vectors (*pounds*)

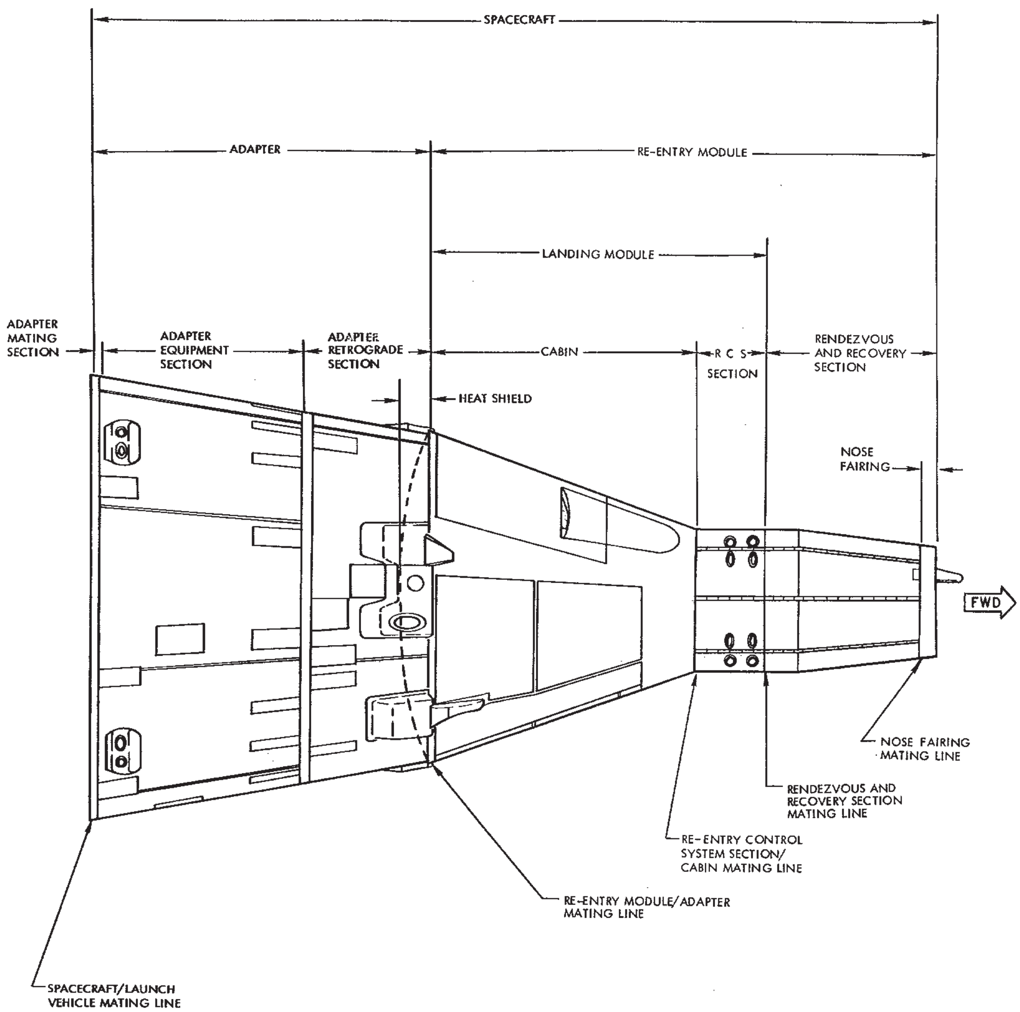

Figure B.2: Gemini Sections [5]

include thrust along the X-axis. This value is critical because these forward-facing jets are canted outward from the spacecraft at an undocumental angle. Rough geometric analysis of engineering drawings in [5] suggest a value on the order of 27 degrees. In the actual spacecraft, these are unique among the translational jets because they have been derated from 100 lb to 85 lb for an unknown reason. However, if we assume that the simulated jets in the report have 100 lb of thrust, as might have been planned early in the program, a suspiciously round canting angle of 20 degrees results in an exact match to the specified resulting retrograde thrust along the X-axis of -187.94 lb. We therefore make an assumption that those jets, 11 and 12, are canted at 20 degrees in the actual spacecraft.

Lateral translation jets (13, 14, 15, 16) were originally designed to thrust parallel to the Y and Z axes. However, as documented in [65], these jets were canted by 2.7 degrees to reduce coupling into rotation during translational maneuvers. Although Y or Z translation therefore coupled into +X translation, this was done to reduce the demand placed upon the 25 lb rotational control jets. Bipropellant attitude control jets were a relatively new technology at the time and making them sufficiently reliable to last for an entire mission proved to be a major challenge during spacecraft development.

Similiarly, the Jaquet [82] report specifies moment arms for the roll, pitch, and yaw jets to a specified center of mass location. From that we can calculate that the OAMS attitude control jets are located at X=20 inches. The moment arm data also allows us to calculate Y and X-axis locations for the attitude control jets. Thus the locations of OAMS jets specified in Table B.4 are believed to be very good estimates.

B.3 Control System

Gemini has four primary modes of manual attitude control.

In DIRECT, displacing the Rotational Hand Controller (RHC) past 2.5 *deg* in any axis closes switches that supply power directly to attitude control jets, bypassing the attitude control logic. In this mode the jets will continue to fire until the RHC is neutralized in that axis.

In PULSE, displacing the RHC past 3.5 *deg* closes switches that cause the associated jets to fire for a specific length of time (0.02 *sec*). The RHC must be neutralized and displaced again to fire the jets again. The minimum impulse for Gemini OAMS and RCS jets are specified in Table B.6.

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
1	20.0	-44.9	44.9
2	20.0	44.9	44.9
3	20.0	44.9	44.9
4	20.0	44.9	-44.9
5	20.0	44.9	-44.9
6	20.0	-44.9	-44.9
7	20.0	-44.9	-44.9
8	20.0	-44.9	44.9
9	20.0	0	-54.7
10	20.0	0	54.7
11	103.2	-45.8	0
12	103.2	45.8	0
13	104.8	-45.8	0
14	104.8	45.8	0
15	104.8	0	45.5
16	104.8	0	-45.5

Table B.4: Gemini OAMS Jet Locations (*inches*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
1	0	0	-25
2	0	0	-25
3	0	-25	0
4	0	-25	0
5	0	0	25
6	0	0	25
7	0	25	0
8	0	25	0
9	100	0	0
10	100	0	0
11	-79.9	29.1	0
12	-79.9	-29.1	0
13	4.7	99.9	0
14	4.7	-99.9	0
15	4.7	0	-99.9
16	4.7	0	99.9

Table B.5: Gemini OAMS Thrust Force Vectors (*pounds*)

Jet Type (Thrust)	Minimum Impulse ($lb * sec$)
Attitude Control (25 lb)	0.25
Translational Control (85 lb)	21.3
Translational Control (100 lb)	25

Table B.6: Gemini Minimum Impulse

Command	Jet Response
+Pitch	5 + 6
-Pitch	1 + 2
+Yaw	3 + 4
-Yaw	7 + 8
+Roll	3 + 7
-Roll	4 + 8

Table B.7: Gemini RCS Command Responses

Command	Jet Response
+Pitch	5 + 6
-Pitch	1 + 2
+Yaw	3 + 4
-Yaw	7 + 8
+Roll	(3 + 7) or (1 + 5)
-Roll	(4 + 8) or (2 + 6)
+X	9 + 10
-X	11 + 12
+Y	13
-Y	14
+Z	16
-Z	15

Table B.8: Gemini OAMS Command Responses

In RATE CMD (Rate Command), displacing the RHC past a 1 degree neutral zone will command a specific angular rate about that body axis linearly proportional to the displacement. The maximum commandable rate is 10 deg/s in pitch or yaw. The early configuration, Gemini 3 through 8, also had a maximum commandable rate of 10 $degs$ in roll. For the late configuration, Gemini 9 through 12, this was changed to a maximum of 15 deg/s in roll for improved entry control.

In RATE CMD (RE-ENT) (Rate Command, Re-Entry), the pilot again commands a specific angular rate via RHC displacement. However, roll commands are also cross-fed into the yaw channel as to rotate about the velocity vector and remain in aerodynamic trim. Pitch and yaw rates are automatically damped.

Gemini had a single mode of translational control. Displacing the Translational Hand Controller (THC) closes a switch that supplies power directly to the associated OAMS translational jets. The jets will continue to fire for as long as the THC is displaced. No translational capability exists when using the RCS (entry configuration).

Jet firing logic is documented in Tables B.7 and B.8.

Parameter	Orbit	Deorbit	Entry
Weight (*pounds*)	7817	5475	4781
c.m. Location (î) (*inches*)	107.41	131.21	136.89
c.m. Location (ĵ) (*inches*)	-0.46	0.13	0.08
c.m. Location ($\hat{k}$) (*inches*)	-1.31	1.47	1.49
Moment of Inertia (I_{xx}) ($slug * ft^2$)	1499	724	555
Moment of Inertia (I_{yy}) ($slug * ft^2$)	4795	1678	1230
Moment of Inertia (I_{zz}) ($slug * ft^2$)	4799	1678	1230
Product of Inertia (I_{xy}) ($slug * ft^2$)	-52.2	-19.9	-14.8
Product of Inertia (I_{xz}) ($slug * ft^2$)	-107.2	-40.9	-30.4
Product of Inertia (I_{yz}) ($slug * ft^2$)	15.1	6.2	3.9

Table B.9: Gemini Mass Properties

B.4 Mass Properties

Spacecraft mass and center of mass location data are from the Gemini 6A mission report [6]. Orbit configuration moments and products of inertia are from Jaquet [82], scaled to actual mission weight, and with signs of the products reversed to reflect the positive integral standard. Estimates using a simplified geometric model yield approximately similar values for moments of inertia, from which scale factors are computed. Those scale factors are then used to correct the model for the deorbit and reentry configuration moments of inertia. The model is known to significantly underestimate products of inertia because it assumes uniform mass distribution within various spacecraft segments. Therefore, products of inertia for the deorbit and reentry configurations are computed by scaling the values given for the orbit configuration as a function of corrected spacecraft moments. This results in products of inertia that appear to be reasonable estimates given the lack of any additional data from the Gemini program.

Equipment Section	Structure	1628.71
	OAMS Propellant	713
	Total	2341.71
Retro Section	Total	694.17
Cabin Section	Structure	4222.74
	RCS Propellant	72
	Parachute	110.81
	Total	4405.55
Rendezvous Section	Total	375.57
Full Orbit Configuration	Total	7817

Table B.10: Gemini Estimated Weight Distribution (*pounds*)

Maximum Axial Velocity	1.5 ft/s
Angular Misalignment	0 to 10 deg
Radial Displacement	0.0 to 1.0 ft
Radial Velocity	0.0 to 0.5 ft/s

Table B.11: Gemini-Agena Docking System Constraints [57]

Appendix C

Apollo Command and Service Module (CSM) Spacecraft Data

C.1 Overview

The Apollo Command and Service Module (CSM) is a three-person spacecraft used for lunar and Earth orbit missions from 1968 through 1975. The spacecraft consists of a conical pressurized Command Modulde (CM) containing the cockpit, crew equipment, docking mechanism, and guidance system. The cylindrical Service Module (SM) contained the large translation engine, propellant tanks, fuel cells, and other equipment. The combined vehicle was known as the Command and Service Module (CSM).

The Apollo coordinate systems are defined in the mass properties report [37]. As is the modern standard, the X-axis points forward, the Y-axis to starboard, and the Z-axis to nadir to complete the right handed system.

C.2 Propulsion System

C.2.1 Command and Service Module (CSM)

The Apollo CSM propulsion system consists of the Service Module Reaction Control System (SM RCS) and the large Service Propulsion System (SPS). The SM RCS consists of four independent 'quads' consisting of four RCS jets, propellant tanks, and other supporting hardware. The SM RCS quads are not exactly on the Y and Z axes, they are all clocked 7.25 *deg*. The

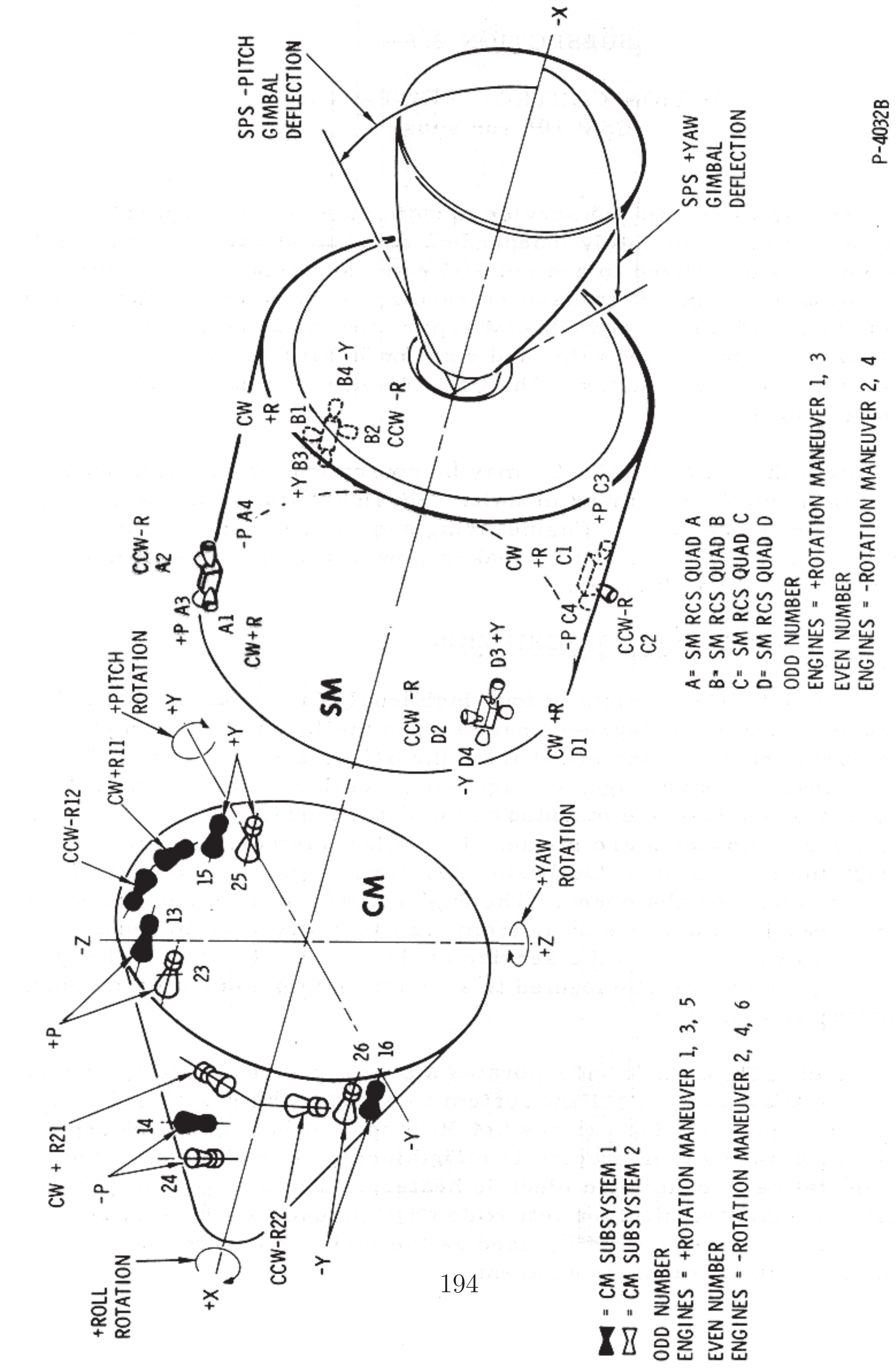

Figure C.1: Apollo CSM Jet Layout [17]

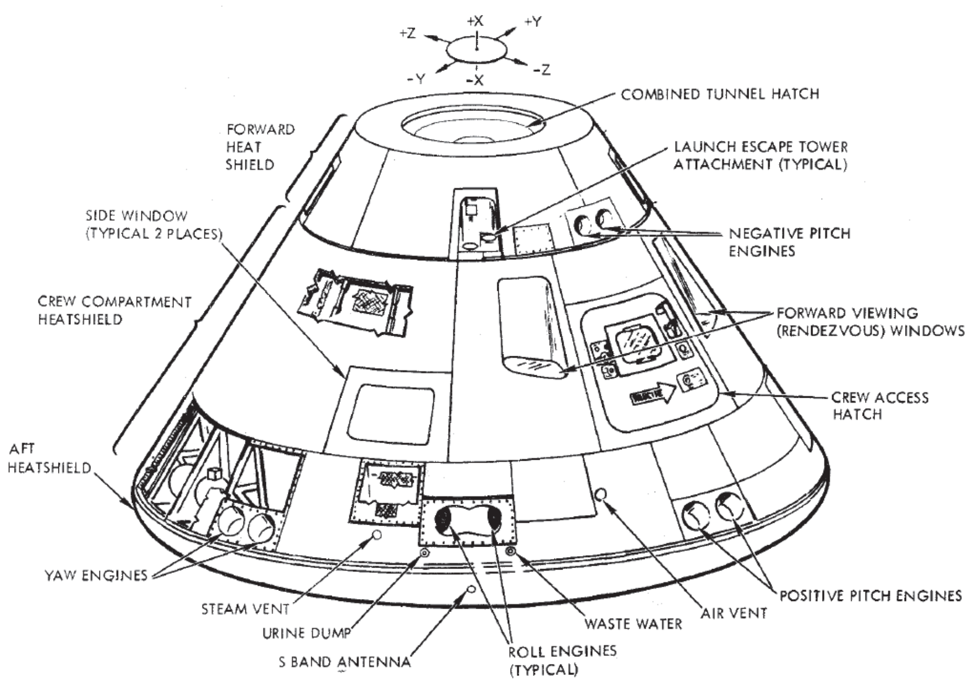

Figure C.2: Apollo CM Outside View [17]

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
A1	958.0	-10.5	-82.2
A2	959.9	-10.5	-82.3
A3	959.0	-10.4	-81.7
A4	959.0	-10.4	-81.7
B1	958.0	82.4	-10.5
B2	959.9	82.3	-10.5
B3	959.0	81.7	-10.4
B4	958.9	81.7	-10.4
C1	958.0	10.4	82.3
C2	959.9	10.5	82.3
C3	959.0	10.4	81.7
C4	959.0	10.4	81.7
D1	958.0	-82.4	10.5
D2	959.9	-82.3	10.5
D3	959.0	-81.7	10.4
D4	958.9	-81.7	10.4

Table C.1: Apollo SM RCS Jet Locations (*inches*)

SPS consists of its own propellant tanks and the large 20,000 *lb* thrust SPS engine. Both the SM RCS and SPS operate using hypergolic propellants.

SM RCS jet locations and force vectors are listed in Tables C.1 and C.2 respectively. These force vectors do not take into account the self-impingement caused by the SM to CM umbilical cover which is assumed to negligable.

Characteristics of the Service Propulsion System (SPS) are shown in Table C.3.

C.2.2 Command Module (CM)

The minimum thrust impulse for a Command Module Reaction Control System (CM RCS) jet, as documented in [9], is approximately 1 $lb * sec$, equivalent to a 0.014 *sec* full thrust firing time.

Command Module RCS jet locations are listed in Table C.4; the associated jet force vectors are in Table C.5.

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
A1	0.0	102.68161	4.93215
A2	0.0	-98.17605	30.48447
A3	-101.23824	2.25278	17.70831
A4	101.23824	2.25278	17.70831
B1	0.0	-4.93215	102.68161
B2	0.0	-30.48447	-98.17605
B3	-101.23824	-17.70831	2.25278
B4	101.23824	-17.70831	2.25278
C1	0.0	-102.68161	-4.93215
C2	0.0	98.17605	-30.48447
C3	101.23824	-2.25278	-17.70831
C4	-101.23824	-2.25278	-17.70831
D1	0.0	4.93215	-102.68161
D2	0.0	30.48447	98.17605
D3	101.23824	17.70831	-2.25278
D4	-101.23824	17.70831	-2.25278

Table C.2: Apollo SM RCS Thrust Force Vectors (*pounds*)

Effective Position	833.2, 0±0.25, 0±0.25 *in*
Angular Offset	0.95 *deg* yaw, -2.15 *deg* pitch
Specific Impulse	314.1 *sec*
Thrust	20,510 *lb*
Gimbal Range	±4.5 *deg* (Both Axes)
Gimbal Rate	8.6 deg/s (Nom), 6.9 deg/s (Min)
Gimbal Accel	171.9 deg/s^2 (1963 Requirement)

Table C.3: Apollo SM Service Propulsion System Characteristics

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
11	32.30	51.98	-50.35
12	32.30	51.98	-50.35
13	27.68	4.42	-72.28
14	85.12	3.93	-35.57
15	27.68	72.28	-4.42
16	27.68	-72.28	4.42
21	32.30	-51.98	-50.35
22	32.30	-51.98	-50.35
23	27.68	-4.42	-72.28
24	85.12	-3.93	-35.57
25	27.68	72.28	4.42
26	27.68	-72.28	-4.42

Table C.4: Apollo CM RCS Jet Locations (*inches*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
11	-7.513	5.952	97.229
12	-5.231	-96.763	4.298
13	-69.823	-4.111	67.208
14	-3.894	-10.783	97.629
15	-70.153	67.008	4.098
16	-70.153	67.008	-4.098
21	-5.231	96.763	4.298
22	-7.514	-5.952	97.229
23	-69.823	4.111	67.208
24	-3.894	10.783	97.629
25	-70.153	-67.008	-4.098
26	-70.153	67.008	4.098

Table C.5: Apollo CM RCS Thrust Force Vectors (*pounds*)

Command	Jet Response
+Pitch	A3, C3, or (A3+C3)
-Pitch	A4, C4, or (A4+C4)
+Yaw	B3, D3, or (B3+D3)
-Yaw	B4, D4, or (B4+D4)
+Roll	A1, B1, C1, D1, (A1+C1), (B1+D1), or (A1+B1+C1+D1)
-Roll	A2, B2, C2, D2, (A2+C2), (B2+D2), or (A2+B2+C2+D2)
+X Trans	(A4+C3) or (B4+D3)
-X Trans	(A3+C4) or (B3+D4)
+Y Trans	(A1+C2)
-Y Trans	(C1+A2)
+Z Trans	(B1+D2)
-Z Trans	(D1+B2)

Table C.6: Apollo SM RCS Command Responses

C.3 Control System

The Apollo CSM or CM could be flown using either one of two control systems: the Primary Guidance Navigation and Control Systems (PGNCS) or the Stability and Control System (SCS). The systems are not completely independent in that the PGNCS relies on parts of the SCS in order to function. The somewhat unusual nature of the overall system design can be explained by the fact that the SCS was originally intended to be the sole means for controlling the spacecraft. The PGNCS later assumed primary control responsibility and relegated the SCS to a secondary and supporting role.

The Stability and Control System (SCS) consists, in part, of two sets of three Body Mounted Attitude Gyroscopes (BMAGs) that can sense either attitude or attitude rate about each body axis. In practice, one set of BMAGs is typically used for attitude and the other set for attitude rate information. Special purpose electronic systems combine inputs from the BMAGs and Rotational Hand Controller (RHC) to operate either the Reaction Control System (RCS) jets or Service Propulsion System (SPS) engine Thrust Vector Control (TVC) system. When under RCS control, the SCS allows the pilot to control the spacecraft in Direct, Minimum Impulse, or Proportional Rate (with attitude hold) modes. During an SPS engine firing, the pilot can select either Proportional Rate or Proportional Acceleration modes. Maximum

Command	Jet Response
+Pitch	13, 23, or (13+23)
-Pitch	14, 24, or (14+24)
+Yaw	15, 25, or (15+25)
-Yaw	16, 26, or (16+26)
+Roll	11, 21, or (11+21)
-Roll	12, 22, or (12+22)
Contingency Deorbit	-Pitch (continuous) and +Pitch (control)

Table C.7: Apollo CM RCS Command Responses

Prop Rate Mode	Max Roll (deg/s)	Max Pitch (deg/s)	Max Yaw (deg/s)
SCS (Low)	0.7	0.7	0.7
SCS (High)	20.0	7.0	7.0
PNGCS (0)	0.05	0.05	0.05
PNGCS (1)	0.2	0.2	0.2
PNGCS (2)	0.5	0.5	0.5
PNGCS (3)	2.0	2.0	2.0

Table C.8: Apollo CSM Maximum Maneuver Rates (SCS and PGNCS)

maneuver rates when in the Proportional Rate mode are selectable via two-position hardware switch for Low and High rates. Values for those rates are shown in Table C.8.

The minimum impulse control mode commands a 0.014 *sec* RCS jet firing.

The Primary Guidance Navigation and Control System (PNGCS) uses an Inertial Measurement Unit (IMU) and digital computer to provide vehicle control capability to the pilot. As with the Stability and Control System (SCS), the PNGCS provides Direct, Minimum Impulse, and Proportional Rate (with attitude hold) control. Maximum maneuver rates when in the Proportional Rate mode are software selectable from among four pre-defined values as shown in Table C.8. There is no provision for PNGCS manual control after SM separation when the Entry Digital Auto-Pilot (DAP) software is in control. During this phase of flight the pilot must use the SCS to

Axial (Closing) Velocity	0.1 to 1.0 ft/s
Radial (Transverse) Velocity	$\leq$0.5 ft/s
Angular Velocity (Any Axis)	$\leq$1.0 deg/s
Radial Displacement	$\leq$1.0 ft
Angular Alignment of Approach Axis	$\leq$10 deg
Roll Angle	60$\pm$10 deg

Table C.9: Apollo CSM-LM Docking System Constraints [89] [18]

Parameter	Heavy	Medium	Light	ASTP
Weight (*pounds*)	66850.6	37851.3	26371.4	29473.9
c.m. Location ($\hat{\imath}$) (*inches*)	933.9	944.0	972.1	999.6
c.m. Location ($\hat{\jmath}$) (*inches*)	5.0	3.9	1.2	0.70
c.m. Location ($\hat{k}$) (*inches*)	4.7	3.3	4.0	2.63
Moment of Inertia (I_{xx}) ($slug * ft^2$)	36324	21393	15133	15301
Moment of Inertia (I_{yy}) ($slug * ft^2$)	80036	60071	44626	69668
Moment of Inertia (I_{zz}) ($slug * ft^2$)	81701	64427	43874	69264
Product of Inertia (I_{xy}) ($slug * ft^2$)	-2111	-2408	-743	-650
Product of Inertia (I_{xz}) ($slug * ft^2$)	273	1359	865	-1115
Product of Inertia (I_{yz}) ($slug * ft^2$)	2268	-650	-1109	-997

Table C.10: Apollo CSM Mass Properties [23]

exercise manual control.

Table C.9 lists docking system constraints for Apollo CSM and Apollo LM.

C.4 Mass Properties

Apollo CSM mass properties are documented in Table C.10 with data from Apollo 15. The heavy configuration is immediately following separation from the Saturn S-IVB launch vehicle. The medium configuration is after lunar orbit insertion. The light configuration is immediately before CM separation prior to entry. All of these are without a docked Lunar Module. The table also documents the Apollo-Soyuz CSM with attached Docking Module (DM)

Parameter	Heavy	Medium	Light
Weight (*pounds*)	103184.8	76132.2	42393.0
c.m. Location (î) (*inches*)	1040.8	1084.2	974.8
c.m. Location (ĵ) (*inches*)	3.1	2.0	3.9
c.m. Location ($\hat{k}$) (*inches*)	3.3	1.8	2.2
Moment of Inertia (I_{xx}) ($slug * ft^2$)	62333	48150	23723
Moment of Inertia (I_{yy}) ($slug * ft^2$)	576387	442009	113756
Moment of Inertia (I_{zz}) ($slug * ft^2$)	579309	448208	118406
Product of Inertia (I_{xy}) ($slug * ft^2$)	-11114	-8533	-2407
Product of Inertia (I_{xz}) ($slug * ft^2$)	-5066	-594	59
Product of Inertia (I_{yz}) ($slug * ft^2$)	2008	-999	-933

Table C.11: Apollo CSM+LM Mass Properties

just prior to the initial docking with Soyuz.

Table C.11 documents Apollo 15 CSM mass properties with attached Lunar Module (LM). The heavy, medium, and light configurations are the same as Table C.10.

Table C.12 documents Apollo 7 CSM mass properties at perigee when the crew encountered control problems due to interaction with the upper atmosphere.

Tables C.13 and C.14 document mass properties for SPS burns on Apollo 7 and 9 respectively.

Table C.15 documents mass property data for the Apollo 15 CM just prior to entry.

Parameter	Value
Weight (*pounds*)	30050
c.m. Location (î) (*inches*)	954.4
c.m. Location (ĵ) (*inches*)	0.9
c.m. Location ($\hat{k}$) (*inches*)	6.3
Moment of Inertia (I_{xx}) ($slug * ft^2$)	17096
Moment of Inertia (I_{yy}) ($slug * ft^2$)	54373
Moment of Inertia (I_{zz}) ($slug * ft^2$)	57175
Product of Inertia (I_{xy}) ($slug * ft^2$)	-1475
Product of Inertia (I_{xz}) ($slug * ft^2$)	511
Product of Inertia (I_{yz}) ($slug * ft^2$)	-127

Table C.12: Apollo 7 Low Perigee Mass Properties [7]

Parameter	Value
Weight (*pounds*)	27342
c.m. Location (î) (*inches*)	962.2
c.m. Location (ĵ) (*inches*)	0.2
c.m. Location ($\hat{k}$) (*inches*)	6.6
Moment of Inertia (I_{xx}) ($slug * ft^2$)	15805
Moment of Inertia (I_{yy}) ($slug * ft^2$)	49917
Moment of Inertia (I_{zz}) ($slug * ft^2$)	51624
Product of Inertia (I_{xy}) ($slug * ft^2$)	-1003
Product of Inertia (I_{xz}) ($slug * ft^2$)	304
Product of Inertia (I_{yz}) ($slug * ft^2$)	-210

Table C.13: Apollo 7 SPS Burn 5

Parameter	Value
Weight (*pounds*)	66214
c.m. Location ($\hat{\imath}$) (*inches*)	1088.9
c.m. Location ($\hat{\jmath}$) (*inches*)	1.0
c.m. Location ($\hat{k}$) (*inches*)	3.5
Moment of Inertia (I_{xx}) ($slug * ft^2$)	38792
Moment of Inertia (I_{yy}) ($slug * ft^2$)	375899
Moment of Inertia (I_{zz}) ($slug * ft^2$)	379869
Product of Inertia (I_{xy}) ($slug * ft^2$)	-3827
Product of Inertia (I_{xz}) ($slug * ft^2$)	-4760
Product of Inertia (I_{yz}) ($slug * ft^2$)	994

Table C.14: Apollo 9 SPS Burn 3

Parameter	Entry Configuration
Weight (*pounds*)	12912.2
c.m. Location ($\hat{\imath}$) (*inches*)	39.1
c.m. Location ($\hat{\jmath}$) (*inches*)	0.1
c.m. Location ($\hat{k}$) (*inches*)	5.7
Moment of Inertia (I_{xx}) ($slug * ft^2$)	5917
Moment of Inertia (I_{yy}) ($slug * ft^2$)	5273
Moment of Inertia (I_{zz}) ($slug * ft^2$)	4736
Product of Inertia (I_{xy}) ($slug * ft^2$)	61
Product of Inertia (I_{xz}) ($slug * ft^2$)	-387
Product of Inertia (I_{yz}) ($slug * ft^2$)	-10

Table C.15: Apollo CM Mass Properties

Appendix D

Saturn S-IVB Spacecraft Data

D.1 Overview

The Saturn S-IVB, pronounced "Ess Four Bee," was the upper stage of both the Saturn 1B and Saturn V rockets and was used for all manned Apollo flights. It was used to complete the ascent into orbit and, for lunar flights, was subsequently restarted to place the Apollo spacecraft on a lunar trajectory. (This was called the Trans-Lunar Injection or TLI burn.) The S-IVB had a single large gimbaling J-2 engine for primary propulsion and a separate Reaction Control System (RCS) known as the Auxiliary Propulsion System (APS). The APS was used to provide roll control during burns, to settle propellants in preparation for a zero-gravity start of the J-2 engine, and to provide three degree of freedom (3-DOF) attitude control during coasting flight.

The S-IVB was normally controlled by its own internal guidance and computer system but it was also able to be controlled manually from the Apollo spacecraft while still attached. This backup capability was exercised only once as a test during the Apollo 7 mission. After achieving orbit and shutting down the J-2 engine, and just prior to Apollo spacecraft separation, the crew took over manual control and performed roll, pitch, and yaw maneuvers with the APS using a discrete rate control system. They then returned the S-IVB to automatic control and subsequently separated.

Figure D.1 shows the S-IVB configuration prior to Apollo CSM separation. On most missions the CSM would separate, pitch around, and dock with the Apollo LM in a maneuver known as transposition and docking.

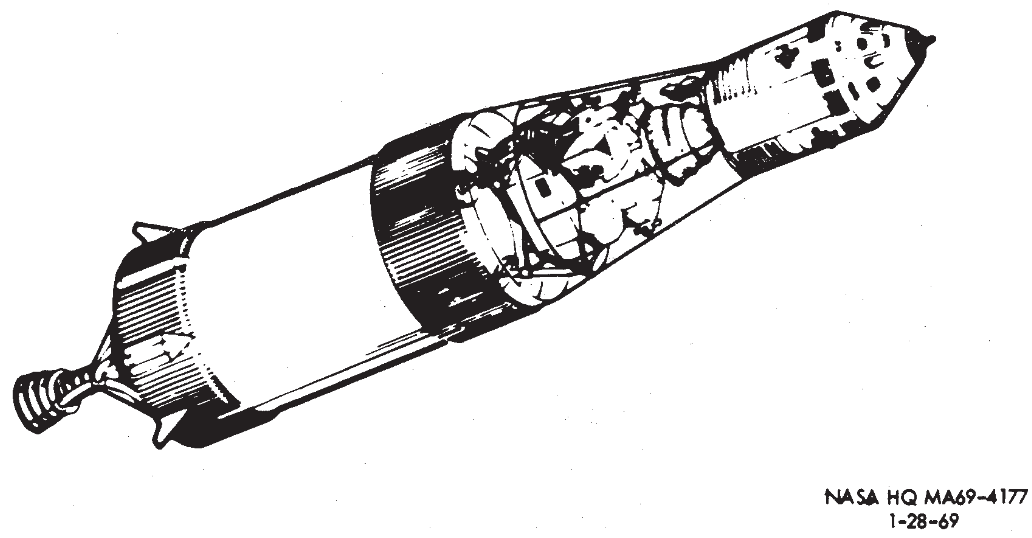

Figure D.1: Saturn S-IVB and Apollo CSM [14]

The CSM/LM stack would then separated from the S-IVB. On Apollo 7 and Apollo 8 there was no LM but the overall configuration remained the same otherwise.

The coordinate system used here is in the modern spacecraft standard. The X-axis points forward, the Y-axis to startboard, and the Z-axis to nadir to complete the right handed system. The origin is arbitrarily set at the aft structural ring of the stage.

D.2 Propulsion System

The Saturn S-IVB's Auxiliary Propulsion System (APS) consists of two pods near the aft of the vehicle along the +Z and -Z axes. Each pod has four jets using hypergolic propellants. One jet fires along the Z axis for pitch, two jets fire in the +Y and -Y directions for roll and yaw, and a single smaller jet fires aft for cryogenic propellant settling prior to main engine ignition.

Documentation on the APS is scarce. The jet nomenclature in this document is arbitrarily assigned and the jet locations listed in table D.1 are estimates. The APS pod on the -Z side of the vehicle is arbitrarily called A and the pod on the +Z side is B. Jet 2 fires along the Z-axis, jets 1 and 3

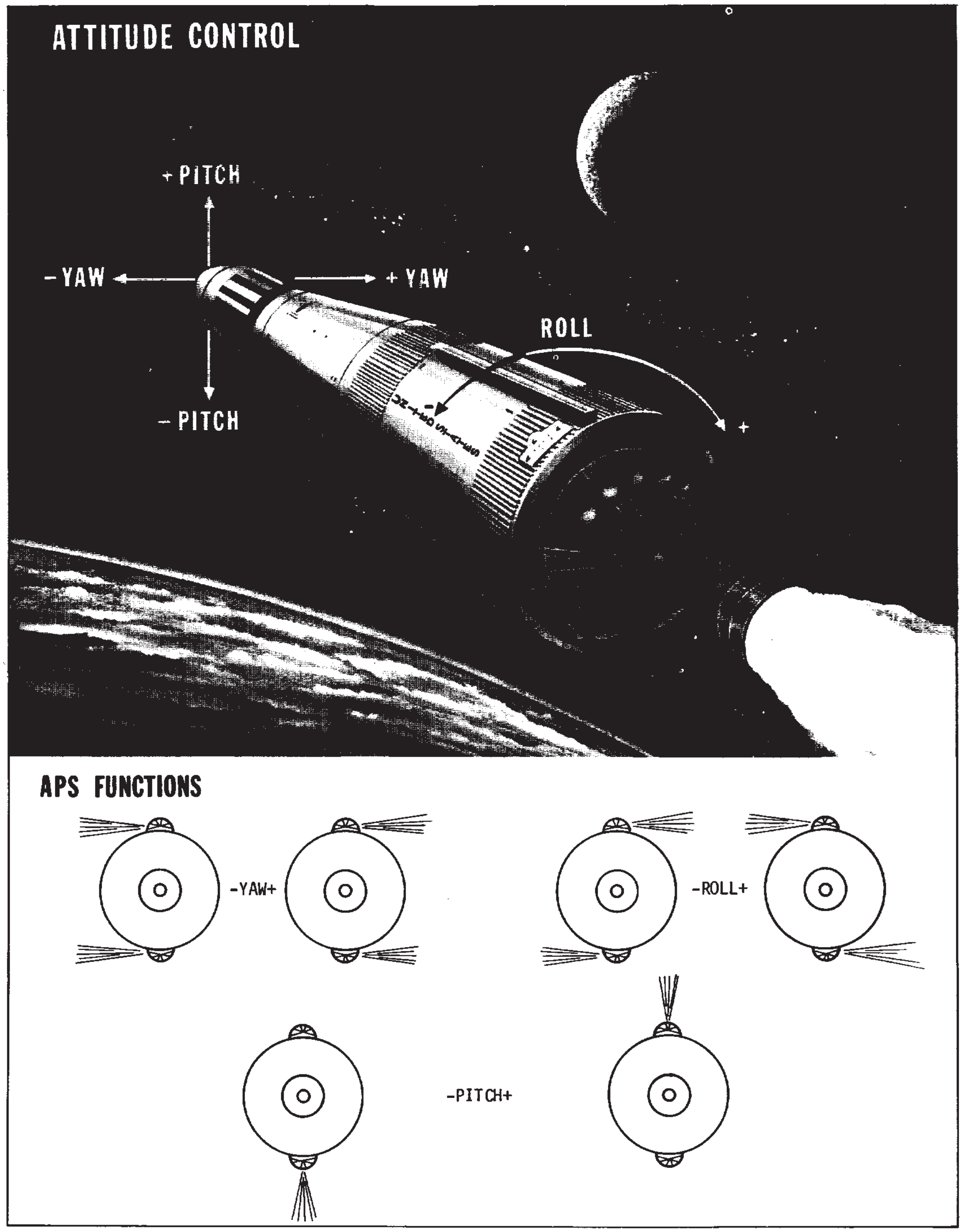

Figure D.2: Saturn S-IVB APS Jet Layout [12]

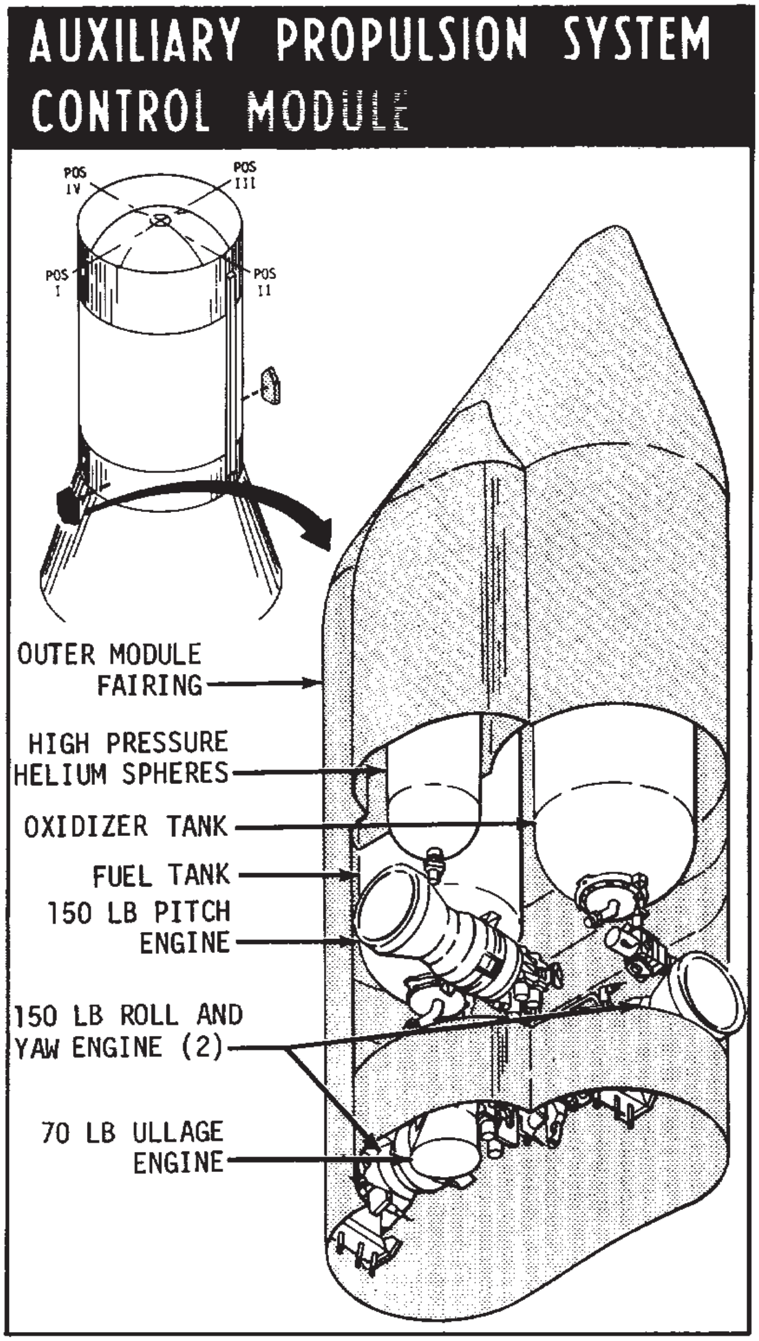

Figure D.3: Saturn S-IVB APS Pod [12]

Jets	$\hat{i}$	$\hat{j}$	$\hat{k}$
A1	38	0	-130
A2	50	0	-130
A3	38	0	-130
A4	38	0	-130
B1	38	0	130
B2	50	0	130
B3	38	0	130
B4	38	0	130

Table D.1: Saturn S-IVB APS Jet Locations (*inches*)

Jets	$\hat{i}$	$\hat{j}$	$\hat{k}$
A1	0	150	0
A2	0	0	150
A3	0	-150	0
A4	70	0	0
B1	0	150	0
B2	0	0	-150
B3	0	-150	0
B4	70	0	0

Table D.2: Saturn S-IVB APS Thrust Force Vectors (*pounds*)

Command	Jets
+Pitch	A2
-Pitch	B2
+Yaw	A3 + B3
-Yaw	A1 + B1
+Roll	A1 + B3
-Roll	A3 + B1
+X Translation	A4 + B4

Table D.3: Saturn S-IVB APS Command Responses

Roll Rate (deg/s)	Pitch Rate (deg/s)	Yaw Rate (deg/s)
0.5	0.3	0.3

Table D.4: Saturn S-IVB APS Discrete Maneuver Rates

fire along the Y-axis, and jet 4 fires along the X-axis.

Table D.1 documents estimated jet locations and table D.1 documents estimated jet thrust force vectors [12].

D.3 Control System

The Saturn S-IVB APS control system is straightforward. Jets fire as described in Table D.3 for attitude control and propellant settling.

In coasting flight the Saturn S-IVB could be manually controlled using a discrete rate control system. The maneuver rates as of Apollo 7 are documented in Table D.4 [15].

D.4 Mass Properties

Mass property data for the Saturn S-IVB with attached Apollo spacecraft, as estimated for the manual control test during Apollo 7, is given in Table D.5. The Y,Z location of the center of mass is only described in documentation as "radial," so is arbitrarily placed along the Z-axis. No data for products of

Parameter	Value
Weight ($pounds$)	67,830
c.m. Location (î) ($inches$)	1759.8
c.m. Location (ĵ) ($inches$)	0.0
c.m. Location ($\hat{\text{k}}$) ($inches$)	4.0
Moment of Inertia (I_{xx}) ($slug * ft^2$)	97,532
Moment of Inertia (I_{yy}) ($slug * ft^2$)	2,627,343
Moment of Inertia (I_{zz}) ($slug * ft^2$)	2,629,729
Product of Inertia (I_{xy}) ($slug * ft^2$)	0
Product of Inertia (I_{xz}) ($slug * ft^2$)	0
Product of Inertia (I_{yz}) ($slug * ft^2$)	0

Table D.5: Saturn S-IVB Mass Properties (Apollo 7 Manual Control Test)

inertia are available and thus those values are set to zero.

Appendix E

Apollo Lunar Module (LM) Spacecraft Data

E.1 Overview

The Apollo Lunar Module (LM) was a two-stage spacecraft designed to descend from lunar orbit, land, operate on the surface for up to three days, ascend into orbit, rendezvous with the Apollo Command and Service Module (CSM), and dock. It carried two crewmembers. The LM was originally known as the Lunar Excursion Module (LEM). Early designs had a second docking mechanism in the forward hatch but that was removed to decrease weight. Later versions, starting with Apollo 15, had a heavier descent stage to carry more batteries, the Lunar Rover, more propellant, and other equipment.

The Apollo coordinate systems are defined in the mass properties report [37]. The coordinate system's X-axis is positive out the top hatch, the Y-axis towards the starboard landing gear, and the Z-axis in the direction of the forward hatch. This system is in the modern spacecraft standard if one imagines the LM flying in orbit with the top of the spacecraft forward and main windows pointing down to the lunar surface.

E.2 Propulsion System

The LM had three propulsion system. The Descent Propulsion System (DPS) had a powerful, throttlable engine used for descent and landing. The ascent

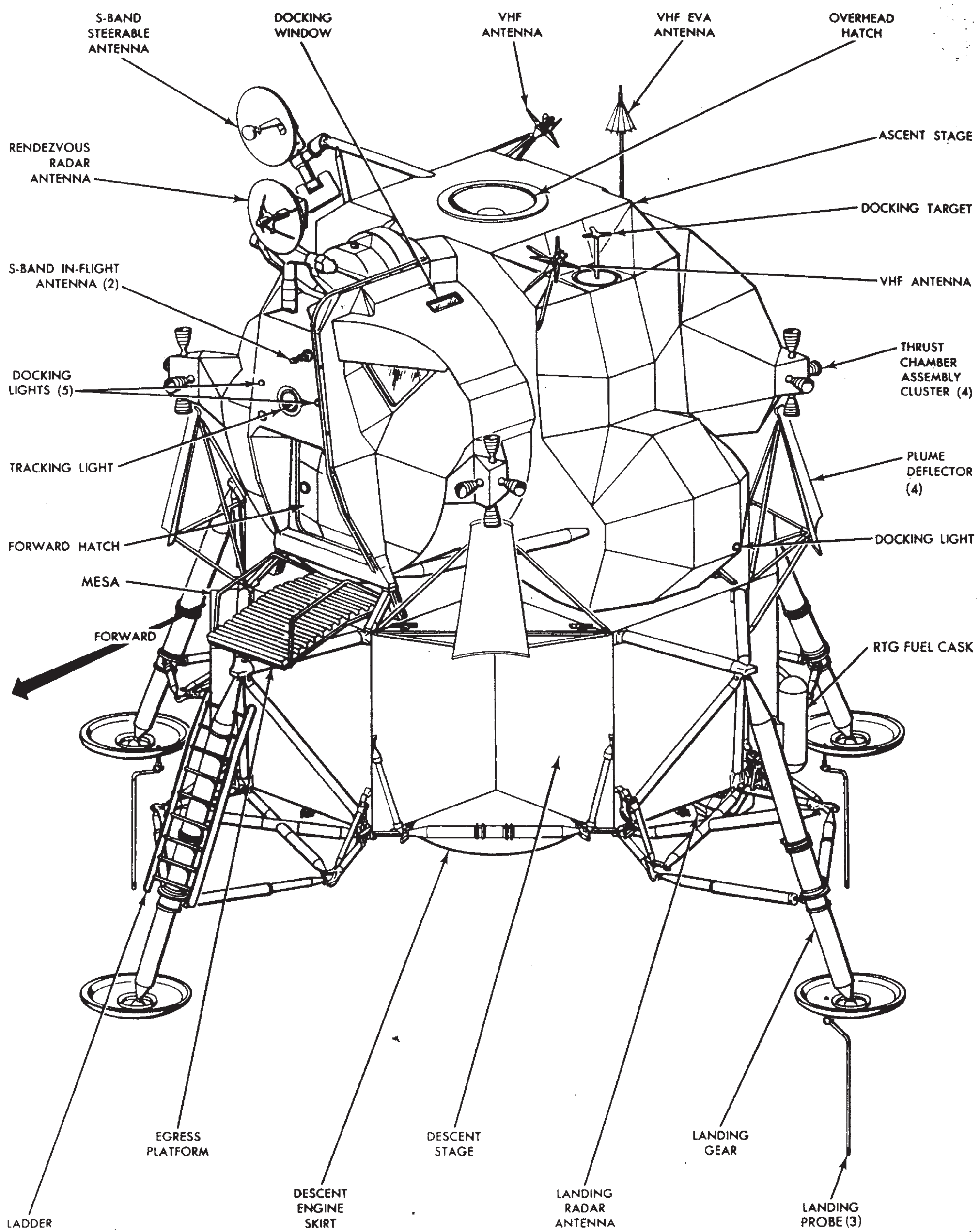

Figure E.1: Apollo LM Overview [21]

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
A1F	254.0	-61.5	66.1
A1U	254.0	-66.1	66.1
B1D	254.0	-66.1	66.1
B1L	254.0	-66.1	61.5
A2A	254.0	-61.5	-66.1
A2D	254.0	-66.1	-66.1
B2L	254.0	-66.1	-61.5
B2U	254.0	-66.1	-66.1
A3R	254.0	66.1	-61.5
A3U	254.0	66.1	-66.1
B3A	254.0	61.5	-66.1
B3D	254.0	66.1	-66.1
A4D	254.0	66.1	66.1
A4R	254.0	66.1	61.5
B4F	254.0	61.5	66.1
B4U	254.0	66.1	66.1

Table E.1: Apollo LM RCS Jet Locations (*inches*)

stage was equipped with the Ascent Propulsion System (APS) engine and Reaction Control System (RCS). All three systems used hypergolic propellants and the APS and RCS propellant systems could be interconnected.

LM RCS jet locations are specified in Table E.1 and the associated thrust force vectors in Table E.2.

The Ascent Propulsion System (APS) engine location and thrust data are given in Table E.3.

E.3 Control System

The Apollo Lunar Module (LM) could be flown via either one of two control systems: the Primary Guidance and Navigation System (PGNS) or the Abort Guidance System (AGS).

The LM PGNS utilized hardware and software very similar to the Command Module (CM) PNGCS. An Inertial Measurement Unit (IMU) provided data to a digital computer that, in turn, controlled the Reaction Control Sys-

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
A1F	0.0	0.0	-100.0
A1U	-100.0	0.0	0.0
B1D	100.0	0.0	0.0
B1L	0.0	100.0	0.0
A2A	0.0	0.0	100.0
A2D	100.0	0.0	0.0
B2L	0.0	100.0	0.0
B2U	-100.0	0.0	0.0
A3R	0.0	-100.0	0.0
A3U	-100.0	0.0	0.0
B3A	0.0	0.0	100.0
B3D	100.0	0.0	0.0
A4D	100.0	0.0	0.0
A4R	0.0	-100.0	0.0
B4F	0.0	0.0	-100.0
B4U	-100.0	0.0	0.0

Table E.2: Apollo LM RCS Thrust Force Vectors (*pounds*)

	$\hat{i}$	$\hat{j}$	$\hat{k}$
Location (*in*)	232.96	0.0	3.75
Thrust (*lb*)	3498.80	0.0	91.62

Table E.3: Apollo LM Ascent Engine Location and Thrust Vectors

Prop Rate Mode	Max Roll (deg/s)	Max Pitch (deg/s)	Max Yaw (deg/s)
AGS (Low, Unstaged)	0.2	0.2	0.2
AGS (High, Unstaged)	3.33	3.33	3.33
AGS (Low, Staged)	0.75	0.75	0.75
AGS (High, Staged)	12.5	12.5	12.5
PNGCS (Fine, Undocked)	4.0	4.0	4.0
PNGCS (Normal, Undocked)	20.0	20.0	20.0
PNGCS (Fine, Docked)	0.4	0.4	0.4
PNGCS (Normal, Docked)	2.0	2.0	2.0

Table E.4: Apollo LM Maximum Maneuver Rates (AGS and PGNCS)

tem (RCS). During non-descent flight, the system provided Direct, Minimum Impulse, and Proportional Rate attitude control modes. Maximum maneuver rates when under proportional rate control were selected from pre-defined values in software and are shown in Table E.4.

The LM Abort Guidance System (AGS) utilized body-mounted gyroscopes and a small digital computer to provide vehicle control. The system provided Direct, Pulse Train, and Proportional Rate attitude control modes. Maximum maneuver rates when under proportional rate control were selected from High and Low via hardware switch and are shown in Table E.4.

The manual control functions of the LM PGNS Digital Auto-Pilot (DAP) are quite sophisticated in implementation in order to yield good control characteristics despite the use of a very limited computer even after RCS failures. See Reference [16] for a detailed description.

Note that during powered ascent, when the Ascent Propulsion System (APS) engine is firing, the upward firing jets are normally disabled when under automatic control. This increases ascent performance at the cost of reduced control authority. This is an automatic software function in the PGNS but is controlled using the balance couple switch if using the Abort Guidance System (AGS).

The minimum impulse control mode commands a 0.014 sec RCS jet firing.

$$\omega_c = 0.000453335\delta\left(|\delta| + 10.5\right)\omega_{max} \tag{E.1}$$

The LM utilizes non-linear shaping for the proportional rate being com-

Parameter	Pre-PDI	Touchdown	Liftoff	Docking
Weight (*pounds*)	36658.3	17746.7	10849.1	5730.6
c.m. Location (î) (*inches*)	185.0	210.2	243.8	256.6
c.m. Location (ĵ) (*inches*)	0.4	0.7	0.1	0.1
c.m. Location (k̂) (*inches*)	-0.4	-0.6	2.8	5.3
Moment of Inertia (I_{xx}) ($slug * ft^2$)	27262	15343	6744	3263
Moment of Inertia (I_{yy}) ($slug * ft^2$)	28465	16120	3405	2866
Moment of Inertia (I_{zz}) ($slug * ft^2$)	27061	17411	5955	1980
Product of Inertia (I_{xy}) ($slug * ft^2$)	84	41	65	65
Product of Inertia (I_{xz}) ($slug * ft^2$)	809	847	180	95
Product of Inertia (I_{yz}) ($slug * ft^2$)	175	203	-35	-31

Table E.5: Generic Apollo LM Mass Properties

manded via the Rotational Hand Controller. The relationship is governed by Equation E.1 where ω_c is the commanded rate about the body axis, δ is an integer value linearly proportional to RHC deflection where 0 is no deflection and ± 42 is maximum deflection, and ω_{max} is the maximum body rate. This was done to allow finer control during lunar touchdown while still allowing large maneuver rates for obstacle avoidance.

E.4 Mass Properties

Apollo Lunar Module mass properties for representative configurations are shown in Table E.5. This data are from Apollo 15 and is highly representative of the J-series missions (15, 16, 17). Data from specific points in the Apollo 9 and 10 missions to support historic anaysis is shown in Table E.6.

Parameter	Apollo 9 Docking	Apollo 10 IMU Alignment
Weight (*pounds*)	9932	8052
c.m. Location ($\hat{\imath}$) (*inches*)	243.5	245.9
c.m. Location ($\hat{\jmath}$) (*inches*)	-0.7	0.5
c.m. Location ($\hat{k}$) (*inches*)	3.1	3.5
Moment of Inertia (I_{xx}) ($slug * ft^2$)	5976	4784
Moment of Inertia (I_{yy}) ($slug * ft^2$)	3515	3412
Moment of Inertia (I_{zz}) ($slug * ft^2$)	5195	4036
Product of Inertia (I_{xy}) ($slug * ft^2$)	49	45
Product of Inertia (I_{xz}) ($slug * ft^2$)	184	190
Product of Inertia (I_{yz}) ($slug * ft^2$)	-7	-16

Table E.6: Apollo 9 and 10 LM Mass Properties

Appendix F

Soyuz 7K-TM Spacecraft Data

F.1 Overview

Soyuz is a Russian spacecraft operated from 1967 through the present day in many variations. It originally carried two crew but has been modified to carry three in modern versions. In contrast to the Apollo CSM it is a three module vehicle consisting of an aft Propulsion Module (PM), a central Descent Module (DM) containing the cockpit, and a forward Orbital Module (OM) containing additional living space and forward mounted docking mechanism. After the deorbit burn the three modules separate and only the DM lands. The other two modules disintegrate during entry. Landing is via parachute onto dry land with solid braking rockets fired just before touchdown to soften the landing.

The version analyzed in this work is the Soyuz 7K-TM used almost exclusively for the Apollo-Soyuz Test Project (ASTP) mission in 1975. it carried two crew members and had a unique androgenous docking mechanism known as APAS-75[1] with an equivalent on the Apollo Docking Module. The Apollo CSM+DM and Soyuz 7K-TM are shown in Figure F.1.

The Soyuz coordinate system and mass properties are documented in the ASTP Technical Requirements for Stability and Control [26]. The Soyuz system is right-handed with the X-axis pointing aft, the Y-axis to zenith, and Z-axis to point. The mass property data here has been converted to the modern system in which the X-axis points forward, the Y-axis to starboard, and the right-handed system is completed by having the Z-axis point to nadir.

[1]Androgynous Peripheral Attachment System

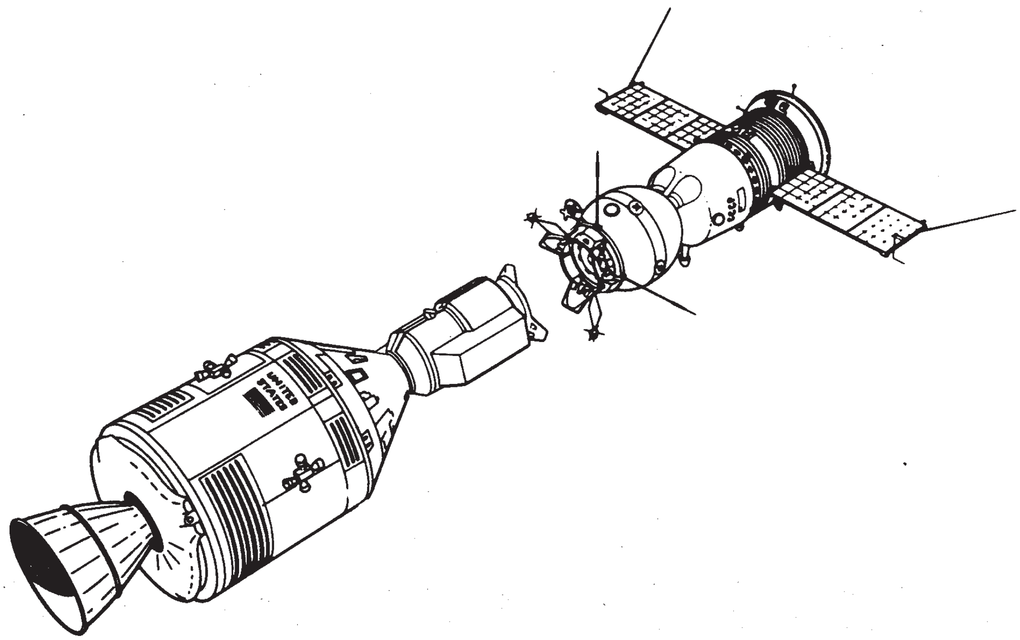

Figure F.1: Apollo-Soyuz Test Project Docking [26]

F.2 Propulsion System

Soyuz 7K-TM used H_2O_2 monopropellant jets for reaction control.

F.3 Control System

The Soyuz control system contains two systems of hydrogen peroxide jets. One system is for rotational control only and uses 1 kg_f thrust jets. The

Axis	1 kg thrust jets (deg/s)	10 kg thrust jets (deg/s)
Roll	0.03	0.77
Pitch	0.007	0.06
Yaw	0.006	0.06

Table F.1: Soyuz Attitude Pulse Magnitudes

Axis	Soft Stop (deg/s)	Hard Stop (deg/s)
Roll	0.5	3.0
Pitch	0.5	3.0
Yaw	1.0	3.0

Table F.2: Soyuz Maximum Attitude Rates

Translation Axis	Minimum Impulse (m/s)
±X	0.003
±Y	0.002
±Z	0.003

Table F.3: Soyuz 7K-TM Minimum Translation Impulses (Estimated)

other system is for translation and rotation and uses 10 kg_f thrust jets. When used in pulse mode, a short, constant duration firing signal is sent to the appropriate rotational control jets. Using the supplied mass properties, jet thrusts, jet locations, and resulting rotational impulses, we can estimate the firing pulse duration to be approximately 0.1 seconds. This value is used to estimate the minimum firing time for translational control jets and, therefore, the minimum translational impulse shown in Table F.3.

Docking constraints for Apollo and Soyuz are given in Table F.4.

Axial Velocity	0.05 to 0.3 m/s ((0.16 to 0.99 ft/s)
Radial Velocity	0.0 to 0.1 m/s (0.00 to 0.33 ft/s)
Radial Displacement	0.0 to 0.3 m (0.00 to 0.99 ft)
Pitch-Yaw Angular Displacement	0 to 7 deg
Roll Alignment	0 to 7 deg
Angular Velocities	0 to 1 deg/s

Table F.4: APAS-75 Docking System Constraints [126]

Parameter	Value
Mass (kg)	6697.9
c.m. Location $(\hat{\imath})$ (m)	2.9
c.m. Location $(\hat{\jmath})$ (m)	-0.005
c.m. Location $(\hat{k})$ (m)	-0.01
Moment of Inertia (I_{xx}) $(kg * m^2)$	4805.3
Moment of Inertia (I_{yy}) $(kg * m^2)$	21574.6
Moment of Inertia (I_{zz}) $(kg * m^2)$	22555.3
Product of Inertia (I_{xy}) $(kg * m^2)$	-49.0
Product of Inertia (I_{xz}) $(kg * m^2)$	294.2
Product of Inertia (I_{yz}) $(kg * m^2)$	-19.6

Table F.5: Soyuz 7K-TM Mass Properties

F.4 Mass Properties

Mass property data are shown in Table F.5.

Appendix G

Space Shuttle Data

G.1 Overview

The Space Shuttle was a cargo-carrying manned aerospace vehicle operated from 1981 through 2011.

The Space Shuttle orbiter structural coordinate frame is a right handed system in which the X-axis points aft, the Y-axis points to starboard, and the Z-axis points to zenith. The origin is forward of the spacecraft nose. Reaction Control System (RCS) jet locations and mass properties are published in this frame. The data here have been converted to the spacecraft GNC frame in which the X-axis points forward, Y-axis points starboard, and Z-axis to nadir. Keeping the origin in the same location results in all X coordinates on the structure having negative values.

Radial position tolerance for Shuttle docking to the ISS is from a publically available NASA web page [1].

G.2 Propulsion System

While in orbit the Shuttle propulsion system consisted of three RCS systems (forward, left, and right), each RCS jets and propellant tanks, and two Orbital Maneuvering System (OMS) pods each containing propellant tanks and engine. The left and right RCS systems were contained within the left and right OMS pods respectively. The forward RCS was contained in the forward pod. All three pods were designed to be easily removable for ground processing in facilities equipped to handle toxic propellants. Propellant could be

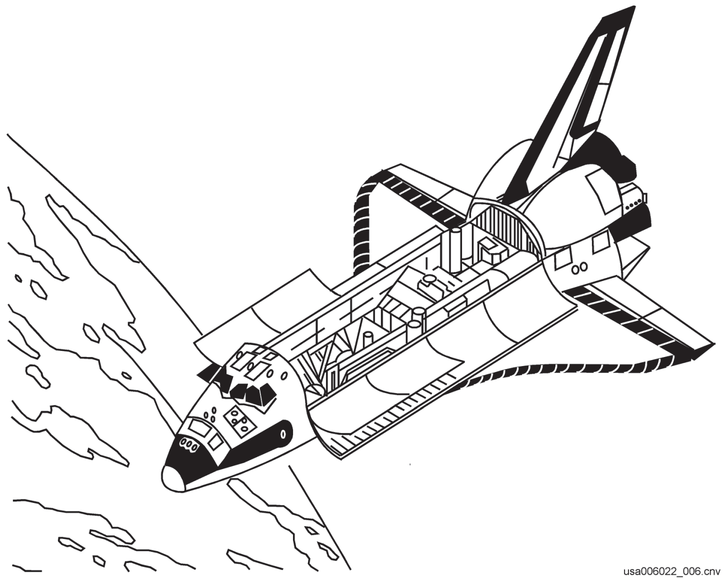

Figure G.1: Shuttle General Configuration [35]

interconnected within the left or right pod to use OMS propellant for RCS jets. The left and right pods could also share OMS or RCS propellant using crossfeed lines. The forward RCS was propellant isolated.

Each RCS system contained a mix of high thrust 'Primary' jets and low thrust 'Vernier' jets. The Vernier RCS (VRCS) was used for fine attitude control. The Primary RCS (PRCS) was used for attitude control and translation. With a pod groups of two, three, or four PRCS jets fired in the same direction. The jets within these groups were prioritized such that the highest priority non-failed jet would fire when required. The priority was set on a rotating basis between missions to equalize long term wear. Jets within a group are considered to have equal capability despite the small differences in moment arm.

The Shuttle general configuration in shown in Figure G.1 and the RCS jet layout, from the same perspective, in Figure G.2. The primary jets are on propellant manifolds 1 through 4, the vernier jets are on manifold 5.

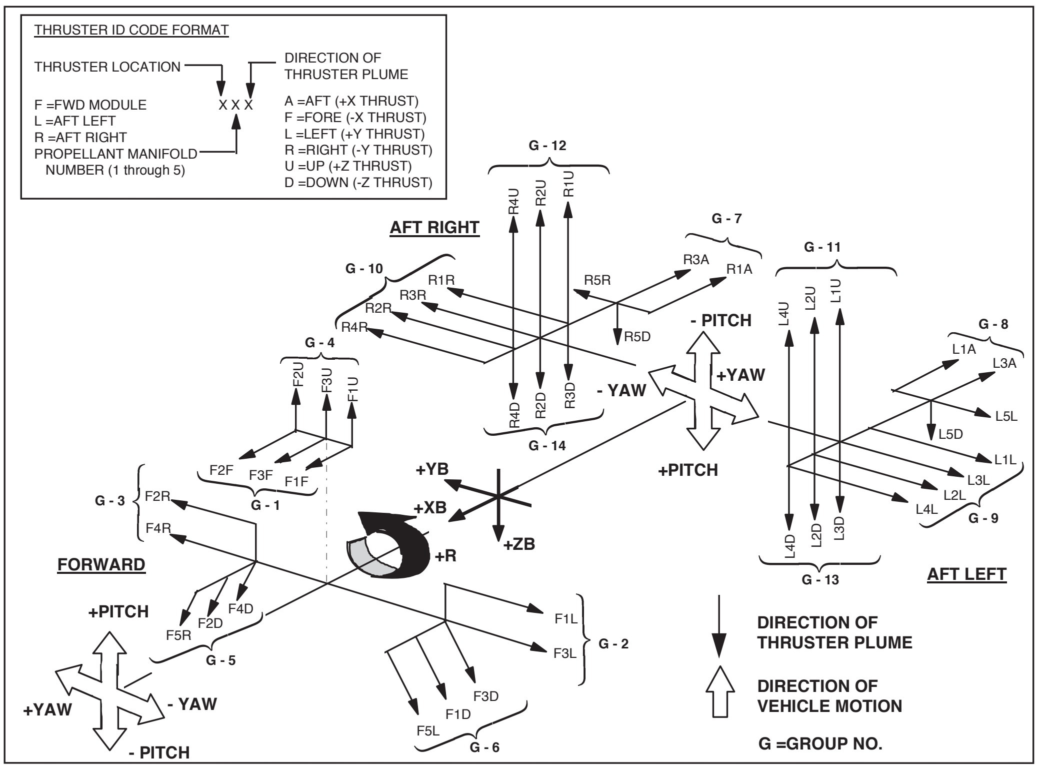

Figure G.2: Shuttle RCS Layout [34]

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
F2F	-306.72	14.65	-392.96
F3F	-306.72	0.00	-394.45
F1F	-306.72	-14.65	-392.96
F1L	-362.67	-69.50	-373.73
F3L	-364.71	-71.65	-359.25
F2R	-362.67	69.50	-373.73
F4R	-364.71	71.65	-359.25
F2U	-350.93	14.39	-413.46
F3U	-350.92	0.00	-414.53
F1U	-350.93	-14.39	-413.46
F2D	-333.84	61.42	-356.95
F1D	-333.84	-61.42	-356.95
F4D	-348.44	66.23	-358.44
F3D	-348.44	-66.23	-358.44
F5R	-324.35	59.70	-350.12
F5L	-324.35	-59.70	-350.12

Table G.1: Shuttle Forward RCS Jet Locations (*inches*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
L3A	-1555.29	-137.00	-473.06
L1A	-1555.29	-124.00	-473.06
L4L	-1516.00	-149.87	-459.00
L2L	-1529.00	-149.87	-459.00
L3L	-1542.00	-149.87	-459.00
L1L	-1555.00	-149.87	-459.00
L4U	-1516.00	-132.00	-480.50
L2U	-1529.00	-132.00	-480.50
L1U	-1542.00	-132.00	-480.50
L4D	-1516.00	-111.95	-437.40
L2D	-1529.00	-111.00	-440.00
L3D	-1542.00	-110.06	-442.60
L5L	-1565.00	-149.87	-459.00
L5D	-1565.00	-118.00	-455.44

Table G.2: Shuttle Left RCS Jet Locations (*inches*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
R3A	-1555.29	137.00	-473.06
R1A	-1555.29	124.00	-473.06
R4R	-1516.00	149.87	-459.00
R2R	-1529.00	149.87	-459.00
R3R	-1542.00	149.87	-459.00
R1R	-1555.00	149.87	-459.00
R4U	-1516.00	132.00	-480.50
R2U	-1529.00	132.00	-480.50
R1U	-1542.00	132.00	-480.50
R4D	-1516.00	111.95	-437.40
R2D	-1529.00	111.00	-440.00
R3D	-1542.00	110.06	-442.60
R5R	-1565.00	149.87	-459.00
R5D	-1565.00	118.00	-455.44

Table G.3: Shuttle Right RCS Jet Locations (*inches*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
F2F	-875.1	-26.2	148.0
F3F	-875.1	0.0	150.9
F1F	-875.1	26.2	148.0
F1L	-26.3	873.6	18.2
F3L	-21.0	870.3	0.5
F2R	-26.3	-873.6	18.2
F4R	-21.0	-870.3	0.5
F2U	-32.3	-11.7	874.4
F3U	-31.9	0.0	873.5
F1U	-32.3	11.7	874.4
F2D	-28.0	-616.4	-639.5
F1D	-28.0	616.4	-639.5
F4D	-24.8	-612.6	-639.4
F3D	-24.8	612.6	-639.4
F5R	-0.8	-17.0	-17.6
F5L	-0.8	17.0	-17.6

Table G.4: Shuttle Forward RCS Thrust Force Vectors (*pounds*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
L3A	856.8	0.0	151.1
L1A	856.8	0.0	151.1
L4L	0.0	870.5	-22.4
L2L	0.0	870.5	-22.4
L3L	0.0	870.5	-22.4
L1L	0.0	870.5	-22.4
L4U	0.0	0.0	870.0
L2U	0.0	0.0	870.0
L1U	0.0	0.0	870.0
L4D	170.4	291.8	-801.7
L2D	170.4	291.8	-801.7
L3D	170.4	291.8	-801.7
L5L	0.0	24.0	-0.6
L5D	0.0	0.0	-24.0

Table G.5: Shuttle Left RCS Thrust Force Vectors (*pounds*)

Jet	$\hat{i}$	$\hat{j}$	$\hat{k}$
R3A	856.8	0.0	151.1
R1A	856.8	0.0	151.1
R4R	0.0	-870.5	-22.4
R2R	0.0	-870.5	-22.4
R3R	0.0	-870.5	-22.4
R1R	0.0	-870.5	-22.4
R4U	0.0	0.0	870.0
R2U	0.0	0.0	870.0
R1U	0.0	0.0	870.0
R4D	170.4	-291.8	-801.7
R2D	170.4	-291.8	-801.7
R3D	170.4	-291.8	-801.7
R5R	0.0	-24.0	-0.6
R5D	0.0	0.0	-24.0

Table G.6: Shuttle Right RCS Thrust Force Vectors (*pounds*)

Command	Jet	Jet	Jet	Jet	Jet	Jet
+Roll	R1U	L3D				
-Roll	L1U	R3D				
+Pitch	F4D	F3D	L1U	R1U		
-Pitch	F3U	L3D	R3D			
+Yaw	F3L	R3R				
-Yaw	F4R	L1L				
+X	R3A	L3A				
-X	F1F	F2F				
+Y	F3L	L1L				
-Y	F4R	R3R				
+Z	F3U	L1U	R1U			
-Z	F4D	F3D	L3D	L2D	R3D	R2D

Table G.7: Shuttle RCS Command Responses (Primary, Norm Z) [52]

Command	Jet	Jet	Jet
+Roll	L5D	L5L	F5L
-Roll	R5D	R5R	F5R
+Pitch	F5L	F5R	
-Pitch	R5D	L5D	
+Yaw	F5L	R5R	
-Yaw	F5R	L5L	

Table G.8: Shuttle RCS Command Responses (Vernier, Typical) [52]

Effective Position	-1518, ±88, -492 *in*
Angular Offset	±6.5 *deg* (inboard) yaw, -15.82 *deg* (downward) pitch
Specific Impulse	315.1 *sec*
Thrust	6087 *lb*
Gimbal Range	±6.0 *deg* (Pitch), ±7.0 *deg* (Yaw)
Gimbal Rate	5.0 deg/s

Table G.9: Shuttle Orbital Maneuvering System (OMS) Characteristics

G.3 Control System

The Shuttle control system is complicated and evolved significantly throughout the program. In brief, attitude control was performed using either VRCS and PRCS but not a combination. Translation, except for Hubble and International Space Station (ISS) reboost, always used PRCS jets. When using VRCS jet selection was computed by taking into account the vehicle center of mass and resulting moments created by the individual jets. This allowed for control even in cases when the center of mass was far outside the vehicle, as when docked to the ISS, or with a large payload on the robot arm. PRCS attitude control could be done using similar logic as VRCS or via lookup table. Also when using PRCS, the forward RCS could be disabled and all attitude control done using the left and right RCS. Forward (+X) translation was normally done using two +X jets but four were using during ascent and deorbit. Finally, +Z translation could be done using two aft and one forward upward firing jet, this was called 'Norm Z,' or by using the slight upward cant of forward and aft firing jets to avoid pluming a payload or the ISS directly avoid the payload bay ('Low Z'), or by using all upward firing jets ('High Z').

Rotation and translation control modes were selectable on a per-axis basis. On-orbit rotation supported impulse and discrete rate. Direct was available by displacing the RHC past the soft stop. On-orbit translation supported impulse and normal. Rotation rates, deadbands, and impulse size were all configurable in software.

Jets were fired in increments of 0.08 *sec* due to the GNC flight software cycle time. Because of the different numbers of jets fired the resulting minimum translation impulse varied depending upon the commanded direction.

G.4 Mass Properties

Typical mass properties are shown in Table G.10.

Property	Post ET Separation (Heavy)	ISS Docking (Medium)	Entry Interface (Light)
Weight (lb)	261,076.3	245,001.3	205,229.6
c.m. ($\hat{i}$) (in)	-1104.45	-1087.27	-1082.15
c.m. ($\hat{j}$) (in)	-0.14	-0.01	-0.38
c.m. ($\hat{k}$) (in)	-381.41	-375.53	-371.31
I_{xx} $(slug * ft^2)$	994,941.1	961,915.9	873,823.4
I_{yy} $(slug * ft^2)$	8,079,915.7	7,664,325.1	7,212,848.6
I_{zz} $(slug * ft^2)$	8,341,120.6	7,968,249.1	7,479,806.3
I_{xy} $(slug * ft^2)$	3634.0	4661.0	1434.1
I_{xz} $(slug * ft^2)$	271,139.4	225,264.1	152,380.8
I_{yz} $(slug * ft^2)$	432.0	-166.4	532.4

Table G.10: Shuttle Mass Properties (STS-133)

Appendix H

Manned Maneuvering Unit (MMU) Data

H.1 Overview

The Manned Maneuvering Unit (MMU) provided propulsion and control to enable free-flying Extra-Vehicular Activity (EVA) during several Space Shuttle missions. All MMU information is from [47], with the exception of mass property information which is from [113] and Figure H.2 which is from [27].

The MMU coordinate system is shown in Figure H.2. Following the modern standard for spacecraft the X-axis points forward, the Y-axis point starboard, and the Z-axis points to nadir to complete the right-handed system.

H.2 Propulsion System

The MMU propulsion system consists of two independent subsystems consisting of a high-pressure nitrogen tank and 12 cold-gas 1.7 *lb* jets for rotational and translational control arranged in eight triads. The two subsystems are normally operated simultaneously.

Jet nomenclature consists of a three character sequence. The first character (F,B,L,R,U,D) describes the direction of the force exerted by the jet (forward, backward, left, right, up, down); the plume direction is opposite. The second character (1,2,3,4) indicates the quadrant containing the jet where 1 represents the upper-right quadrant (as seen from the perspective of the

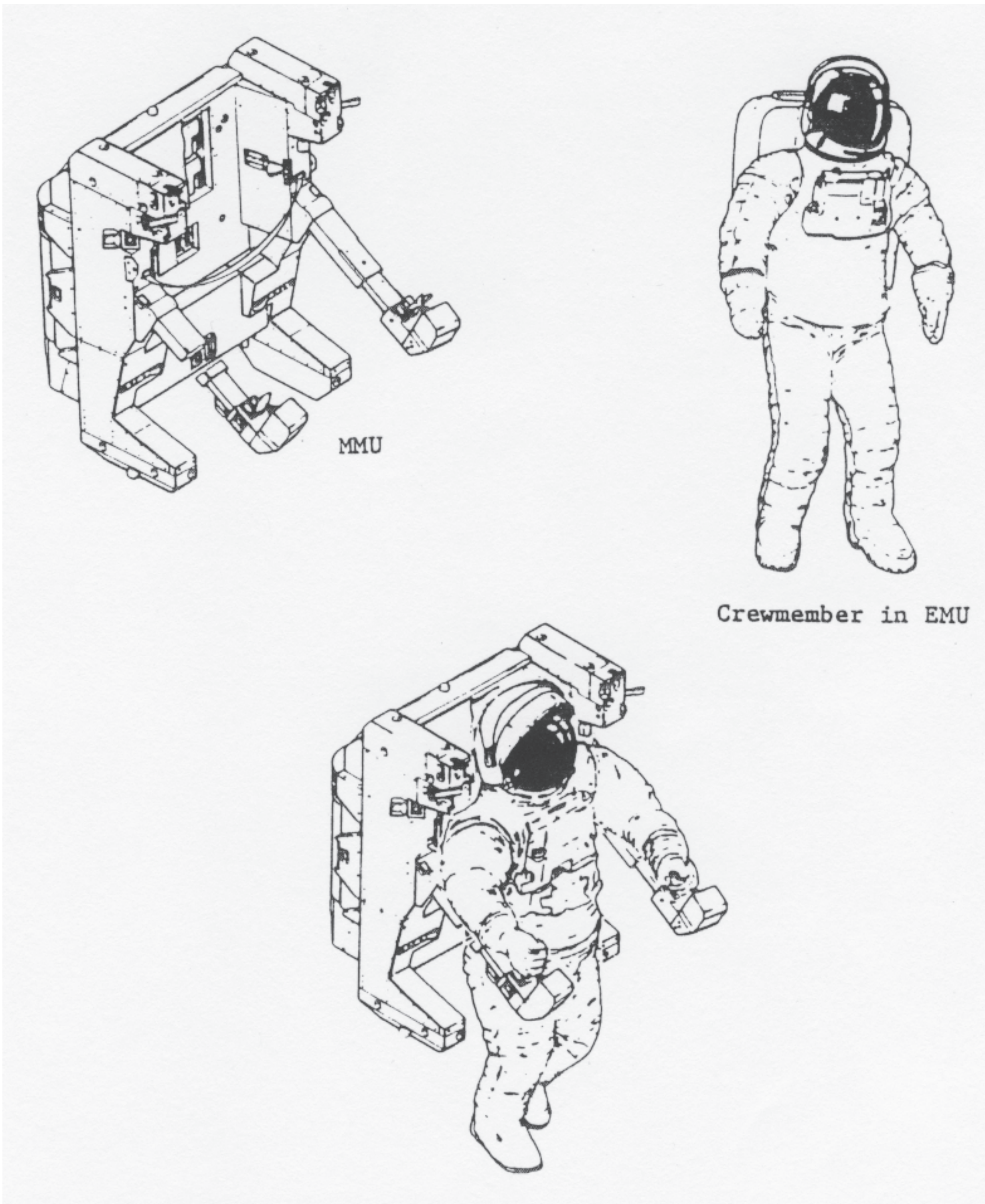

Figure H.1: Manned Maneuvering Unit (MMU) Overview [47]

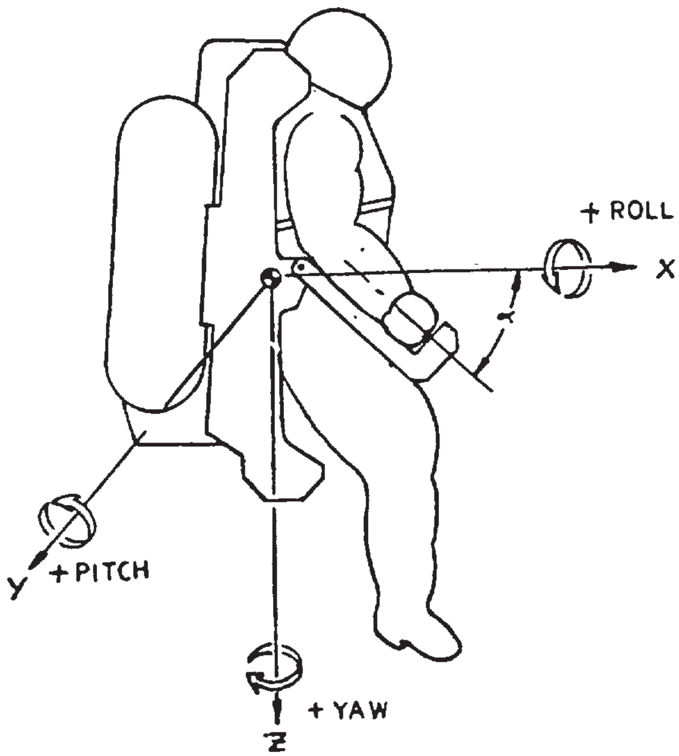

Figure H.2: Manned Maneuvering Unit (MMU) Coordinate System [27]

Jets	$\hat{i}$	$\hat{j}$	$\hat{k}$
B1A, D1A, L1A	4.5	13.45	-21.0
D1B, F1B, L1B	-4.5	13.45	-21.0
B2B, D2B, R2B	4.5	-13.45	-21.0
D2A, F2A, R2A	-4.5	-13.45	-21.0
B3B, L3B, U3B	4.5	13.45	21.0
F3A, L3A, U3A	-4.5	13.45	21.0
B4A, R4A, U4A	4.5	-13.45	21.0
F4B, R4B, U4B	-4.5	-13.45	21.0

Table H.1: Manned Maneuvering Unit Jet Locations (*inches*)

Jets	$\hat{i}$	$\hat{j}$	$\hat{k}$
F1B, F2A, F3A, F4B	1.7	0	0
B1A, B2B, B3B, B4A	-1.7	0	0
R2A, R2B, R4A, R4B	0	1.7	0
L1A, L1B, L3A, L3B	0	-1.7	0
D1A, D1B, D2A, D2B	0	0	1.7
U3A, U3B, U4A, U4B	0	0	-1.7

Table H.2: Manned Maneuvering Unit Thrust Force Vectors (*pounds*)

pilot), 2 is the upper left, 3 is lower right, and 4 is lower left. The third character (A,B) indicates the subsystem.

The jet locations are documented in Table H.1. Table H.2 documents the direction and magnitude of the thrust force vectors.

The jets generate 1.7±0.09 lb of thrust with a minimum firing time of 10.5 *ms*. Specific impulse (I_{sp}) is 66 *sec*.

H.3 Control System

The MMU control system is more complicated than described here and includes a mode used to stabilize a captured satellite, logic to cope with failures, and logic to account for simultaneous control inputs. The simplified (from [47]) jet firing logic in Table H.3 assumes that both propulsion subsystems (A and B) are operating normally and that no simultaneous control inputs, such as combined rotation and translation, are made. Rotations are split between the A and B subsystems because they would normally alternate to evenly use propellant. Translation is normally done using both A and B subsystems simultaneously. In other words, rotations are normally performed with two jets to create a couple, alternating between A and B subsystems and translations are normally done with four jets of which two are subsystem A and two are subsystem B. If one subsystem were to fail, rotation would still occur with normal control authority but translation would be at half normal control authority.

In general, the MMU performs automatic inertial attitude hold until, on a per-axis basis, a manual rotation is commanded. From then on, the vehicle is in free-drift about that axis with with jets firing continously as long as the

Command	Jets
+Pitch	(B1A + F3A) or (B2B + F4B)
-Pitch	(F1B + B3B) or (F2A + B4A)
+Yaw	(B1A + F2A) or (B3B + F4B)
-Yaw	(F1B + B2B) or (F3A + B4A)
+Roll	(R2A + L3A) or (R2B + L3B)
-Roll	(L1B + R4B) or (L1A + R4A)
+X Translation	F1B + F2A + F3A + F4B
-X Translation	B1A + B2B + B3B + B4A
+Y Translation	R2A + R2B + R4A + R4B
-Y Translation	L1A + L1B + L3A + L3B
+Z Translation	D1A + D1B + D2A + D2B
-Z Translation	U3A + U3B + U4A + U4B

Table H.3: Manned Maneuvering Unit Command Responses

RHC is displaced. Pushing the attitude hold button on the RHC resumes attitude hold about all three axes. Attitude hold uses phase plane logic with deadbands of ± 1.25 degrees in attitude and ± 0.01 degrees/s in attitude rate.

Translational control is purely manual. Displacing the THC causes continuous jet firing until neutralized.

H.4 Mass Properties

The *MMU Operational Data Book* [47] gives performance and summary mass property data for lightweight and heavyweight configurations. The *MMU User's Guide* [113] gives detailed mass property data for a single mediumweight reference configuration including weight, center of mass, moments of inertia, and products of inertia. That reference configuration is summarized in Table H.4. Preflight analysis documentation [66] for Space Shuttle mission STS-41C gives similar data for MMU mass properties at the time of capture of the Solar Maximum satellite, and that data are also presented in Table H.4.

A good summary of MMU design and operation is presented in the Proceedings of the 28th Symposium of the Society of Experimental Test Pilots [133].

Parameter	Reference Configuration	STS-41C Configuration
Weight (*pounds*)	783.1	744.3
c.m. Location (î) (*inches*)	0.22	0.2
c.m. Location (ĵ) (*inches*)	-0.05	0.0
c.m. Location ($\hat{\text{k}}$) (*inches*)	-2.51	0.4
Moment of Inertia (I_{xx}) ($slug * ft^2$)	37.17	41.6
Moment of Inertia (I_{yy}) ($slug * ft^2$)	38.96	42.7
Moment of Inertia (I_{zz}) ($slug * ft^2$)	25.04	24.1
Product of Inertia (I_{xy}) ($slug * ft^2$)	0.06	-0.05
Product of Inertia (I_{xz}) ($slug * ft^2$)	2.69	1.68
Product of Inertia (I_{yz}) ($slug * ft^2$)	0.01	0.03

Table H.4: Manned Maneuvering Unit Mass Properties

Appendix I

Pilot Performance Plots and Model Data

This appendix contains plots of real and simulated pilot performance performing attitude maneuvers. Discussion of the test that generated human pilot data starts on Page 130.

Plots for real and simulated pilot performance using a simulated Space Shuttle deorbit burn using thrust vector control are shown in Figures I.1 through I.14. The runs represent varying levels of control authority by altering thrust and engine gimbal rate. The X-axis is time from the point at which data are available (attitude error within 5 *deg*) and the Y-axis represents the attitude error of the spacecraft in *deg*. The solid lines at ± 1 *deg* of attitude error represent the band of acceptable performance as the pilot attempts to capture and maintain the desired attitude. The dashed red line represents human pilot performance, the solid blue line represents simulated pilot performance. Performance of the human pilot is based on assigned Cooper-Harper rating, performance of the simulated pilot is considered to be acceptable if the spacecraft enters an stays within the tolerance band.

The simulated pilot consists of a time delay, rate command function, and zero rate probability function. The fitted rate command function is a segmented line passing through the following points where the X axis is the attitude error in *deg* and the Y axis is the commanded attitude rate in *deg/s*:

$$X = \begin{bmatrix} -5.0064 & -0.8069 & -0.1740 & 0 & 0.1704 & 0.8069 & 5.0064 \end{bmatrix} \quad \text{(I.1)}$$

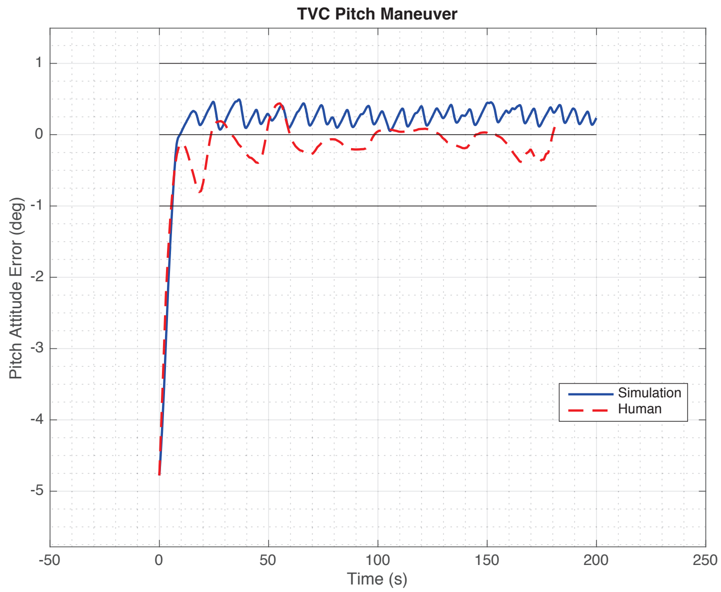

Figure I.1: Space Shuttle TVC Pilot Performance Run 52

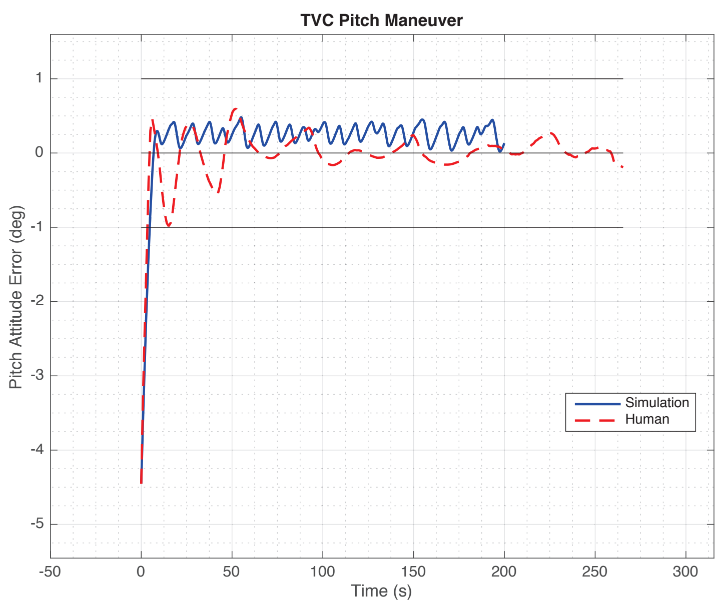

Figure I.2: Space Shuttle TVC Pilot Performance Run 53

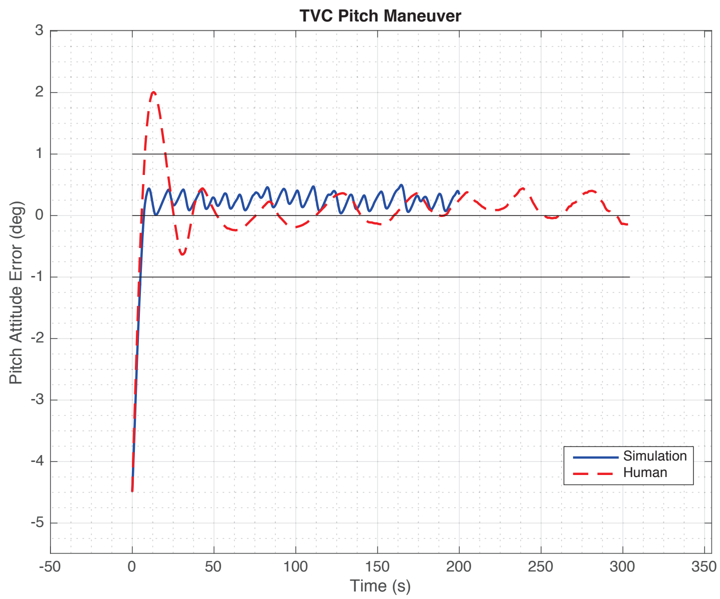

Figure I.3: Space Shuttle TVC Pilot Performance Run 54

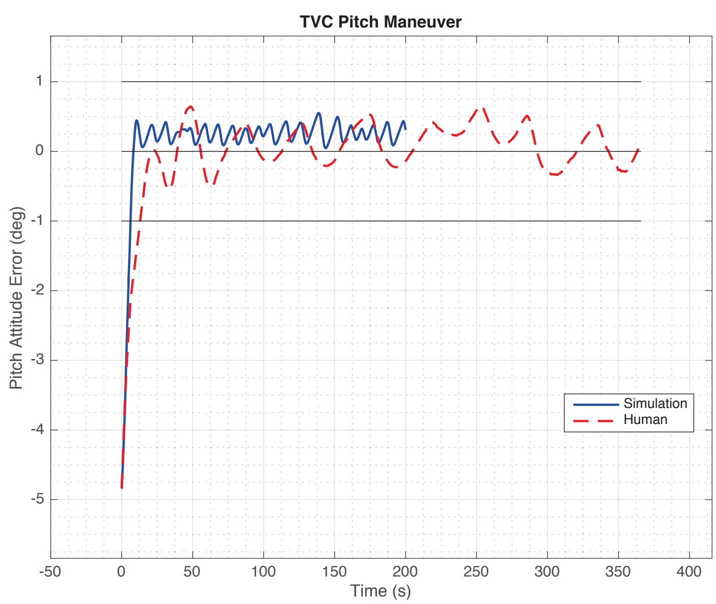

Figure I.4: Space Shuttle TVC Pilot Performance Run 55

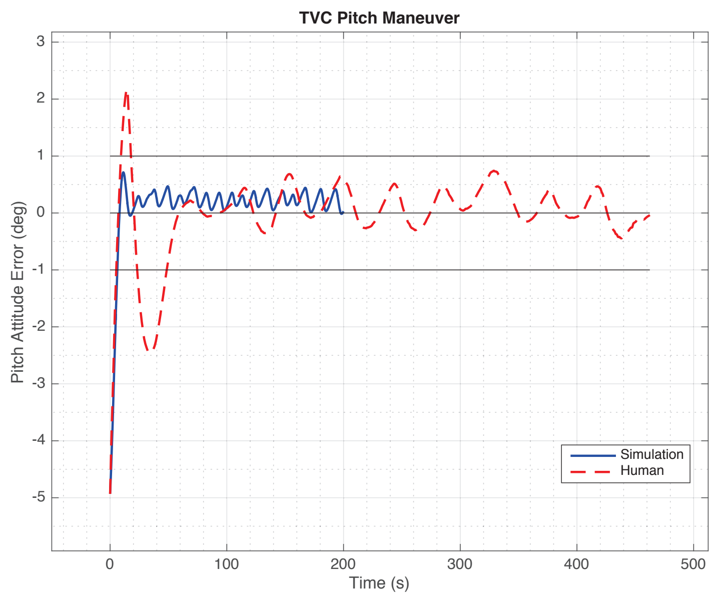

Figure I.5: Space Shuttle TVC Pilot Performance Run 56

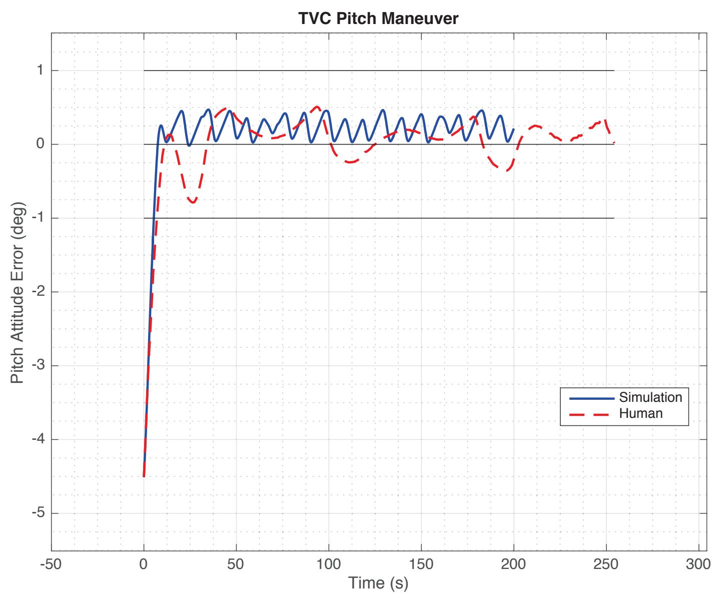

Figure I.6: Space Shuttle TVC Pilot Performance Run 57

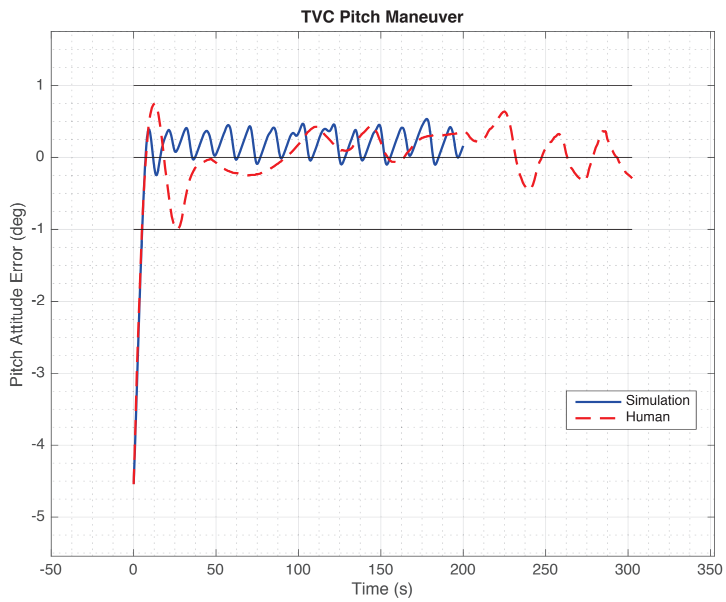

Figure I.7: Space Shuttle TVC Pilot Performance Run 58

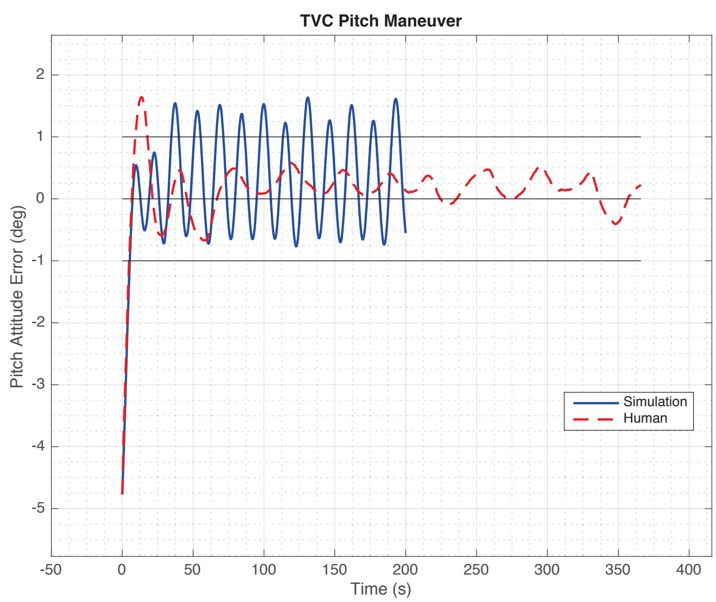

Figure I.8: Space Shuttle TVC Pilot Performance Run 59

243

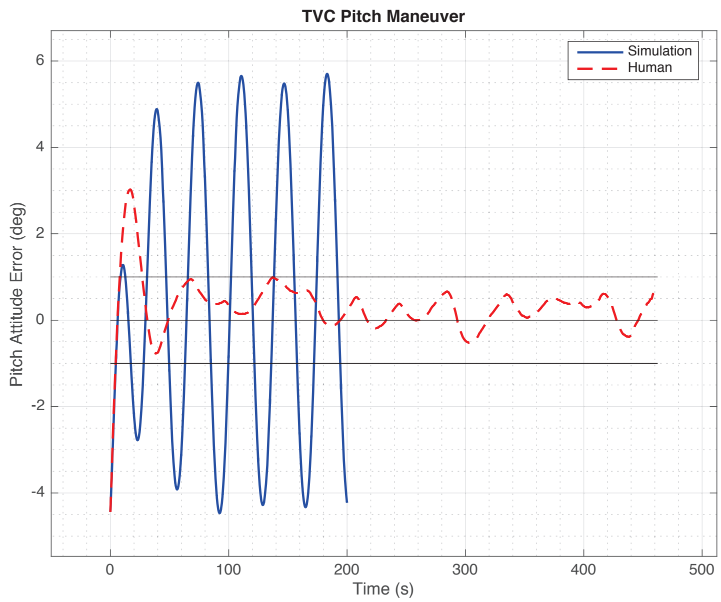

Figure I.9: Space Shuttle TVC Pilot Performance Run 60

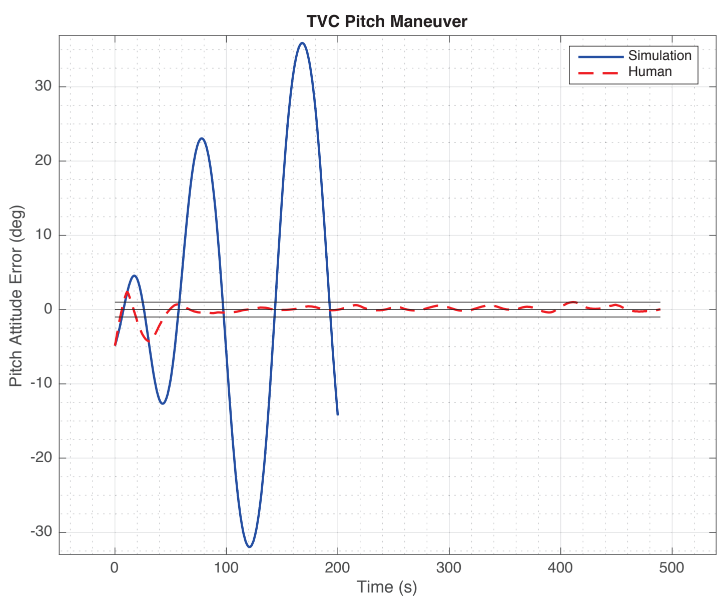

Figure I.10: Space Shuttle TVC Pilot Performance Run 61

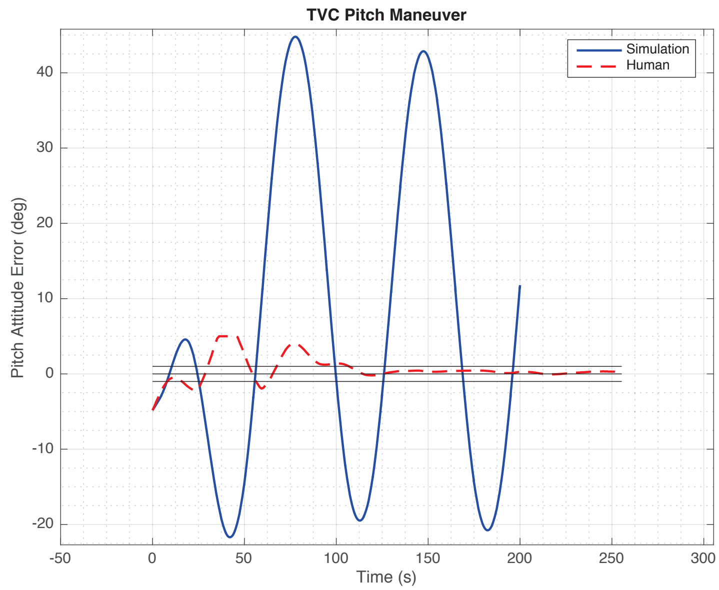

Figure I.11: Space Shuttle TVC Pilot Performance Run 62

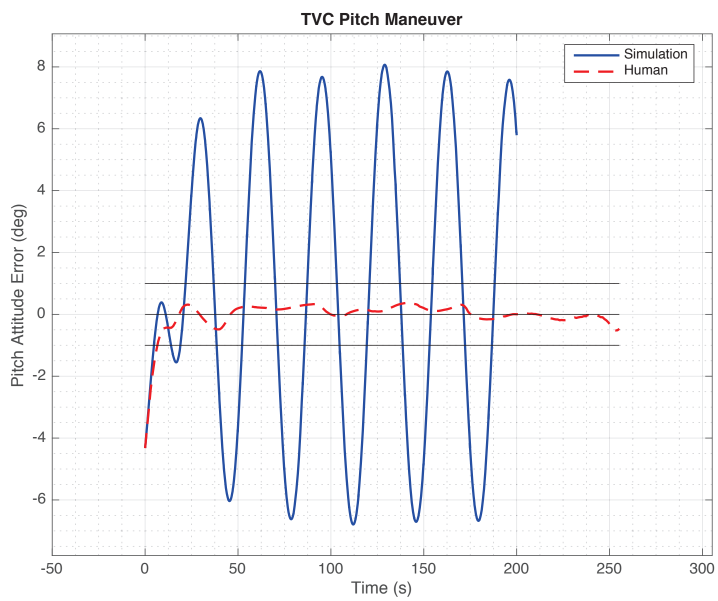

Figure I.12: Space Shuttle TVC Pilot Performance Run 63

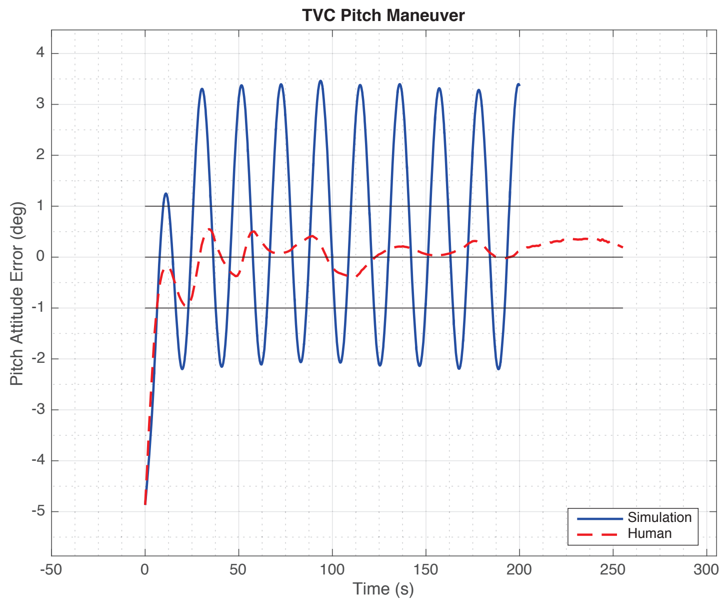

Figure I.13: Space Shuttle TVC Pilot Performance Run 64

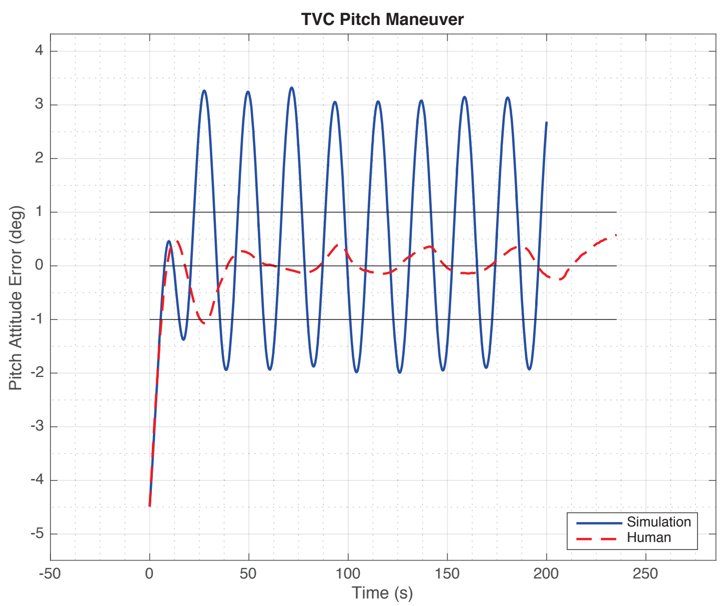

Figure I.14: Space Shuttle TVC Pilot Performance Run 65

$$Y = \begin{bmatrix} -0.8469 & -0.3870 & -0.1786 & 0 & 0.1786 & 0.3870 & 0.8469 \end{bmatrix} \quad (I.2)$$

The zero rate probability function describes the probability of commanding a zero attitude rate (overriding the primary rate command function) as a function of attitude error near to desired attitude. The X coordinates are the attitude error in degrees and the Y coordinates are the probability of commanding zero rate.

$$X = \begin{bmatrix} -1.0 \\ -0.8 \\ -0.7 \\ -0.6 \\ -0.5 \\ -0.4 \\ -0.3 \\ -0.2 \\ -0.1 \\ 0.0 \\ 0.1 \\ 0.2 \\ 0.3 \\ 0.4 \\ 0.5 \\ 1.0 \end{bmatrix}^T \quad (I.3)$$

$$Y = \begin{bmatrix} 0.0 \\ 0.045 \\ 0.08 \\ 0.194 \\ 0.358 \\ 0.427 \\ 0.624 \\ 0.870 \\ 0.973 \\ 0.990 \\ 0.979 \\ 0.865 \\ 0.642 \\ 0.347 \\ 0.267 \\ 0.0 \end{bmatrix}^T \tag{I.4}$$

Appendix J

Historic Crew Debriefing Comments

This appendix contains excerpts from historic crew debriefings, focusing on comments made regarding handling qualities.

J.1 Mercury

J.1.1 Mercury-Redstone 3 (MR-3)

These post-flight debrifing excerpts are from an internal NASA memorandum[128] published after the mission.

Q: Let's get to the reaction control system now. Do you have any comments on this system in addition to those you've already made?

A: Well, let's see. I discussed, I think, the fact that, on occasion, I was aware of the noise of the jets primarily when the high-thrust jets were working. On other occasions, I wasn't aware of it at all and I noticed the reaction of the capsule by the visual cue of the scope or from the instruments. This indicates to me that if you're in a high-thrust level, you can hear it inside and if you're in a low-thrust level, you can't. This internal noise is just about the same at your ears as the other external noise. I didn't have any problem at all with the stick forces. There was plenty of adrenalin working and any time I wanted to move the stick, even though I was obviously bumping into the parachute with the right hand, I didn't have any trouble. I didn't always move it in the right direction but any time I wanted to move it, it moved fine.

Q: I guess this question is more applicable to an orbital mission where you're worried about an hour and a half rather than a couple of minutes.

A: I do comment about the microswitches. I think, particularly down at the Cape, they're aware of what problems we have with respect to ringing in the microswitches of the fly-by-wire and friction of manual system. I was going to try to work the control handle on the way out, to find out whether or not varying load factors had anything to do with friction in the system, but unfortunately I didn't. This first time I tried it at zero-g it was free with no additional friction that I could notice. Here again, because of the microswitches, I had a tendency to overcontrol on fly-by-wire. Manual, I didn't seem to have much trouble. I didn't always control the right way but when I did what I wanted to do, I didn't have any trouble doing it.

Q: Did you notice overshooting, then, when you were on fly-by-wire? The point that Chambers is making is that if you were on both manual and fly-by-wire you should not have overshoot.

A: Well, I wouldn't say this was true because when you displace the control stick from center, you don't always get the low thrust (the one or six pound thrusters) but sometimes you get the high and before you want it. Whether or not I was in manual and fly-by-wire simultaneously, I still got more rate than I wanted and I think this is primarily a function of microswitch position rather than the addition of manual proportional.

Q: I understood the switches were not set up according to design.

A: They were set up the best they could do and we decided to take it was it was.

Q: Do you think your difficulty was due to the an incorrect setting of these switches or do you think it's just the basic system of having a low thrust and then a much higher thrust?

A: I think it's probably the basic system, but I think it's something we shouldn't change around now since my complaint is a low order complaint. I'd much prefer to use it as a backup system for the manual control using the automatic jets than I would to cross-connect the manual and the automatic, for example. So this is a low order notation and I think we ought to try and get the microswitches as close to specs as we can and just accept it that way.

Q: One other thing along the same line. You, of course, had quite a bit more experience training with manual proportional than with the fly-by-wire control system. How much of this difference of ease of control do you think could have been made up through more equal training on the two?

A: Well, it might be better if you tried a little more fly-by-wire. You could be better prepared.

Q: What I'm really trying to find out here is for future planning. As far as ease of the man using a control system, would you say it was easier to use a proportional system than the fly-by-wire system, or does the fact that you do better on the proportional system stem mainly from the amount of practice you've had with it?

A: Well, you've got to describe the requirement first. If you're talking about maintaining an attitude using small rates, then the manual is easier, and practice on the fly-by-wire would be a prerequisite here. If you're talking about preparing for reentry and holding position during retro when you're calling for the much larger stick deflections and rates, then it doesn't make a bit of difference I don't think. Because you're pulsing the stick, (at least I am) to make care of a rate and the fact that you're getting full manual or full automatic thrust as a result of the high-thrust microswitches being depressed wouldn't make any difference. I think it would be more profitable to practice using fly-by-wire for retrofire control although I didn't use fly-by-wire for controlling retros since there isn't much difference when you're calling for large rates. And so you don't notice the difference as much in this situation as you do when you have to have fine control.

J.1.2 Mercury-Redstone 4 (MR-4)

These post-flight debrifing excerpts are from an internal NASA memorandum[129] published after the mission.

Q: Describe the capsule response to the manual control system operation, automatic control system operation, and rate command control system operation during the mission (manual control system operation).

A: Well, I felt that response was rather sluggish. I had difficulty getting the rates that I wanted. As I tried to get a pitch-up rate of 4 deg/sec it seems that it took longer than it should have and when I did get to 4 deg/sec I overshot. I tried to bring it back and get it pinned down to 4 deg/sec exactly and I went beyond it again down to less than 4 deg/sec. Then I decided that the pitch axis was working so I'd better get back to retroattitude and try yaw. At the same timme I was having trouble getting roll to zero. My roll rate from the turnaround wanted to hang in. Yaw appeared a little bit sluggish to me also and I'm not sure what rates I got in yaw. I don't think I got up to 4 deg/sec in yaw. After I came back to something that approximated zero yaw attitude, I skipped the roll check and started my 45 degree left yaw maneuver. Here again it seemed like it took a very long time to get over to about 45 degrees. I checked the yaw indicator to make sure that I was over near 45 degrees. Then Al (Sheppard) gave me my mark at 4 min and 30 sec and it seemed to take an extremely long time to get back to my retroattitude.

[...]

Q: Rate command control system operation.

A: The rate command control system seemed to work better to me than the manual system. This sort of surprised me because I usually do much better in the trainers with manual control than I do with rate command. But the rates did damp out pretty well to within the limits that the system was designed to work, around 2 to 3 deg/sec. I had no trouble holding the reentry attitude pitch and zero yaw. I thought the rate command system functioned better than the manual proportional system.

J.1.3 Mercury-Atlas 6 (MA-6)

[Narrative Account]

I could control on fly-by-wire and manual very adequately. It was not difficult at all. Fly-by-wire was by far the most accurate means of control, even though I didn't have accurate control in yaw at all times.

[...]

Q: Did the ASCS sequence properly and did it hold the correct attitude (rate damping, turnaround, etc.)?

A:

[...]

The fly-by-wire system is excellent. That's one that really gives you fine control. On fly-by-wire you can control right to zero rates with no problem at all. I liked it very much. The manual system was not quite as good as on the procedures trainer. It felt mushy. I think this had been predicted from the tests that were run on capsule 15. On manual, I didn't feel I had as accurate control as I did with fly-by-wire. The low thrust fly-by-wire is excellent for very accurate control when it works. Yaw was the only dimension that had any problem. There was never any problem on fly-by-wire in roll or pitch.

Q: Could you feel angular accelerations during capsule motions?

Only at the higher rates. If you get up to a rate of about 5 degrees per second, you are usually accelerating rapidly enough in achieving that rate that you can feel the acceleration. Most of your rates, of course, are much lower than that, down around zero to 2 degrees per second. Thus, during most of your maneuvering you just don't feel much in the way of acceleration and deceleration when you start and stop.

Q: What control mode was used during reentry? Comment on effectiveness.

I went to manual control after retrofire because I set my roll rate in at about the time we had reached a quarter or a half g. The early part of the damping was okay. I. didn't feel that I had all the authority that I wanted when the oscillations started building up and I went to fly-by-wire in addition to the manual. I don't think this was until after .05g. I'd like to reserve comment on that until we look back to the record because I'm not real positive where I went to fly-by-wire in addition to manual.

[...later...]

In orbit my drift rates varied from just barely perceptible movement to about 5 degrees per second. The most rapid rate occured in yaw. I probably had around 5 degrees in each axis at some time. Most of the rates, however, were kept down to 0.5 deg/s to 1 deg/s. To get low rates on manual proportional, you just bang it. For low rates it essentially winds up as an on-off fly-by-wire system. The most accurate control was on the low thrust fly-by-wire. It really puts the capsule where you want it.

[...]

Controlling to a certain attitude was no problem at all, I had active control, I could stop it where I wanted, could control it more then one axis at a time. I could run the gyros right up to the stops where you reach the limit of that particular attitude indication and play with it right on the edge of the stop, without losing accurate control.

[...]

I didn't really control on RSCS. I had planned to control some, using it later in the flight, but I didn't because I was busy with the ASCS or the manual all the time. During the controls check, I checked the RSCS by letting it damp, but I didn't actually go ahead and control on RSCS. This is a check to see if the dampening functioner is working all right.

[...]

When the fly-by-wire one-pound thruster was not actuating in yaw, I was using a real fast flip of the high thruster in the mode that the one-pound thruster was not operating to control. I couldn't control this as accurately as you can with the one-pound thruster, not nearly as well, so what I did several times was when I would overshoot in rate with the 24-pounder, I would use my one-pounder on the other side to bring it back into zero and stop right on zero. I think you can control within a half degree per second with the 24-pound thrusters and this is probably pretty close control. I wouldn't call this desirable. Those one-pound thrusters are the best ones for control in orbit. You can control right on the money with those.

Q: Describe the capsule response to manual control system operation, automatic control system, and rate command system operation during the mission.

A: We didn't use rate command at any time. John Conlon predicted it would be a springy. The manual control system was not as crisp and sharp in flight as it was in the trainer, as John Conlon predicted. It was more of a mushy, inaccurate type system. I would up using it either on or off with fast blips to try and control the action of the capsule rather than going to intermediate settings, and trying to get capsule control that way.

The fly-by-wire system and the automatic system worked just as I expected. It was just like the trainer. I found no differnces in fly-by-wire reactions from what the trainer simulation gives us.

Q: If any maneuvers were made in 2 or 3 axes simultaneously, how did attitude display compare to the display on the procedures trainer, procedures trainer two, the centrifuge indicator mockup capsule, ALFA trainer?

A: Very similar.

Refering again to the 2 or 3 axis control. I don't think we intend to do a lot of three axis control, particularly in orbit where you're trying to control the same three precisely. Even with the little one-pound thrusters, I think I can almost exclusively control one axis very accurately then another axis and control it accurately. There were times when I didn't control all the axes but it was only when we were doing rougher-type maneuvers, or recovery from maybe a capsule dropping into orientation mode, something of that nature.

Q: What flight control procedures should be improved and in what way?

Well, I particularly like the way the fly-by-wire system worked. I was able to control the capsule accurately with it.

J.1.4 Mercury-Atlas 7 (MA-7)

Q: Comment on the quality of the manual control system for each control mode used.

A: For maneuvering in orbit, there is no need for the 24-pounders. I feel that they should be wired out in orbit. All the control systems worked perfectly throughout the flight. The manual proportional was very smooth and I still prefer it. Manual proportional is exactly what you want. If you touch the controller very gently, you get the rate you want and you can vary it gradually. With the fly-by-wire low thrusters you get very imperceptible needle movements and you must wait to pick up the desired rate. Once you know the low thruster is operating you hold the stick in position until you have got the desired rate. If you want as much as three degrees per second, it requires either a long wait on the low thrusters or use of the high thrusters. On manual you can get three degrees per second in just about the time you need it. To my mind, manual proportional was very good. I used rate command once, possibly two or three times, and was not aware of the 'boot' you get in yaw right, pitchdown, and roll right. As far as I am concerned, the 'boot' was not present. The 'boot' is supposed to make you overcontrol, but I think that this little gas pocket disappeared in flight because there was no tendency to overcontrol. Rate command is a good mode for re-entry or for retrofire but is no good in orbit. You do not need that type of control. I much prefer the manual system. For normal maneuvers, fly-by-wire low thrusters are the best system. For a tracking task, it would be best to have manual proportional. The fly-by-wire high thrusters, the rate command, and auxiliary damping systems are not needed in orbit as far as I'm concerned. I was very pleased by the performance of all the manual control systems. They were effective. There was no backlash; slop was not noticeable, no binding or lag. The rates produced by the low fly-by-wire thrusters are so imperceptible that you can go past low and not know that you have activated them, particularly if you are doing something else, such as talking, at the same time. I think we need another stick for fly-by-wire low. Then there would be no danger of overshooting and using the high torque thrusters. I did this a number of times. I overshot and activated the high thrusters because it's a natural thing for me to do. If, for instance, you want to roll left; you move the stick to left. If the rates are not exactly what you want, the natural tendency is to increase the displacement of stick, as you do in an airplane. Soon you overshoot and activate a high torque thruster and then you have too much thrust. I would like to get rid of the high torque thrusters when maneuvering in orbit. Another problem is that you do not really get a chance to get a good feel of the control system on the ground, because you can't operate the valves dry. It would be good to be able to tell by feel when the thrusters are ready to come on. A pencil stick would be very good for this. When you get to the stop on each side you've got fly-by-wire low thrusters. I think that would be good.

Q: Comment on the following maneuvers: Sustainer Tracking, ASCS Zero Pitch, 180 degree Yaw, 180 degree Roll, Forward Inverted Flight, Drifting Flight, 720 degree Roll (for radar test).

A: Sustainer Tracking: With the low relative motion between the sustainer and the spacecraft, fly-by-wire low torque thrusters worked very well. I did not track very long, but I stayed on the stick and kept the sustainer right in the open center plus mark. I convinced myself that it is quite an easy task to line up a point on the window with the sustainer and track it. I did not track very long because I also wanted to get some pictures of the sustainer at this time. Tracking and picture taking are not compatible. Tracking is only a function of the components of the control system. With one to four pounds of thrust you could get proportional control down to low levels. If you want tracking, I feel this would be ideal.

ASCS Zero Pitch: I do not think that I ever held ASCS zero pitch. I doubt that this wouId be any different than ASCS in any other pitch attitude. You are without any reference to the horizon and this is alright unless you have cause to doubt your attitude indicators. You must cross-check your rates in the periscope. The zero pitch mark on the periscope horizon line is very valuable for gyro alignment. I used it a great deal.

180 degree yaw: This is no problem. I used varying rates in performing this maneuver without any difficulty. However, it is easy to confuse yourself when you have rates in more than one axis at a time. This produces a coupling effect and you don't get a lot of good out of the window, I did not, at least.

180 degree Roll: I think the only thing that I can say about this maneuver is that you do get pure roll without coupling. Rates in the other axes stay roughly at zero. I cannot remember doing a complete roll. I was supposed to do two over White Sands. I was talking to the Guaymas Cap Com then. I called and said something about "Give me a mark on the White Sends radar test," and it seems that he said, "Begin six-degree roll rate now." At that time I was not in the right attitude and my gyros were caged. Had I performed the radar test it would have yielded meaningless readings, since I wasn't rolling around the correct yaw axis. I told Guaymas Cap Com to wait until I got in attitude. I realized that I couldn't make it in time. I do not feel I can give a good story on 180 degree roll, although I do remember noticing that pure roll stayed pure roll. It did not couple into pitch or yaw.

Forward inverted flight: This is beautiful. That is the way to fly. It is nice to have the horizon ahead of you in view, or to be looking straight down. I think you can pick out your nadir point very easily without reference to the horizon. You can, whether you are looking straight down or off at an angle. I do not know how you do it, but I felt that I could tell whether I was looking straight down or ten or twenty degrees off to the side.

Drifting flight: This is a thrill, a tremendous thrill, except it is not much fun when you don't have any rates, because you see the same things all the time. If you pick up a rate on any axis and watch the world go by, you have a moving picture up there. You see something new all the time. Everything, of course, is brand new. You can't beat it. It is wonderful. Drifting flight is really the most fun.

720 degree roll: I have commented on the 720 degree roll from radar. I didn't do it. It certainly would be no problem.

J.1.5 Mercury-Atlas 8 (MA-8)

[Pilot's Self Debriefing]

[Orbital Flight]

At SECO (Sustainer Engine Cut-Off) the capsule lighting did not seem to help very much. The lights themselves were somewhat dim, and I knew the events better by the feel and sound than I did by the effect of the light itself drawing my eye to it. I immediately selected Aux Damp and knowing from my previous training that there was no rush, I selected Fly-By-Wire Low, then came back and placed the Mode Select Switch in Fly-By-Wire and commenced turnaround. I resisted every impulse to look out of the window at this point, as I wanted to make the turnaround a fuel-minimum turnaround. The turnaround obviously in that case was done on the gyros, I discussed the turnaround as I was performing it and got exactly what I wanted – approximately four degrees per second left yaw and had no trouble with any of the low thrusters at this time or ever after. I believe I got into retro attitude at about six minutes and 50 - 55 seconds. By this I mean in retro attitude to where I could have accepted retrofire if I needed it.

[...]

At about 10 plus 30 I went to Fly-By-Wire Low, again, and tracked the sustainer as it traversed down through the window, and it was a thrill to realize the delicate touch that you could have with Fly-By-Wire Low. This delicate touch is an art that a pilot hopes to acquire in air-to-air gunnery to get some hits. In this case the control system was so sweet that it just amounted to a light touch and a few licks in either axis to get the response you wanted. I could point the spacecraft at anything I wanted to. I did feel while looking at the sustainer that, "Yes," I could see it, that I could track it, but I did not feel that the two relative motion problems would be so easy to solve that I could blithely say, "Yes," I could steam along and join up with him.

[...]

At Canaries, the flight itself had settled into a very normal pattern. I was content with the autopilot function. Having pitched up with Manual Proportional, I was content that the system was exactly as I felt it would be. The Manual Proportional system that we have simulated in the Procedures Trainer at the Cape now is almost identical to what I experienced in flight. I don't think I could judge one thing different than the other, meaning that MR-4's description of the Manual Proportional system was very accurate. The greatest effect I did notice was the tail-off rather than the response to control input. As a result, you have a tendency overshoot, and you can't park the spacecraft in the attitude you want it in without having to counteract and then recounteract a tail-off. As a result of this evaluation for almost every case where I went from Manual Proportional back to Automatic mode, I switched to Fly-By-Wire Low to kill these small rates down to where I could transition to Automatic mode without going into orientation high thrusters. And to my knowledge, except for two goofs which I will discuss later I did not get high thrusters.

[...]

It was rather fun as I said not to worry about fuel usage. And I feel in my mind, that the Manual Proportional is not necessary as a control system requirement since it definitely did not give me what I wanted, and I feel that I would like to fly next time with two fly-by-wire systems. We've put that to bed.

[Reentry]

Then I set up Rate Command to give it a small check. It responded very well. I was satisfied that the system was working and was so satisfied that I even came up with a requirement that was way out in left field as far as remembering it and as far as importance is concerned – but I did zap off a blood pressure. This is how content I felt at this time.

[Flight Operations Debriefing]

Q: Comment on the turnaround maneuver procedures.

A: The turnaround was accomplished strictly on instruments. As soon as

I felt spacecraft separation, I selected Aux Damp, went down to the fly-by-wire low select switch, then came back up to the fly-by-wire control mode select switch. I did not race through the turnaround maneuver. I dialed in 4 degrees per second yaw just as exactly as if I were sitting in that Procedures Trainer. It was just as simple as that. I had to play with roll and pitch coupling just as I would have done on the trainer. Each axis responded immediately. There was no delay in light off. I would say the thrusters were on the line just as if they were simulated by an electronic computer. There was no difference whatsoever.

Q: Describe the sustainer tracking procedures you used.

A: [...] Then I went into the tracking. The fly-by-wire low is easier to track with than any airplane I had ever flown for an air-to-air gunnery problem. I think that's the best way to describe it. I got immediate responses and cutoffs, which was the other thing. There was no residual thrust from minute, little, tiny blips, and that's what they were, just "barely think" shots rather than using large stick deflections even though I knew I wouldn't get anything but fly-by-wire low. I'd say these were minute pops on any one thruster or any one axis. And there was no problem at all to hold it there, and while tracking it the rates, that I described for the sustainer, were exactly the same. There weren't any that should have caused it to wind up, I know.

Q: Comment on ASCS flight.

A: At no time did I ever feel that the ASCS was not acting as predicted. I did not detect the low thruster pulses to maintain ASCS attitude be it reentry or retroattitude. The rates were so minute in correcting that they were barely visible. They were on the order of 1 degree per second, which is about what I would accept as my sloppy controlling on fly-by-wire low. They were much lesser orders of magnitude as far as rates, and I'm convinced on numbers of occasions I saw as much as 10 degrees off nominal attitude, yet there was no case of going out seeking orientation mode. It came back in again. I saw it, and I think the best way to check this, of course, is on the attitude readouts onboard. I did comment on it a couple of times. I think I saw it in left roll once or twice. The others, in pitch and yaw, they were fairly tight far as being within 5 degrees or so.

Q: Comment on manual (proportional) control.

A: The Procedures Trainer at the Cape right now is identical to what I saw in flight. If anybody wants to find out what manual control is like, at least for what I had, that was it. Every time I used manual and was coming back to ASCS mode, be it reentry or retroattitude, I was not satisfied with my control fineness. I would go off manual into fly-by-wire low to polish it up and then plunk in. That will give you an example of what I thought of it. When I came back up to retroattitude on the first attempt using manual proportional - this is coming off the sustainer, I guess I had a fetish on the fuel which was kind of obvious from how much I had left, I guess - when I came back to retroattitude that first time, I said, “Baloney,” and went to fly-by-wire low and dropped into ASCS. I just didn’t want to throw in the high thrusters to get back into orbit mode.

Q: Comment on fly-by-wire control.

I think I’ve talked so glowingly about it there is no reason to talk any more about it.

Q: Were you adequately trained in spacecraft maneuvering?

A: Once in orbit there is very little training required, for orbit mode motions, this is meaning low thruster action. The system is that easy; I think anyone in this room could handle the fly-by-wire low, no problem. And that’s the way a control system should be designed.

J.2 Gemini

J.2.1 Gemini Titan-3 (GT-3)

Q: Describe and comment on the control system performance.

Grissom: [...] Rate command rates were almost deadbeat.

[...]

The only thing that was surprising, and wasn’t as I expected it, was the reentry rate command. Those dead bands were something tremendous. They were on the order of plus or minus 5 or 6 deg/sec. I was glad we had already made up our minds to fly in direct, because those dead bands were just too big. It would have been difficult to control.

Young: I thought pulse mode was just beautiful. It did just exactly what I expected it to. It did what it did on the simulator. There was a little drift, but there is going to be a little drift in a system that is not damped about any axis. I was pleased. Rate command was dead beat. It was just right on the money. When you let go after putting in a full rate command of 10 deg/sec, it just stopped it right now. You couldn’t ask for any better control system.

Grissom: I prefer to fly in pulse mode.

Young: Yes, it's easiest. It uses less fuel.

Q: With respect to the 1:33 OAMS translation, describe and comment on the following: [...] The attitude control mode used.

Grissom: We used rate command. I had no difficult controlling the attitudes. It was just as I had expected. The alignment of the thrusters with the CG was just about as I had expected. I got a very slight pitchdown, and had to continually pitch up to hold my attitudes.

Q: With respect to the 2:20 translation system check, describe and comment on the following items: b.The visual appearance of the forward-firing thruster plume

[...]

Grissom: I used the direct system to control attitudes and had no problem. The attitudes, displays, and IVI's all worked like we expected. No problems.

Q: Comment on the operation of the pulse mode during the tracking task.

Grissom: The pulse mode isn't adequate for the tracking task. I was moving along too fast and the pulse mode can't keep up. Maybe, if I could have gotten a target in mind early, I might have been able to do it with the pulse mode. We didn't have very good visibility and I had difficulty picking up a target. By the time I did, it was almost underneath me. At this time the pulse mode wouldn't begin to keep up with it, so I used direct and controlled to within a few degrees of the target. You can't see the pipper on the target on the bright earth, so it is difficult to tell. The pipper was really faint.

Q: Did the performance of the various control modes compare with what you expected as a result of training on the various simulators?

Grissom: Other than the reentry rate command, the control modes compared almost exactly with what we saw on the trainer.

Q: What was the control mode selected for retrofire? Backup?

Grissom: Rate command, both rings used for retrofire. It held us absolutely tight. We didn't deviate 1 degree from the center of that 8-ball.

Q: What control modes were used during the reentry?

Grissom: I used direct, both rings after retrofire. I just wanted to make sure both of them were working. I went to pulse for about 1 minute. I didn't know when this thing was going to start reentering, so I went to the mode I was going to use for reentry. I went to direct both rings and stayed there.

Q: Comment on the performance of each selected control mode.

Grissom: The selected control mode was perfect for reentry. No problem. I think it will be far superior to reentry rate command. I guess you could fly inside that 4 degree deadband. Direct was very good. I had no problem damping out the rates. John had the rates on his FDI needles, and I could see on the ball the displacements we were getting, so I didn't worry very much about them, unless John said the rates were getting high. Then, I would look over and damp them out. I could damp them out in about one or two actuations of the control handle.

Q: Describe the spacecraft oscillations during reentry. Maximum rate and amplitude.

Grissom: The oscillations during reentry were not bad.

Young: I was on the low scale on the FDI.

Grissom: The rates never got up more than 4 deg/sec and probably not more than 2 deg/sec. Just one or two blips of the control, and they would dampen out.

Young: And they did just like the book says they will do - going up the g-curve, the frequency would build up and the amplitude damped down. Coming down the back side, they built up a little, but nothing significant, and definitely no instability that I could see.

Grissom: The maximum rate was never more than 4 deg/sec.

Young: I don't think it was that high.

Grissom: Well, those needles got about half scale at one time, but the amplitude was never very great. I looked on the ball, and it wasn't varying very much at all.

Q: Comment on the computer display of down- and cross-range errors on the FDI during reentry. When and how did you verify that the closed loop guidance was operating properly?

Grissom: Okay. I'll go through the whole thing here. After retrofire, I rolIed to inverted attitude - max lift attitude - and at about 4 minutes after retrofire time, I got a command from my roll needle directing me to roll inverted. That was at about 400 k - just about one time. It started working, and at 6 minutes after retrofire, I rolled to my 45 degree bank angle. It was just shortly after that, I got guidance on my needles. The crossrange needle was all the way to the right. The downrange needle was about half-scale, and it moved up slightly, and then came back down a little bit. I think maybe it made one more oscillation, and then hardly moved after that. The crossrange needle came right on in. My time to reverse bank angle was 11 minutes after retrofire, and at 10 minutes 15 or 30 seconds, the crossrange needle was centered. So, I started taking out the bank and holding max lift. I held max lift the rest of the way in. The downrange needle never centered.

It came down a little bit to what looked like 50 to 60 miles short.

Q: Describe and comment on the procedures you used to control the attitude of the spacecraft from retrofire initiation through reentry.

Grissom: I used direct, both rings. I used the ball as prime reference, but cross-checked out the window. I had no problems with control.

Q: Describe and comment on the reentry technique you used. What would you recommend for future missions?

Grissom: I have already described the technique used.

Young: I recommend two-rings direct.

Grissom: You could do it alright on one-ring direct. I don't think it would be any problem. With two-rings direct, you tend to over-control a little bit, until you get the feel of it.

Young: If you got downrange steering where you had to roll around in a hurry, this would be a problem.

Grissom: Yes, you need it in case you have to roll and stop your roll. You need all the authority in there that you have to get the rates you want and then stop them. I recommend two-rings direct in future missions.

[Self Debriefing: Grissom]

The control mode check worked out fine. I could find nothing wrong with the direct control at all. Spacecraft control in direct was easy. Reentry rate command didn't perform like it had on the Gemini mission simulator. It appeared that the deadband was very wide, on the order or 5 or 6 degrees in pitch and yaw. I don't recall what the deadband was in roll. They may be on the onboard tape.

[...]

There's sure a big difference between using one ring of RCS, which I've done before on several occasions, than using two rings. There's a great deal more authority on two rings which you can definitely feel. Two rings give the spacecraft a sharp kick, whereas, one ring gives you a nice, soft shove. It's easier to control on one ring if you're not doing a retrofire, because using two rings you tend to over control.

[...]

I had no difficulty controlling attitudes during reentry. [...] I was using direct with both rings.

J.2.2 Gemini Titan-4 (GT-4)

I remember commenting at that time that the RCS was a lot looser in control than the OAMS. It seemed to me that the OAMS held the spacecraft attitude better. It seemed like it controlled to a rate deadband that was smaller than the RCS deadband. I don't know why you're the same gyros and the same electronics. The only that could be different would be the attitude drivers on the RCS might be activating slower than they are in the OAMS. It seemed like the rates were such a – seems like there must be a lag in the whole system. It seems like the deadband in the RCS was twice what it was in the OAMS. It operated properly. There's so much difference between looking at that ball on firing retros and looking out and actually seeing the nose of the spacecraft moving around out there. There's no comparison with the simulator. You just can't simulate this. When I looked down at the ball and did the retrofire, it was just like the simulator. When I was looking outside and actually seeing what the spacecraft was doing as I controlled it, it seemed like it was a lot sloppier with the RCS than it was with the OAMS.

[...]

I was at zero rates and in the proper attitude. I was in Rate Command when the retrorockets fired. I maintained the attitude very well. It was very easy. There were no deviations at all.

[...]

White: On thing – on the Post-retro Checklist, we decided this time to use Reentry Rate Command rather than Direct.

McDivitt: That's right.

White: That's a deviation on our checklist.

McDivitt: When I got the thing upside down, I was still in Rate Command. I held the lift vector up, head down, until I got down to about 3 minutes and 15 seconds. I got my 3 minute time hack from the ground. I got my clock counting up a 3 minutes. At about 3 minutes and 15 seconds I started the roll. What I did was, I put in about 15 deg/sec, and then we turned off the roll gyro. I just left the thing rolling. I controlled the pitch and yaw inside the rate deadband, which was plus or minus 4 degrees (per second?), just as you would in Direct. I still had the rate deadband to take care of any wild perturbations that we got into.

[...]

McDivitt: And we were going around at a pretty good rate. The needle was off to the left. That's right. It moved out slowly, slowly and got out to about 2 degrees and it just held there. The spacecraft was as stable as rock. I damped the thing a couple of times in pitch and yaw and it just stabilized right on down there. I don't think I even touched the pitch again. I think I maybe touched the pitch four times all the way down and yaw maybe six or seven times.

[...]

McDivitt: Spacecraft control was like a dream. A good engineering description. There weren't any oscillations. It was as stable as a rock. I don't think we need to say much more about that. It wasn't like any failure simulation we've seen. It was the easiest thing to control, easier than any simulation I've seen. Shoot! A baby could have done it.

We started getting oscillations around then and the Reentry Rate Command fired a few times and I damped it in pitch and yaw. There really wasn't any control problem to it at all, I didn't feel.

[...]

White: I think the controls and the switches were all satisfactory.

McDivitt: I think so too. The attitude controller worked fine and dandy. We didn't have any trouble with it. The stick forces weren't too high. We didn't get a chance to use it in any other mode besides Pulse. It seemed to work all right in Pulse. I don't really have any comments to make on the attitude controller.

White: As a matter of fact, I didn't use any rate command.

McDivitt: Didn't you really?

White: We didn't use the Rate Command. I got to use Direct a couple of times. I used Pulse a lot. Everytime you'd go to sleep I'd really have a ball!

McDivitt: I could tell by the wiggling.

White: No. That was really great – flying that spacecraft.

McDivitt: That's right, and I think Pulse is the mode. You can do a lot with it. With a little bit of planning you could get to the aittude – if you start out 5 or 6 minutes ahead of time. That's what we were doing. At 10 minutes before I supposed to be at a certain attitude I'd start, and one or two little pulses and you'd – boop, boop, boop, boop –. The bad thing was if you were in an attitude where you couldn't see the horizon and didn't know where you were. You would give it a couple of pulses and nothing would happen, and you'd have to give it a couple of more pulses. It'd take a long time sometimes before you would get to where you could see. As a matter of fact, if at 5 minutes before we were supposed to be at a certain attitude we weren't approaching it, I'd start pulsing a little harder.

White: You'd hear a series of about five quick pulses.

McDivitt: It was a very economical control mode. The maneuver controller worked the way it was supposed to.

White: What about the deadband? Did you think the deadbands and breakouts were all satisfactory?

McDivitt: Yes, just like the one we used in the simulator. You've got a lot of slop in it when you're making gross maneuvers because you're not fixing your elbow and manipulating around that point. You're fixing your shoulder and your whole arm, and it's just like shoveling coal – you've got about that much finesse to it. I don't think there's much you can say about it. The controls weren't too gross and they weren't too minor. The whole thing was adequate.

[...]

McDivitt: As for the attitude control modes – I mentioned the rate command in OAMS seemed to be tighter than the Rate Command in RCS, although they use the same electronics, the same gyros, and the whole thing. It might have just been my imagination, but I felt that the Rate Command system in RCS was a lot looser than it was in OAMS. The Reentry Rate Command operated just the way it should. It had a 4 degree deadband, and handled the spacecraft very well during reentry. Direct had a lot more authority than I thought it would, but it was pretty straightforward. I think Pulse was the best mode on the spacecraft for the orbit phase. We were able to save all kinds of fuel, it worked fine, and it was just about what the doctor ordered. We didn't use the Horizon Scan Mode during about the first 3 days of flight, except for the second orbit when I think I was in Horizon Scan so that I could have the freedom to help Ed prepare for his EVA. The last day we used the Horizon Scan Mode, and I found it to be an excellent mode. There was only one case when it broke lock and didn't recover. Wasn't that it, Ed?

[...]

McDivitt: I'm sure I fired the upward-firing thrusters a number of times. That isn't any more difficult to control than the ether one. Actually you can fire these thrusters whether you are in Rate Command, Direct, or even in Pulse. When you fire them, you get a rate and you just damp the rate out with the attitude controller.

[...]

McDivitt: The operational checks that we did on the RCS occurred at about TR minus an hour. When I checked the system out it seemed like I had a lot less authority and a lot sloppier Rate Command than I had in OAMS. the operational check consisted of pitching up and down, yawing left and right, rolling left and right on each ring in Rate Command and Direct. Direct worked as I expected it to. In Rate Command, however, as I pitched up and down I noticed that my top left yaw thruster was doing a lot of firing too. I started out checking the Rate Command, so I thought I might possible have one bad pitch thruster that was causing a rolling moment that was being counteracted by the raw-roll jets. When I did it Direct, however, it wasn't doing that. It wasn't rolling either, so I felt that it must just be a very tight deadband that was trying to hold us there. So, the operational checks were all right.

[...]

McDivitt: I used Rate Command, Reentry Rate Command and Pulse control modes. I didn't use Direct. They all operated as I thought they should. I've already mentioned I thought Rate Command was a little sloppier in RCS than it was in OAMS. It certainly did a find job of holding the retro attitude during retrofire. Retrofire attitude control was excellent. We didn't deviate more than about a degree from the attitude we were supposed to hold, and I had plenty of authority there. From my standpoint it couldn't have been any better. I was really happy about it. I used the Reentry Rate Command with roll rate gyro off, so that I had essentially Direct in roll and Reentry Rate Command in pitch and yaw axes. It had the typical 4 deadband that it was supposed to have. It did do rate damping as it was supposed to. It performed just the way it should.

J.2.3 Gemini Titan-5 (GT-5)

Cooper: In one of those, that coeliptic burns and we made our other burns then on Rate Command and man, that Rate Command system is just beautiful. It holds that spacecraft so tight that it can't vary.

Conrad: Yeah. We had a beautiful control system, I thought. When Gordo made any of the burns on the Rate Command or anything that it really responded – well.

Cooper: Rate Command has tremendous torqueing. Boy, it's strong and it's instantaneous and you can just stop it right on the money. Really good.

[...]

Cooper: We used dual ring RCS rate command for retrofire only. Then we turned Ring B off and did the whole reentry on ring A.

Conrad: Pulse.

FCSD Rep: You operated Ring A all the way?

Cooper: The last I saw of Ring A in the reentry, down before we went to drogue chute out, I still couldn't see any decrease in Ring A.

[...]

FCSD Rep: Let me see now. You rolled it upside down, what did you you hold? You held 20 degrees –

Cooper: 20 degrees until it started trimming out. Then, I'd switch between rate and attitude. I'd just hold that attitude and when I'd see a little tiny rate creep in – I was on single-ring pulse – I'd just pulse that rate out. Of course, that was establishing my trim angle right there. You'd see it on the rate. You'd see the pitch rate needle start to move just a little tiny bit. That was showing you that you weren't quite on trim. Then I'd tweek it and it would sit right there, and it would just start trimming itself out on the ball.

FCSD Rep: When it trimmed out you damped the rates. You were in single-ring direct?

Cooper: Well, at 400 K I went to single-ring direct.

Conrad: Yes, we were in pulse –

Cooper: Yes, single-ring pulse.

Conrad: Single-ring pulse to 400 K –

Cooper: Then I went to Rate Command on the attitude control selector and took the ACME RCS switch to direct – one to direct, the other one was to off. Then I used single-ring direct throughout the reentry, until very late when the oscillations got so rapid that I had to concentrate too much on them rather than the attitude. Then I went into ACME – just put the RCS switch to ACME and then flew the attitude with the stick and allowed the RCS to damp the oscillations.

FCSD Rep: Still one ring?

Cooper: Still one ring.

Conrad: We didn't go on dual-rings until below 70,000 feet.

Cooper: We had the drogue out before we went on dual-rings.

FCSD: Was there any problem?

Conrad: The thing was steady as a rock all the way.

[...]

Cooper: I think the whole retrofire and reentry is so much easier than Mercury that I can't believe it. It is really a piece of cake.

[...]

Cooper: Spacecraft control was beautiful. There was no problem at all. I was on single ring Direct and then had gone fairly late down in the guidance program there when the oscillations got to be often enough in there that it was taking concentration to damp the oscillations as well as to watch the guidance. I just went over to single ring ACME or Rate Command ACME and let the Rate Command damp the oscillations and I was doing the steering, with the Rate Command also. Still single ring.

[...]

Conrad: Now, I'll tell you that RCS was really working. Now, we were in Rate Command, not Reentry Rate Command, we were in Rate Command. So, it would. I mean, it was firing full time.

Cooper: Yes, it was really working.

Conrad: We were outside the rate command bands.

FCSD Rep: You didn't use the reentry command?

Conrad: Heck no!

Cooper: No, no that's useless.

Conrad: We had fuel up the kazoo.

Cooper: We had all kinds of fuel. We figured to just go into Rate Command. That's exactly what –

Conrad: ... to see how smooth a reentry you could make.

Cooper: The only thing we deviated from our very carefully calculated preflight plan was that I, instead of going to dual ring RCS, I put the drogue out at 70K.

[... Technical Debriefing ...]

Cooper: That Rate Command just flat snaps you in. In the simulator, when you come around in Rate Command and you let off it will go through 5 to 10 degrees. You have to let off on it 5 to 10 degrees early. By golly, in the spacecraft you don't have to let off even a degree early. When you let go, it stopped right there just like you put on the brakes.

Conrad: Yeah. It was good and it was tight.

Cooper: It was so tight that you almost had to —

Conrad: That was OAMS Rate Command.

Cooper: You almost had the feeling that the OAMS Rate Command was almost bending the Adapter Section. It had such high torquing rate.

Conrad: On day 2 and 3, our OAMS system was working completely correct. I was extremely impressed with how nice a control system it was. We made several maneuvers using this control system and didn't have any gripes on that system at all. As Gordo said we were really impressed with the Rate Command system.

[...]

Cooper: [...] We didn't use Rate Command very much, mainly just for the burns. In fact, the burns are the only times we used Rate Command. I used the Direct system several times and I thought the Direct was really good. It was good and crisp and you had good authority with it.

Conrad: I had the impression that the spacecraft was a lot more stable vehicle in Direct than it was in the simulator.

Cooper: That's right.

Conrad: In the simulator you tend to sit there and go too much and go too much. When Gordo'd stick a shot of Direct in to go someplace, it never showed up in another axis. An equal shot in the other direction would stop it right now.

Cooper: Yes.

Conrad: The effects momentum of the spacecraft didn't seem to be as great in flight as they were in the simulator. You didn't have to lead as much.

Cooper: That's right. The Direct system was a much more precise system in the spacecraft than it is in the simulator.

Conrad: I thought it was quite easy to fly, but there's no doubt about it, boy, that Rate Command eats up the fuel.

Cooper: Direct used quite a bit of fuel also.

Conrad: We did use a little fuel that one day. We were doing so many experiments in a row that we had to very rapidly get the spacecraft back to a zero-zero-zero or a pitch down 30 position. When you track one of these targets and come through the nadir and keep on going, boy, you're really smoking towards a rearward direction.

Cooper: You're sitting inverted BEF.

Conrad: That's right, you've got rate built up going away from you and you'd have to use Direct to stop those rates, get yourself moved all the way back up here and stop them again. Maybe it'd be so tight that you'd use Direct to get down and start on it, and then switch to Pulse and track in Pulse and then right back up and start doing something else. Well, we did eat up a lot of fuel that day, but we got everything done that day. We hit darned near all targets.

Cooper: Direct is a real responsive, real fine way to maneuver.

[...]

Cooper: Selector controls and switches were all right. Attitude controller was fine. Maneuver controllers. We had every intention of checking the right one and we never did check it because of other problems. Inflight malfunction irregulatorities we've already covered pretty well.

Cooper: Attitude Control Modes, Rate Command was excellent. Reentry Rate Command we never checked.

Conrad: I don't even think you need it.

Cooper: And I think it could be removed from the spacecraft as far as I'm concerned. I never used it or need it on the simulator. I never liked it.

Conrad: Pilots aren't going to tolerate these higher rates. They will damp before these rates are reached.

Cooper: Direct is a good mode. There's nothing at all wrong with Direct. I thought it was much crisper, much crisper in the spacecraft than in the simulator show that it is. The Pulse mode was very economical on fuel and I felt that in the simulator you had a little more authority than you actually did in the spacecraft. The spacecraft had slightly less authority in Pulse than the simulator does. Incidentally, you can use Pulse just for a month of Sundays and never see the fuel go down on the OAMS gage at all. You can use Pulse all day long with using little fuel usage.

[...]

Cooper: OK - RCS Operational Checks - We did just like we had planned in our little book. We activated the RCS and Check Ring A and ACME and direct – all three axis - Ring B - Check Ring B in ACME and direct – all three axis and they worked beautifully.

[...]

Cooper: (RCS) Control Modes - We used pulse and we used horizon scan –

Conrad: We didn't even check reentry rate command –

Cooper: We used direct, used pulse. We used the rate command. We used horizon scan. [...] And they all worked very adequately. I thought the rate command system, I mean the RCS system was an excellent system. It was really crisp and just really, I thought, it was a really good solid system. Rate command was much more –

FCSD rep: What about the retrofire - how did it hold retrofire?

Cooper: Beautifully, it was just no effort at all – hold –

FCSD rep: ±1 degree or less?

Cooper: Oh, yeah, easily. We had a little offset in number 3 and number 4. I could feel them offsetting us. I just cranked in a little bit of RCS. But, it just glued it right in there, it just wasn't about – I felt like we could have had four or five times the offset we had – and never have budged it off there. RCS, I mean the rate command – One thing on rate command before retrofire and just after retrofire, waiting for retrojet, and then starting the pitch up to go up and roll over inverted and go to zero lift, the dual ring rate command is just more than you can handle. It's just a lot more control authority than you want – you tend to over-shoot on things because there is just so much control torque in there. As I had stated, after I fired retro and jettisoned the retropack and pitched up to roll over then from there on I went to single ring pulse, and used that. Reentry rate command – we didn't use. Direct - used direct to do the reentry on single ring direct and used the pulse mode from retrojet to 400K.

FCSD rep: On the single ring direct reentry did you have – did you feel like you had all the authority you wanted?

Cooper: Yeah – until very late – as I stated some time down, oh, half way thru the reentry where you really beging to get the high g, after your high g, in fact, along about coincidental with a real high g, when you begin to get some fairly good oscillations, very rapid rate, I had no problems damping them at all but I didn't have the time to keep switching back and forth from rate to attitude and go back to rate and damp them real quick and then go back to attitude and decide where I was on the guide and then go back to rate and damp them and go back to guidance, so I finally – they got to getting fairly good where I had to devote a little bit of time to damping them, and I finally just went to guidance and stayed on guidance and just flicked over to single ring rate command to damp the oscillations and then used the attitude control in the rate command to steer the computer steers. Which worked out very well and there was – there never was really any oscillating - you never really – I could go to rate on there and you could hardly ever see the rate needles jiggle – single ring was holding it just as tight as could be. Retrofire attitude control - I had already mention there there - dual ring. Rate command, reentry attitude control – I had already mentioned how we shot the reentry.

[...]

Cooper: [...] Plus, I don't think we are using the right torqing moments on our Rate Command system. The trainer doesn't have anywhere near the brute power that the actual RCS Rate Command has. It is a great deal of difference.

Conrad: Yes, it was a pretty tight system. This is probably a function of each individual system because I remember Jim mentioning the fact that it was so much sloppier in Rate Command RCS and there is a difference in the tolerance. But it sure wasn't apparent to us. Both the OAMS and RCS Rate Command systems were just as tight as they could be.

Cooper: Well, the OAMS Rate Command system definitely was tighter because you could come zapping around with it and the second you let go of the handle it stopped right there. Bam, it never even quivered, just held right there.

Conrad: Yes, we must have had an outstanding set of rate gyros. The RCS Rate Command there had a wider band. There was so much power and authority in the RCS Rate Command that it actually gave me a bit of problem just hitting the point, getting lined up for retrofire. There was just so much authority you had trouble getting just small amounts of control force until you got used to it. There was so much power there, almost more power than you needed for fine control. It would be interesting to simulate similar control torques on the GMS to see what kind of off-sets it would take before control problems are encountered. I don't believe that you would actually set one of the rockets off enough to bother you. Possibly, you could since it is not a straightline function.

J.2.4 Gemini Titan-6 (GT-6)

Stafford: [...] practically every burn was made in the Platform mode.

Schirra: No. The out-of-plane burn was made in Rate Command.

Stafford: The out-of-plane burn was made in Rate Command. All the rest were Platform. [...]

[...]

We made the NSR burn in platform mode SEF, that's platform attitude control, using aft-firing thrusters. Then I corrected out the balance on the IVI's with downward thrust to compensate for the downward component, which is a much more efficient way of doing it than trying to hold a two degree angle which is almost impossible to read with the attitude ball presentation.

[...]

Schirra: Spacecraft 7 was BEF and we were SEF. Frank was maintaining his attitude with his reticle above the horizon and I merely sat on his nose, I guess at about 15 or 20 feet in align and merely maintained position with the translation thrusters. We were in the complete SEF position, meaning 0 roll, 0 pitch, 0 yaw.

The question was asked, “Is it easier to tell if the platform is ‘off’ in pulse rather than platform attitude control mode?” In platform mode you really can’t tell whether the platform is off because it runs through the excursions. I believe the textbook answer is plus or minus 1.1 degree per axes, and that is about the way it was flying. In Pulse mode we hold it down to decimal degrees per axis. The tighter you hold it the better the alignment, so at this point I was in platform mode and merely just gave the platform the full 10 minutes to take out all the errors. Typically, errors are still being smoothed as late as 5 to 7 minutes, so through a ten minute alignment period you give the platform all the alignment it needs.

[...]

Schirra: [...] On the night side, there was no difficulty in maintaining any position we wanted. Interestingly enough, if we were in plane, either ahead or behind the target vehicle, or out of plane at a 90 degree point, it was very simple to hold station.

[...]

Schirra: [...] The night pass– getting back to staion keeping–had no surprises, no new events for us. We maintained station, I would say, between 10 feet to possibly 40 or 50 feet at night. And felt free to let Spacecraft 7 move without holding attitude. Now, this in itself was a challenge that we hadn’t really faced before, and readily accepted, it turned out. This came about, of course, due to the fact that Spacecraft 7 was worried about its electrical power supply and its total fuel budget. As a result, we let them act as if we weren’t there. Those were the instructions I gave to Frank. I said, “Just ignore us and we’ll hang around here as long as we can.” It turned out we could have stayed there as long as we wanted to. We merely found that we needed to do other things. Station-keeping was then a proven facility from the training we’d had. It might be worthwhile to bring up something else that made station-keeping obvious to us. This was the old D-2 experiment, where we did the in-plane fly-around. When we initially started, we tried it in Rate Commend with the maneuver thrusters to force us up and around in-plane. The first fuel budget was something like 34 pounds of fuel for a period of about 15 minutes. If the motions are kept down to a bare minimum, the problem of station-keeping is minimized and the fuel Budget is minimized, which, of course, is our intent. I think we ended up doing what I had hoped to do after we’d finished the flight plan items. That is, we did our station-keeping on the first orbit, really, the first orbit after being in rendezvous. On the next day period there were two experiments that had to be conducted by 7, so we delayed doing anything while they performed these experiments. This was their D-4/D-7, I believe. Once they completed those experiments they maintained yaw reference. We did fly around a stable vehicle–the in-plane fly around. Now, we had turned the radar off shortly after maintaining the initial position in orbit with 7–did not use the radar again–and we turned the computer off. It had no function for us. We left the platform on all this time. On this next day pass after completing the test with 7 we commenced an in-plane fly-around with an eyeball ranging system. I let the spacecraft move out to about 100 to 200 feet – this you can judge quite readily from the optical sight and the size of the target vehicle. I would say at about one point we got out to 150 to 180 feet, somewhere in that order, and it was quite easy with these very slow moving rates to just tap the aft-firing thrusters and maneuver back in. This is a normal technique flying around in-plane. As you initially start from where we did, which was SEF, I started slight little blips up, which then, of course, caused us to go up and translate slightly. Then the radial velocity need to be added continually as we came around through this circle of in-plane. All of this control is in Pulse mode. In fact, the whole station keeping exercise, but for the initial platform align, was in Pulse mode. We never did go back to Platform again after that. The problem in Pulse mode versus Platform mode is practically negligible if you once get everything stopped. And that is the key to station-keeping – it's not to pick up any large velocities. The translation velocities were very very slow. I think they can be better observed and documented by the movies that we took with the Maur camera which was at real time velocity, 16 frames per second. You can easily see that the rates were very very low, and that's the rule for station keeping.

Shepard: Did you notice the closing effect when firing the lateral thrusters?

Schirra: Oh very readily. That's a good question to ask, Al. The effect of any translation thrusters, but the forward-firing thrusters, is to bring you closer to the target and you continually find you have to back off a bit–use a little blip once in a while to back out. Also, I was concerned about whether the attitude thrusters would cause some unknown velocities. They were not discernible at all. I thought they might be. They are not. And I think this is due to the fact that they are such small pulses that even in accumulation they are masked within the other pulses for translation. [...]

Schirra: The second daylight period I did the in-plane fly around–came back and pulled in to about 60 feet and said, "Tom it's all yours", and Tom did the out-of-plane fly around. Subsequent to that I did one as well. And we did many of them, really. We shared quite a bit of time. I'd like to say that the best way to fly around a spacecraft is out-of-plane. It's the easiest way because you have a horizon there all the time as an attitude reference, and you can't come into the cockpit. It's much like flying formation on another airplane. You don't get in the cockpit when you fly formation; you know, you very discreetly take a sneak in and check and see if the guy's flying the same place you want to go, whether your fuel is all right, whether your engines are all right, and you rip right back out again and eyeball that other vehicle. The same thing is applicable here.

FCSD Rep: At about what range were you in your out-of-plane fly around? At about the same as in-plane fly around?

Schirra: I would say that you could pick any range you want and you are safe at–you know, I had reservations about this. I said I was never going to go beyond 60 feet. I think that is probably a good place to call it for in-plane. That's a little hairy.

Stafford: On the out-of-plane I think you can maintain attitude out there in a good stabilized position very easily at 100 feet because you have the broad side view of the other spacecraft, and you can detect any relative motion instantaneously, and make a small minute correction to hold it. Also, you can traverse from one given point to another one very easily. The one thing that also helps you on the reference cues, particularly during daytime, is to see the horizon and the other spacecraft.

Schirra: And of course he is above you if you are flat with him, tangent to the earth.

Stafford: After Wally completed his in-plane fly around, to save fuel they went to the Horizon Scan mode and started to drift off. Now, when I performed my out-of-plane fly around, they had yawed nearly 180 degrees. We talked about it, and we developed the technique of having our X-axis point toward their center of mass, around somewhere near the heat shield.

Schirra: Remember we have talked about this before? It works.

Stafford: So, they can be at any attitude. It is at times confusing because you will pick up a rotational rate on the target spacecraft as a translational velocity by your spacecraft. But if you aim at the center of mass, this will help greatly as far as any position going around.

Schirra: There was one time when we had an illusion and it was really amazing. They were moving in yaw while we were stationary. Actually, it looked like they were flying right by us. It looked like they were really "modocking". This is why I asked Frank before they launched to be in a fairly tight mode, because I didn't know how we would handle it until we tried it. But before we left them 7 had some problems with this dose of water that came out of Frank's inlet hose, and he was quite concerned about it. So they told him that on the next daylight pass to roll up at a rate of 10 degrees per second. We were still in formation with him and Frank asked me to move out a little bit, so I moved out about another 5 feet from about 10 feet. That is as far as you have to go. He started this roll rate and it was the most delightful thing you ever saw in your life. This big–big, of course, to us at this range–this big object and you could see this thing starting to move around in roll, just gently rolling. Then you could see the whole thing couple. It would go into a pure roll maneuver, and then finally translate into pitch and yaw and all axes were just going. I guess it was at this point that we realized that station-keeping, no matter how this beauty was moving, was no problem at all. Just a piece of cake. We developed this technique as we went along. If I had come up there and saw something like that to begin with, I would have been horrified.

Shepard: What would you judge the minimum distance to be on a random drifting spacecraft?

Schirra: As long as I know that it is not translating, which is the problem with tracking the booster, I would come in within 10 feet of its nearest part. Some part is going to come by. What really backed us away one time when I was fairly close, I would say maybe 2 or 3 feet as they yawed around, were the darn cords flying around out there. We both elected to back off a little bit so we wouldn't snag those things.

Shepard: Suppose you had an Agena where you know it has no translation capacity because it has lost attitude control. Would you think with a slow rate like that you would want to go up and try to get into a target adapter?

Schirra: You know, we heard about some studies that were done and I think the numbers I heard of were something like an object, meaning target vehicle in this sense, moving more that 2 degrees per second, or something like that, would be almost impossible to dock with. I dispute that. I can't claim that I could do it, of course, but we could move with any facility we wanted. For example, when they started this roll thing, I said, "Frank, you have got a big blob of water." They had this big suit inlet problem and the water boiler is on his side. A large, big blob of ice formed there and the best way to describe it by dimension and size and configuration is it looked like a coot, a small black duck local here in Florida that we shot a boat load of recently. It was the same size, the same appearance, but solid white. I said, "Frank, you have a real blob out there and I want to look at it." I just flew around looking at it no matter where he was going. He was in a random motion. We just sat there and took pictures of it and felt quite blase about maintaining station on that part of his spacecraft.

[...]

FCSD Rep: Could you give an estimate of the maximum range during this station-keeping period and where you spent most of the time?

Schirra: This is going to be fun because I don't have to answer that. It can be answered by photography. I would like to find out myself. As I said, we killed the radar and killed the computer. We didn't need it and that was another nice feeling because I was a little worried about doing this in-plane fly-around. I always felt from the simulation, that it was more difficult than the out-of-plane fly-around. As a result of not knowing my range, I had to work a lot harder, but even then I was content to stop and take pictures and this stopped my rivited attention to the other spacecraft. And it wasn't an ordeal. You were busy. You had to be on your toes. You had to watch for an opening rate that was not acceptable. Why I was concerned was that even on the Agena, I didn't know whether I could keep radar working all the time, or whether I'd get spurious inputs as I changed through different antennas. This is no longer a problem either.

FCSD Rep: Regardless of the range, there were no particular problems in closing, opening or whatever you chose to do.

Schirra: No. I can only stress it– you have to practice it. You don't just go up and do it. We spent a lot of time at MAC doing this, really for the D-2 Experiment. We did it down here and we ultimately got some training out of the docking trainer, where we worked up the Pulse mode for this thing. It is the only control mode that is feasible for this and this requires minimum fuel and that it what you are after.

Stafford: For all the subsequent Gemini missions, in which docking practice is done with the Agena, there is only one control mode to use and that is Pulse for the attitude control and real minute imputs to the maneuver thrusters.

[...]

Shepard: You may have already answered this, but did you do any night fly-arounds with your docking light off?

Schirra: We did not do the actual fly-around. We station-kept on the cabin light. They had their cabin lights up full bright for our benefit. There was no problem at all and that was a perfectly acceptable level of light which I might add is dimmer than the docking cone light of the Agena, so we are not in any trouhle on that light level.

[...]

FCSD Rep: Did you find that the platform was of any particular use to you in station-keeping?

Schirra: Yes, I did. I would say that when we became acclimated to station keeping, we first stopped out of the Platform mode. We used platform mode to feel our way along. The first maneuver, of course, was the in-plane fly-around and you don't use the platform. Other than in this particular maneuver, I depended on the platform to stop me from moving out of plane. I flew around the pitch gimbal band of the ball and if I started sliding off, I would immediately correct for it, much as I do from the second mid-course in. I would keep correcting out-of-plane velocities immediately, so that they don't develop. They are very insidious and very hard to detect unless you have a good star background. That is another point to make. We did not use the star background for station-keeping. We merely used eyeballs and sitances that varied just due to whether we wanted to fly close or father out or wanted to look at something on 7 more carefully. Seven had a limited fuel budget. their cutoff, as I recall, was 11% OAMS fuel remaining. They had something like 14 or 15%. Both Frank and Jim did station-keep for, I would say, a total of their time of about five minutes. We were in a fixed position, and I said "OK, Frank, you've got it" and they started keeping station on us. We maintained our attitude in Platform mode for them. So we were quite stiff. They just moved around much as you would in the target docking trainer, which is a very good tool for this. Now to summarize station keeping.

Schirra: I think starting out with devices we have available and taking the time to use them, station-keeping is not a major job. But when first there I would approach it with caution, remembering the rule of very slow motion. I would recommend, if you have everything working for you, to use your radar and platform. When you get your confidence up, kill the radar and fly in Pulse mode. You can ultimately kill the platform. In fact, it is a very simple mode. Just go into Horizon Scan mode, if you like, and use minute pulses that don't overdrive the pulse mode logic of Horizon Scan. You can station-keep in that mode, which would be a pretty cheap mode. That is probably the key to it–that you don't make a thrust motion that is big enough to overdrive pulse attitude control.

Stafford: With respect to training devices, I feel that the visual display that we had with the Gemini Mission Simulator was invaluable in so far as our training for station-keeping. In actual flight, once you were completely stabilized, it was a slight bit easier than on the GMS. I think this probably arrived from the fact that the pulse input on the spacecraft was a little bit less than what we had in the Gemini Mission Simulator, so we were working with a finer control mode.

Schirra: To qualify that point further, because we have had a chance to think and to talk about it–the Pulse control mode in the RCS is almost exactly like the mission simulator, where I couldn't get the attitudes to really null out in the RCS. You could in the Pulse mode with the OAMS attitude control systern.

[...]

Retrofire

Schirra: [...] At any rate, the first retro fired exactly on time, the disturbances seemed to be fairly light, the control mode was Rate Command, both rings. I did have to steer the spacecraft in a sense to keep it tight, and we fired on a 20 degree pitch attitude, which we had decided on long ago with a gang from FOD. This is an easy index mark. I reject numbers like 19 and 22, you can fly the markings on the ball at 20, but the rest are approximations. The delays between the retro rockets, we've discussed, but not on tape and I think it's best to discuss those and probably I'll take my side and Tom can take his side of it. I felt like it was almost like four separate retrofire maneuvers. This might be a real good way of doing it if you had to do a retro in direct because you'd have time to regroup between them. But this wasn't what we've ever seen before. So it did surprise us considerably. It was absolutely no overlap between them. And you're sitting there just really tight as a drum trying to catch the next one because you don't know what the disturbance will be. But we did get through all four retros, the IVIs settled out, and we have those numbers; the final numbers have been logged all over the place but I recall it was 310, 1 left and...

Stafford: 310, 1 right, and 116 down.

Schirra: 1 right that I didn't recall and 116 down. Initially the fore-aft window read 309. And I recall very well that number changed after jettison retro so we probably were in to the point where we were close to 310 and it took another tiny little impulse to kick it into the 310 readout rather than the 309 readout.

Entry

Schirra: [...] And all I did basically was to continue in the full lift attitude to 400,000 feet and that point, interestingly enough, is within a second or so of the time we had predicted. At that point, I went to the 55 degree bank angle. I believe that update came after the 400,000 feet...

Stafford: The update came after 400,000 ft.

Schirra: And, I am not sure whether it came prior to the 280,000 feet. It must have, because we received it. But at any rate, I held the 55 degree bank until we had guidance initiate. I did use the overlay to maintain a 55 degree bank angle. [...] In addition, the difference in the RCS system and the OAMS system, should be noted. The pulse mode, and I know this is prior to retro, but it is applicable to talk about it now, was very similar to the GMS here at the Cape, and also at Houston. It was, had more authority. We noticed this also to be true in our thruster checks prior to retrofire that direct was pretty strong, the rate command was pretty strong, and obviously so was the pulse mode. It was very difficult to take tiny pulses and put it where I was used to putting it, meaning the needles really nulled out on rates, as I had on the OAMS system. So there is that much more authority in the pulse mode on the RCS system. Approaching 400,000 feet the spacecraft seemed very easy to fly, although it took a little more activity, in pulse mode, to keep a fairly stable attitude in that sense. When we got the 400,000 feet indication, the roll needle displaced fully to the right, asking really for a bank to the right. Of course, we take bank left as our initial bank and when we reached 280,000 feet the bank left was the proper bank, the cross range needle was deflected to the right, which really asked for a left bank. The down range needle, at this point, was about 2.5 degrees down, just below the W on the 8 ball. [...]

[...]

Schirra: [...] Attitudes and rates were very stable. We started out with Ring A, Pulse Mode. [...] As the roll needle crossed, I reversed bank and reversed bank to the point where I needed the bank to arrest the down range needle and not let it move away from where I wanted it to, And favoring the cross range needle. The cross range needle came back cross center and went off the right again and I reversed bank to the right, I selected rate command, not reentry rate command, for these roll maneuvers and left it in rate command once I got to that point. I sort of regret not taking the time to put the attitude control in another mode because I didn't need rate command that long. The control authority of rate command was not required all the way through, but I became lazy and did not switch control modes. The acceleration started building very slowly and seemed to be quite similar to what we experienced in the GMS, although I cannot recall the sound effects of the GMS banks. That is quite a big cue and I became used to it and I was looking for the sound. I didn't hear it.

Stafford: That is the same thing I noticed. There was the air dynamic noise was real slight. It wasn't near as noticeable as what you get in the GMS. In fact, the largest noise you hear at this time are the thrusters firing.

Schirra: That is exactly the cue I felt. We agree on that one hundred percent.

Stafford: You hear the pop pop pop of the thrusters firing, but the noise was very, very low.

Schirra: This cue in the GMS is valid because as you require control authority during certain regimes of the reentry, you hear the popping. When the popping dimenishes you know to go back to Pulse Mode again or direct because the thing is stable again. And we did hear this. That's the time I probably should have come out of rate command to save some fuel, but I did not.

[...]

Schirra: [...] As we proceeded through the reentry, I was rolled right about, I'd say, 45 to 50 degrees, when Ring A was exhausted. I recall very vividly looking up and watching the ball rotating back to full lift. I said, "My gosh, I'm not doing that. What is doing it?" Then I looked out at the nose and I could see that the A ring was getting cold. There was no heat on it. So I, as I hadn't rolled through full lift yet, but I was coming that way, I reached frantically, and was talking, but I guess that was the first time I beat Tom around the cockpit. But I beat him to ring B switch and he hit my hand as I was already moving the switch. [...] So we got the second ring going and I did observe that thruster activity and the ring getting hot.

Systems Operations: OAMS

Schirra: [...] No problem on selector controls and switches, attitude control, maneuver, controller, inflight malfunctions, none. Attitude control modes; Rate Command, very crisp; Reentry Rate Coinmand was never evaluated. Direct was much more precise; the description given by Gordon Cooper is exactly the same as I saw it. Direct is a much easier control mode than the GMS, as is Rate Command, as is Pulse, The Pulse, again, is just about like the Translation and Docking Trainer. Horizon scan, the same; Platform mode is an excellent control mode; and varied, just as technically described to us around 1.1 degrees oscillation about all three axes.

System Operations: RCS

Schirra: [...] Control modes, Rate Command was stronger and had more authority than Rate Command on the OAMS. Reentry Rate Command was not utilized. Direct was stronger. Pulse was stronger.

J.2.5 Gemini Titan-7 (GT-7)

3.2 SECO plus 30 seconds

[...]

Borman: I said thrusting and SEP Spacecraft and we did it and away we went. I thrusted for about 2 seconds. Almost immediately, as soon as we had finished thrusted, I started a yaw right 180 degrees, and the rates were right around, I think around – Of course, you should be able to pick this up off telemetry, but I would estimate they were 3 degrees to 4 degrees per second turning around. As soon as I had the booster in sight, I thrusted back 5 seconds. This is the way we tried in simulations. The simulations in St. Louis were excellent.

Lovell: Turned out that was the best technique to use, 2 seconds for the 2 seconds forward and a 5 second return.

Borman: We turned around and there it was, bigger than the devil!

Lovell: At that distance there was no problem staying in there.

Borman: Now, I did have some problem because the booster was bending so rapidly. It was tremendous. It looked like one of the autogenous lines had been cut. I guess it was cut with a pyro, and it was really bending and this was causing it to translate as well as rotate. And in order to stay with it, I was having to use quite a bit of fuel; although it was certainly a nominal task. I also went through several control modes switchings. I started out in PULSE and I could not get around fast enough, so I went to DIRECT and then slowed it up in RATE COMMAND. Slowed up the direct rate I was using with RATE COMMAND, and left it in RATE COMMAND without using the hand controller for a while. Finally went to PLATFORM. When I went to PLATFORM, we had been off to one side of the booster. When I went to PLATFORM, it yawed me back around, and I lost sight of the booster. So we went out of PLATFORM and flew the rest of it in PULSE Mode using the reticle on the horizon for stabilization and using the maneuver controller thrust. This is all on onboard tape, incidentially. The air to ground communications, through the flight were superior.

[...]

3.3 Insertion Activities

[...]

Borman: I think that we have covered station keeping with stage II booster, partially. I will mention that the booster, being without attitude control, translating also with this impulse it was picking up from the venting, is definitely an order of magnitude more difficult than station keeping with a stable vehicle like Spacecraft 6.

Lovell: First of all, you do not have anyone controlling the thing; you do not exactly know where it is going to go, and it might translate because it is venting and has a slight thrust.

Borman: I know a couple of times we got in a little too close and I backed out, because you just do not dare get as close as you do the way this thing is spewing. [...]

[...]

Borman: I hope they got the data they wanted on the D-4 and D-7 experiments. It was, again, a very uncomplicated maneuver, one that we practiced many times, and it worked just like does in simulation. Had no difficulty at all. The lights on the booster worked fine.

[...]

4.0 Orbital Flight

Borman: We have already discussed the station-keeping. That is no problem. I think the situation that we used, going off with about 2 seconds – 2 to 3 seconds – and thrusting back with 5 seconds while you are still on your side getting back to the booster as quickly as possible, solves the problem and takes a lot of the orbital mechanics out the situation. I hope the film comes out. The one thing that did make it a little difficult on this one is when we looked back, we were looking back into the sun, and the booster was right in line with the sun. It was just like flying formation when the leader makes a turn, and you are down sun. It is difficult to see, and I tried to move off to one side and swing around and look a little bit more to the north. I think it was north. I guess I was trying to look to the south where I could get the sun out of my line of sight. I also had a cut-off on the booster at station-keeping at 88% fuel, so that at 88% fuel we were already in darkness, although we had not reached the time for the D-4, D-7 separation which was to occur at 00:25. I think it was about 00:23 or 00:21. So when we reached this limit and we were in darkness, I went ahead and separated, thrusting down.

[...]

Borman: On the 6 launch, the second time, we were able to track it. We were not able to pick up lift-off because of clouds again, but when it got to the con level, above the clouds, we were able to pick it up and we tracked it using IR until we couldn't see anymore. Even above the con level I think we were tracking the exhaust from the stage two engines using PULSE mode. I hope we got some good data on that.

[...]

5.0 Retrofire

5.1 TR-2:00 Power Up and Alignment Checklist

[...]

Borman: [...] Incidentally because of the fact that we had two degraded thrusters, 3 and 4, we didn't use the PLATFORM mode at all for this alignment. We aligned it all manually. The thrusters were degraded, but there was still enough in them to allow you to get fine maneuvers, fine control. I used less control by turning off the circuit breaker for thruster No. 12 and used 11, giving back thrust and this would give you right yaw.

5.4 TR-256

Borman: Electrical was no problem. Control system, the RCS worked perfectly. It just worked beautifully.

5.6 TR-0

Borman: [...] At TR equals zero the S/C attitude was 20 degrees down. S/C rates were easy to control, but I thought that the thrust from those retro-rockets was high. I really had a sensation of being accelerated. Didn't you Jim?

Lovell: Well, it was different from what I had expected because we were so used to zero g flight.

Borman: The only thing I could do was fly instruments, the needles and the ball. Trying to hold it right on the ball.

Borman: I was very glad that I was in RATE COMMAND. I had to control it in RATE COMMAND a little bit, particularly on the fourth retro rocket. The first three went bing, bing, bing. Then there was a pause of about 0.5 second and fourth one went. The fourth one seemed like it was a little misaligned, I think it was left yaw. I had to bring it back. I would like to emphasize this. I thought those retros were really powerful, and that you were holding on to something that if you didn't have good control it could get away from you pretty easily.

Lovell: But, I was sure happy to hear them go.

Borman: Control mode was Rate Command, and the IVI readouts there - did you write those down?

Lovell: I have them here.

[...]

Borman: The FDI as far as the retrofire goes, it was no problem. It worked out fine, and I just like to have it, I think. If you really were forced into it you could do it on rate needles, but you'd have to have a lot of confidence in your ability to hold it. I wouldn't want to do it without Rate Command; and again, I did it in Rate Command. I'm not even sure how much the thrusters were firing during retrofire. Did you notice? I was watching the ball, and I didn't notice.

[..]

6.0 Reentry

[...]

Borman: During the later part of it I started out in PULSE Mode and rolled over the 55 degrees in PULSE Mode, and then when we got Guidance Initiate I went to DIRECT. I was finding that in order to keep the cross range zeroed, and we had been told that Wally had trouble with his cross range, I was banking back and forth quite frequently maneuvering the spaceecraft around the full lift point, from one side to the other and I was overshooting a little bit in DIRECT. I was also starting to pick up some pitch and yaw oscillations, so then I went to single ring RATE COMMAND. And boy, this was really a great control mode, it was steady as a rock. You could put it right where you wanted and it stayed there. But pretty soon we got down around, I guess it was when the g's were coming off, after 3.9 g's. I started losing it in single ring RATE COMMAND so I threw twos rings on it and it held it like a rock. But they were sure firing.

Lovell: Oh, yes.

Borman: Boy, those thrusters were really firing. And we started getting ablation off the heat shield. It was coming back in and hitting the nose of the rapacecraft, and that was pretty sensational. Jim was giving vivid descriptions on what was happening, and I was watching the ball.

[...]

6.4 Spacecraft Control

Borman: Spacecraft control was excellent until we got down to 100,000 feet or even below 100,000 feet. We turned on the LANDING SQUIB at 100,000 feet and sat there and watched it.

6.5 100K Feet

Borman: I started losing it; I think we may have run out of RCS fuel between 100,000 feet and 50,000 feet; at least I thought we had.

6.6 50K Feet

Lovell: Well, didn't you turn off the RCS?

Borman: I didn't turn that off until after we got on the drogue. We were starting to build up the yaw and pitch rates. Then at 50,000 feet, I was anxiously awaiting the drogue, because these rates were building up a little. They weren't very bad yet, though. I pushed the drogue expecting it to decrease, and all it did was amplify them. And we got a real ride on the drogue for a while, sounded like the one Jim and Ed discussed. It was really going pretty bad.

[...]

7.0 Landing and Recovery

8.0 Systems Operations

8.2 OAMS

[...]

Borman: Right. Inflight OAMS: The only operational check we had is when we lost the complete authority in yaw right, thrusters 3 and 4. We noticed this first in PULSE mode; we switched to DIRECT and in DIRECT we did not get ignition at all as far as I could tell. In the OAMS PULSE yaw right, we were getting slight little pops. It seemed we had about 1/4 control authority that we had before we experienced the problem. We went to DIRECT, to see what effect DIRECT had on it and we got some thrust, but it a whishing. We weren't getting any sound of the thrusters. It was a whishing sound. I think we were only getting an impulse either from the oxidizer or the fuel escaping.

Lovell: We could hear a clicking of the solenoids or the opening of the valves, whatever they were back there. They were working all right, but we were not getting any resulting thrust.

[...]

Borman: [...] The attitude controller, I thought, was fine. No problems. Maneuver controllers were fine.

Lovell: The right hand maneuver controller was a very nice operating controller and it was very handy. Very easy to operate.

Borman: As far as inflight malfunctions or irregularities, we lost authority on thrusters 3 and 4. We got some of our yaw right capability back by turning off the circuit breaker for Thruster 12 and then thrusting backwards with the maneuver controller in order to give us yaw right. This worked very well and enabled us to check yaw right drift rates and enabled us to make yaw right maneuvers. The only thing- you couldn't get very small control inputs with this mode.

Lovell: And you used a lot of gas.

Borman: And you used a lot of gas. I was very happy when we finally enough control out of 3 and 4 to align the platform. When we did this, of course, in order to get yaw control we want to roll Jets - pitch, and that worked fine. I don't have anything to add to that malfunction. We heard the solenoids working. When we went to DIRECT we could feel we did get an impulse, but we did not seem to get ignition, It sounaed more like a swishing noise.

[...]

Borman: RATE COMMAND is a very tight control mode. I'm very glad it was there. I think it is very important to have that for retrofire. We also used it for reentry. I think it is a very good mode. Of course, it is expensive in fuel. We used it also for all our thrusting when we were making orbit adjust maneuvers.

Lovell: Let me ask a question. When did you go to RATE COMMAND during the reentry?

Borman: I went to RATE COMMAND during reentry after guidance initiate and after I started flying the needles.

Lovell: Because you were overshooting with DIRECT?

Borman: Right. I was not able to get the fine control I wanted. It would not stay in there. It seemed like the spacecraft was picking up a torque in roll also, and I was having to watch it too close.

Lovell: And this was different than what we had in the simulation.

Borman: Yes. REENTRY RATE COMMAND we never used. DIRECT we used once for tracking the Reentry Minuteman in order to catch it. It was moving so swiftly. We also used it in the initial phases of reentry, and it worked fine. The PULSE mode, of course, was the one we lived with most throughout the 14 days. I thought it was an excellent mode.

Lovell: It is a gas saver and even when you do have a platform the PULSE mode is adequate for most of the work you can do – for any attitude control, ground terrain observations – except for rapid rotations where you need a faster authority.

Borman: Right. All ground tracking, PULSE was adequate. We did not have any problem at all. We were able to track the Polaris using PULSE.

[...]

Lovell: We might mention here that both Frank and I think making adjust maneuvers without a platform is very feasible. You can use the reticle for alignment and use the stars as a reference. Since you are usually using the aft thrusters, you do not have thruster light to worry about. You can turn down the lights. It takes two people though; one person to burn, hold attitude on the star, and watch the star reference and the other person to time. It required two people, but it is a very feasible method of doing it. I think you get some very good accuracies with it, because we found out from the second burn.

8.3 RCS

Borman: RCS operational checks were nominal. We had no problems at all with the RCS. System monitoring was perfect and it did not drop one bit during the 14 days. After we actuated it, it went from 3,000 to about 2,600 to 2,500 psi on the source pressure. No problem. Control modes, RATE COMMAND. As I have said, it is a very tight and fine mode. We used it during most of the reentry. REENTRY RATE COMMAND we did not use. DIRECT I used for the first part of the reentry, and it seemed that we were picking up rolling torques, and I was also starting to pick up pitch and yaw oscillations as the g's were coming on. They were slight ones but I really wanted to get the spacecraft steady, and I was really trying to lock it in on the attitude indicator, so we went to RATE COMMAND. I didn't see any reason to bring back a lot of RCS fuel anyway. REENTRY RATE COMMAND we did not use. The PULSE mode was used in the reentry prior to guidance initiate, and it worked fine. Retrofire attitude control was excellent and I'm glad we had RATE COMMAND there because we had no outside reference at all. Retrofire was done on the ball with the rate needles, and I thought the rockets were outstanding. Yeah, outstanding, I thought they were a little more powerful than I had anticipated.

Lovell: Quite all right.

Borman: Reentry attitude control deadbands and rate damping was fine. The only thing, I guess, that was wrong with RATE COMMAND was the fact that it uses an awful lot of fuel. But, it certainly holds that spacecraft steady as a rock. [...]

[...]

9.0 Operational Checks

9.1 Apollo Landmark Investigation

[...]

Borman: Spacecraft control. As far as tracking ground targets, you could always achieve the rates in PULSE mode. Fuel was nominal. PULSE was no difficulty. We tried to take everything at a 90 degree angle. We had no problems with spacraft control to acquire and take pictures of the Apollo landmarks.

Borman: Certainly this factor of weather leads me to believe that the whole idea of navigating Apollo by a landmark needs to be reevaluated. It seems to me that a much more desirable feature would be a series of radar beacons placed throughout the world, similar to the ones that are used by SAC, or some type of electronic gadget not dependent upon clear weather. You cannot choose the weather you want, and in our fourteen day mission, for about eleven days we had lousy weather.

11.0 Experiments

11.1 Celestial, Space, and Terrestrial Radiometry (D-4/7)

[...]

Lovell: You could track the Polaris launch in PULSE.

Borman: You could track everything in PULSE except the reentry vehicle. The reentry vehicle was pretty fast and you had to go to DIRECT.

[...]

13.0 Mission Control

13.1 Go/No Go's

13.2 PLA and CLA updates

[...]

Borman: [...] And I might add, based on that reentry, if I had to do it again, that is exactly what I'd want: a rolling reentry, if I did not have a load in that computer. Because I think it is very difficult to look out the window and observe a horizon during a reentry. At least it was during ours; especially during a night reentry.

J.3 Apollo

J.3.1 Apollo-7

Debriefing Part I

4.4 Attitude Control Mode

Cunningham: The only thing we took to do was for about a minute you let me tweek the stick just to see how it flew.

Schirra: That was after (CM/SM) SEP.

[...]

Schirra: Okay. Let's back up to where I yawed left and you waited until I said, "GO" for attitude which is per standard procedures. Then I said to Donn, "ACCEPT", and that was a real powerful blow.

Cunningham: It was a POW.

Schirra: Boy, was that a crack. I didn't have any attitude problems, by the way. I was in RATE COMMAND.

Cunningham: No, I didn't feel any transient.

Schirra: I was still worried about that...

Cunningham: I didn't hear a bunch of jets firing.

Schirra: So, I was willing to expend the energy in RATE COMMAND and have that thing stay in there tight. I just didn't want any problems with it. I know, it was just making swoosh-woosh-woosh wobbles a bit -

Cunningham: The first thing you said after that was, "Boy, it's a beautiful control system."

Schirra: That's right. It worked just right.

[...]

4.5 Guidance

Eisele: [...] He went ahead and configured for ring A the way we had normally done it -

Schirra: That's after reentry attitude.

Eisele: That's right.

Schirra: In the ring A pulse, we called out rate high; and, of course, in pulse it didn't bother me. The only part of it was I had to let Donn fly it, and how beautiful that control system is. It is much better than the simulator. Real nice. We could hear every pulse very clearly.

Eisele: Real clear.

Cunningham: The control where you take your pulse were far less in the spacecraft than in the simulator, which made it very easy to ...

Eisele: If we could write in whatever our attitude was -

Schirra: I don't think we ought to worry about flying that thing in direct.

Eisele: No. I got very jealous.

Schirra: Beautiful. That spacecraft should go into the Smithsonian. It's beautiful; it deserves it.

[...]

Schirra: It was a hot ride to - Well, let's come up to the one that shook the hell out of me. The only that scared the hell out of us was when something on my side went pow -

Eisele: That's right, and when I saw it -

Schirra: Donn said we lost pitch and Walt said "What was that!", and I'm trying like a madman to bring all the thrusters back on the line.

Eisele: We nearly went back to two rings, using everything we could get. But what happened there: we'd been pulsing pretty heavy in pitch and yaw, you see, cycling fairly well -

Schirra: We were rotating, reversing bank.

Eisele: Yes, and the system was fighting all these moments that was going on. All of the sudden, this big hunk of whatever it was went POW. I was looking out the hatch window, and this big hunk of yellow -

Schirra: When I looked out my window, I thought the window - the outer pane of the window had blown out.

Eisele: You must have seen the same thing and all of a sudden. At that time, the thing seemed to stop firing. I said "Good grief, I've blown a pitch thruster."

Cunningham: Wally had a hard time getting over there. It was just like zap, they're all in.

Eisele: Apparently, what happened is that one or more chunks of the ablator came off rather explosively. I don't know how it happened. They just blew off. At the same time, we were into the atmosphere far enough that we had aerodynamic standing and didn't need the tip because you looked at the same the rate meters were moving. They really weren't going very far at this point. I think that's what happened, and we got faked out.

Cunningham: Was this before or after we bought the computer?

Eisele: Oh, this was after that.

Schirra: This was after we had reversed back.

Cunningham: Okay. It was after we had bought the computer.

[...]

Eisele: Well, we were just following our standard rule which said we would not believe the computer to the extent of doing the CMC AUTO until it did something smart with its bank angles. It just took this one forever to deduct and command a bank angle other than zero. I think part of it is that you maneuvered to a 55 degree bank; it started over-anticipating a little early.

Schirra: No, you gave me the .2g, and then I went for it. I didn't go any earlier then that.

Eisele: I think you did.

Schirra: Negative. In fact, I was behind you. Because at that point you said "Is that .2," and I said, "No, 67." You said "Roger," and then I started over. In fact, I didn't come over fast enough; I was real slow.

Cunningham: Here's the thing that got me about it. I was listening to you -

Schirra: It's supposed to be 20 degrees per second going over there, and I didn't go like that.

Cunningham: Well, I was listening to your conversation over there, and we were anxious to buy the computer to get the guided reentry.

Schirra: Well, I wanted that.

Cunningham: Wally was pumping Donn about -

Schirra: Well, I had a good feeling -

Cunningham: - is it okay, and Donn was holding off to the last minute. You know the last minute is funny. The last minute seemed like a long time, but it is the same place he always buys a computer, after the downrange area gets down to less than about 10 miles.

Eisele: The downrange area has to go down to about 9 miles before that thing will command the bank angle other than either zero or 55.

Cunningham: That's right.

[...]

Cunningham: When he finally did buy it, I think we bought it at the right time, and it was kind of a nominal time.

Schirra: You notice how he gave it to us? Voom! ... he flew it right in for us, and she flew. We were watching him like a hawk.

Cunningham: You know from that time on, I was impressed by the way that really blasted across to the other side.

Schirra: That machine is built to do the 20 degrees per second.

Cunningham: I know, but boy, I'd look out the window -

Schirra: - goof this little machine by not rolling fast enough.

Eisele: Yes, Wally flew in a normal, smooth way, I think, but when that thing got in reverse -

Schirra: That thing was wild the way it reversed. It even did one around the bottom which I got a big kick out of. It was smart enough to do that, and I wasn't smart.

Eisele: I didn't even notice it.

Schirra: Yes, it went around the bottom.

That was late, that was after we had already killed off most of the error. Oh, yes, there was a lot of - it got down there where there was a lot of ?? , It would just go swish, swish, swish. Well, it had to swap sides to take out cross range that it still had ...

Schirra: By the way, I want to go on record ... the leather elbow, pipe smoking boys did very well on this mission. You've got to hand them that, and I retract all my snide remarks except for the fact that gimbal lock still terrorizes me.

Apollo VII Technical Debriefing Part II

3.1.3 S-IVB Take-Over Demonstration

Schirra: Demonstration was I appreciated the cutting that time exactly as we planned it, and rapid response of everybody line in half because it was too long the first time we did it. That's one of the few rapid responses we had with DTO. They responded to that almost immediately in Huntsville. The S-IVB flew better than in simulation. I prefer it to go that way than I would the other way.

3.1.4 Return to S-IV Auto Control

Schirra: Return S-IVB automatic control, no problem.

3.1.5 Separation Transposition and Simulated Docking

Schirra: This was a whole new world to me, and I guess that was one of the big things we discussed and lost. I talked to almost all the command pilots out there on the horn. We really concentrated on getting on that Langley simulator. That's the only device that I know of that will do that. I suggest that they don't try to pitch around, particularly if they get faster than 5 degrees per second. I think that's a big mistake.

Eisele: There's no big rush about getting around.

Schirra: I opened at 1 foot per second, and then I descended to one tenth of a foot per second. Then I pitched between two and half and 3 degrees per second. It's still fast, but you get kind of anxious to see what is going on back there. Donn saw it right away and started saying "WOW, what a sight!" You don't know what's going on. I didn't know if it was going to come down on my back like a big train. When I looked out, all I could see was S-IVB all over the place. That one panel was in the way, which discouraged me from going in too close. That was the panel that I couldn't see when I came in. I aligned to the docking target, and we came in close, as the film will show.

Cunningham: I took that picture, and I didn't know we were that close.

Schirra: We were in there. I was afraid I was losing sight of that one SLA panel. It was catty wampus. I think it is a good decision to have the SLA panels go; that's the only way to do it. Get rid of those things.

Eisele: They have got to go out 30 degrees before they go.

Cunningham: I wouldn't guarantee that that was 30 degrees.

Eisele: Maybe 20 or 25 degrees.

Schirra: Those pictures are invaluable on that basis. That is a problem. I really didn't feel comfortable with this machine. It felt like a big, big truck. Another analogy I've used, was first time I had a boat, a trailer, or a house trailer behind my car. I was really scared to back that car up. I had to back the car up countless times before it never bothered me. That's the kind of analogy you get when you first see that S-IVB out there. It's awful big, and it is very difficult to maneuver the command module that precisely. We have a light command service module compared to the rest of the mission. I can only recommend the device we have at Langley for training crews. I wish I had gone up there. I would have known more about it.

3.1.6 SLA Photography

[...]

Schirra: I would like to go - back to that transposition. The mode I used was PULSE in roll and yaw and ACCEL COMMAND in pitch. I think everybody should use that one. Rather than RATE COMMAND in yaw and roll and whatever in pitch. That's the cheapest way to get around. Once you get around, you can start tightening up as you start getting ready to translate; then you might want to use RATE COMMAND for the three attitudes. I do think you need something to stabilize attitude when you translate. You could use DAP pulsively. Jet priority logic on subsequent SC may help the problem.

3.1.11 S-IVB Ventilation

Cunningham: Yes. I want to make note of the fact that we did see trash inside there. It looked like part of that charge stuff there. There were bits and pieces of that floating around. There was a lot of it. There's nothing really to talk about on ventilation, ice clouds, and vapors. They were just there. That wouldn't deter me from pulling in to take the LM. I definitely wouldn't want the S-IVB to start moving around. The CSM isn't that spry of a vehicle that you could go in there and fight some other system and try to fly as well if the S-IVB were moving.

3.2.9 Formation

Schirra: Formation flight is just about the same as transposition and docking. It's an expensive mode in the command module. I have heard people talk about the command module doing the docking with the LM. I think you will find it is much easier to use the LM for docking with the command module. It was just too big to move around. You still have a big load on that command module, but if that is a requirement again, I say spend a lot of time at Langley. We're not lacking for the tools to practice. We don't have a tool in Houston to fly command module active, but we have a tool for flying LM active. That is the only tip I would like to pass on.

3.3.8 ECS Radiator Test

Cunningham: Let's see, the next one is the SCS radiator test. I think it was a big surprise there initially. Donn started the thing out and found out that we were in minimum deadband - the 4 degree deadband, and the machine was kicking off thrusters like mad. Wally had already seen that we hadn't pegged what we call perigee torque yet.

Schirra: I remember you sitting in there for a while, and you were getting real worried saying, "My flight control technique, it's terrible, what is this?"

Cunningham: When Donn got out, I relieved him. Donn had eventually come to the conclusion that we were better off doing it in pulse in all three axes, instead of holding pitch and yaw and rate command. I got in there, and we were holding it in pulse. I must have gotten in there just as we started through perigee, and we were supposed to be holding within 5 degrees, and we ended up 10 degrees off.

Eisele: I said, "This is your crazy DTO, you better fly it."

Cunningham: That's right; he washed his hands of it; he did.

Eisele: I got out, got out, got out of there, went down in the LEB and blew my nose for a couple of hours. I was flying along and found out that the pulse was better than the attitude hold, and I was tweeking it in, holding within a couple of degrees, you know, just going along just fine, and then Walt got in. Apparently, right about then was when we started getting perigee because Walt started hollering about the thing wouldn't stay where it was supposed to. I looked, and he was 10 degrees off.

Cunningham: In pitch and yaw.

Eisele: I wondered what has he been doing wrong, so I got in and tried it again. After a While, it was doing the same thing. It seemed to be intermittent.

Cunningham: We were 90 degrees out of plane for the test.

Eisele: Yes, which is the worst case for the perigee torque business. And we were trying to maintain an ORB rate roll, which meant that we were coupling up between pitch and yaw all the time. I guess we got that comment on tape about how many pulses it was taking when you were in attitude hold.

Cunningham: Yes, we counted them, and it was a fierce number per minute in attitude hold.

Schirra: That is where we became concerned about these tight control modes.

Eisele: And then we went to all pulse modes, manual pulse mode, and the number dropped by a factor of ten, at least.

Cunningham: We finally finished the test, and it was a four and one half hour test. It turned out we were on the nominal amount of fuel which had been alloted for it, which was a lot more than Donn and I had figured we could do it for.

Schirra: I remember. You all got concerned about it, and I did take over towards the end because I wanted to find out what the control problem was.

Cunningham: Yes, you did relieve us for about an hour there.

Schirra: That is when we discovered the perigee kick, because I started calling up 82 and 83 to find out what kind of perigee we had. 83 wasn't any good since we were out of plane, so we called up 82, and I found out we were going through perigee when all these problems came up.

3.3.13 SPS Burn #5

Schirra: All attitudes were great. We started off the burn as a G&N burn, and at 30 seconds, we were scheduled to flip into GDC. [...] The surprise was that the burn itself was perfectly normal. The rate needles were never 5.5; the error needles were never displaced more than a degree. It was easy to control; it would often roll about 4 or 5 degrees, but that's nothing; that's typical. It's just that there is no real roll control in MTVC, just the stick, rather the hand controller. You don't fight that; it is like the old retros in Gemini or Mercury. If you don't fight roll, pitch, and yaw, they start to give you a little trouble. It didn't cup up; I just took out pitch and yaw, then I flipped roll in once in a while to bright it right back on. [...]

3.3.14 Passive Thermal Control Test

Eisele: This was a test aimed at seeing what kind of cross coupling, or coning, you could get if you tried to set up a small roll rate with absolute zero rates in pitch and yaw. It was also to see how long it takes for that attitude to diverge in pitch and yaw in a coupling and whatever torques there were on the spacecraft. It seemed to cone out pretty rapidly during this test. I really think that's because we are in an earth orbit, and even though you are up a couple of hundred miles you're still getting seme torquing and some interference from the atmosphere.

Cunningham: I show that the coning angle went out to about 4 or 5' degrees, didn't it?

Eisele: Yes, in the course of that 20 minutes or so, it was about 4 or 5 degrees. The part of it we were concerned with and discussing was the fact that the test required a period of about 20 minutes in tight deadband prior to the time that you initiated this slow roll and went to free in pitch and yaw. The intent of this period, primarily, was to damp out the pitch and yaw rates. We had found out earlier in the flight, that the best way to damp out the rates was to use the manual pulse mode rather than rate damping. The tight deadband served no purpose other than to eat into the RCS fuel budget, and generate small rates in pitch and yaw, which we never did zero out. We tried to explain that to ground controllers and apparently it never was fully understood by the people responsible for this DTO. So we went ahead and did it as programed and found that the coning was significant.

[...]

Eisele: The other aspect of the test, and they added on another part to it, was to do a slow pitch maneuver rather than a roll maneuver. We performed that in the same manner with the tight deadband for 20 minutes, and then went to free to do the pitch. I don't know if that turned out any better. I don't believe it did; we still had some crossed coupling in the other two axes.

3.3.17 SCS Backup Align

Eisele: The first surprise on this one was that the south set of stars were not sufficient. We found out that the south set stars were only visible during the night pass for about 6 or 8 minutes, and we didn't think that was long enough to permit us to do a proper assessment of these backup alignment techniques. So we consulted with the ground; they came up with the north set of stars, Navi and Polaris. So we used those, and the test of them worked out very well. Wally maneuvered the spacecraft around to the approximate attitude on the IMU ball, and then I took over in the G&N station with the impulse controller. It was a rather difficult and tedious task to try to align the thing very precisely because you have to control all three axes simultaneously. What I attempted to do first was to take the key star, which was Navi, and put it on the 50 degree mark of the telescope's crosshair, and then go to attitude hold in pitch and roll. I figured that would hold it on the spot. Then I did a pure yaw maneuver to bring the other star on the line. Well, when I did that, I forgot that the SPS lets go of the attitude hold in all three axes anytime you break the hand controller out of the detent. So it didn't hold on that 50 degree mark, and I ended up going back to pure pulse for all three axes. After numerous attempts to get both starts in exactly the right position, I finally settled for a condition where I had Polaris right on the line and Navi very close, but not quite right on that 50 degree mark. I tried it several times and finally settled for what I thought was the best feasible thing to do, so we coarse aligned the CDG at that time. Actually, Wally was holding the GDC align button and he released it when I said, “Mark.” We took that as our alignment. We then flew back to the 0-0-0 angles on the GDC ball and made the comparison with the IMU which was also aligned for that purpose. We found that the error was on the order of a quarter of a degree, which I thought was pretty fantastic. I'm not sure whether we just lucked out or whether it's really that good. The point is, it's tedious and time consuming and uses some amount of RCS fuel, but it does work, and it works very well. I would not hesitate at all to use that for either an IMU or an SCS backup alignment if I had to.

6.0 Systems Operation

6.1 Guidance and Navigation

6.1.5 G&N Controls and Displays

Eisele: [...] All I can say is that the rotational hand controllers worked just as advertised throughout the flight except for one time when we had an apparent sticking of a breakout switch in pitch on hand controller number 2. It was toward the end of a very active day, and we decided rather than troubleshoot it right then that we would power down the system and check it the next time we came up. The next time we came up, it wasn't there, so we never did find out what caused it or where it went. The number 2 controller hardly got used at all. We did run through a check of it through the use of the computer by calling up the appropriate channels and looking at the input channels to the computer. We could verify that the number 1 hand controller was putting out the right signals. [...]

6.2 Stabilization and Control

Schirra: Okay, that's no problem. All attitude reference systems were great. The only thing I can stress was the surprise - and it shouldn't be - that if this feels like a big ball, just imagine how big it's going to feel when they pull off the S-IVB.

Eisele: And when you got the lunar module hanging on the front end to boot.

Schirra: Accel command is a great mode and I like it. The only problem with accel command is that you've got a “hot stick” and if anybody bumps it, you've blown it. Where in pulse, if you're “hot stick,” all you get is one pulse if the guy bumps you. We had one case where it was a combination of problems: I left pitch in accel command, and all three of us raced over to look out Walt's number 5 window to see the hurricane. Donn came up and kicked the stick, and I never before got back into my couch so fast. We had about 1 degree per second in pitch and I stopped it. That was the end of it. I goofed by leaving in accel command and Donn goofed by hitting it.

Eisele: That's a good point. There's an awful lot of traffic in and out of that center couch and both hand controllers are right there. You do have to discipline yourself to remember to keep the doggone stick locked up when you're not using it. You also have to discipline yourself when you're going through that passageway to be careful you don't bump into those things.

[...]

6.2.1 Control

Schirra: We ran a fairly careful calibration of how many pulses in pulse mode were required to produce a given rate in all three axes. The rate we used was .2 degrees per second. In roll, with two-quad authority rather than four, we had seven to eight pulses required for two tenths of a degree per second rate. For pitch and yaw, it was about ten to eleven pulses per two tenths of a degree per second rate, which really [text cuts off]

6.5.11 Cryogenic System

Schirra: [...] I found that for any rate more than one tenth of a degree per second, it was much more practical to use acceleration command. I used RATE COMMAND only for attitude holding when we were translating if you either had ullage or were translating during the braking phases or rendezvous phases.

Eisele: For line of sight measurements during rendezvous also, that's about the only time.

Schirra: For any other line-of-sight measurement such as the COAS alignment, pulse was the only way to go, other than when we switched from one star to another. I wanted to go RATE COMMAND there, but I had to have the cockpit completely dark, and as a result, I used the pulse in that case, but it was more expensive than I would have liked to have made it.

Eisele: I guess the point is that the pulse mode is your fundamental control mode for just about anything you want to do.

Schirra: That's terribly luxurious.

Eisele: I think that the postflight data will show that their design intention was way off what we really saw up there because that thing really cycled back and forth very rapidly.

Schirra: That can be avoided, though; you don't need to redesign just to -

Eisele: Oh, no.

Schirra: People have just got to understand that we know how to fly it.

Eisele: What you have to do is do your roll in pulse so that you control the roll deadband effectively by your manual inputs and not allow the automatic to do it. The other deadband modes seem to work pretty well. I don't know what the fuel usage rates actually were, but they were far less than the flight plan.

Schirra: There's one we should make note of, and that was the early phase of the flight where we did the yaw deadband. I got some data on that in my zip flight plan here. When we were venting (while it was working the first part of the mission), it caused us to go off to the right, yaw right, and it cycled between 7.9 degrees yaw right and 7.1 degrees yaw right. So it actually flew on the edge of the deadband; it oscillated back and forth in that regime for a long period of time, never leaving it. I'm just trying to find out what the delta time was because it was rather surprising to stay over there like that.

Schirra: I think it was a minute and 55 seconds, or a minute and 5 seconds. The conditions were SCS attitude 1, rate 2, limit cycle ON, attitude MAX, rate, attitude deadband MAX, rate 5. That roll, approximately 174 degrees, pitch 349 degrees, yaw varied between plus 007.10; that's 7 hours 17 minutes 3 seconds to plus 007.82 degrees which is a delta of .72 degrees. At 7 hours 18 minutes 56 seconds, which was 1 minute and 53 seconds, it cycled back and forth, roughly between these numbers, meaning it was yawed right and rode the right edge of the deadband. The only variable that was causing this was the - this was not the perigee torque; this was early in the mission. This was caused by the steam vent water boiler combination, forward in the spacecraft. We tried all control modes, but for the very, very high rate modes, which weren't required, they did work during the rendezvous modes. I don't believe in spacecraft checkouts for control systems, like airplane drivers like to do it. It's very expensive. You use it; if it works right, it's fine; that's rather than this classical manual maneuver in G&C control mode .05 degrees per second, .5 degrees per second and 4 degrees per second. We never at any time flew at rates of 4 degrees per second. Even the pitch turnarounds were at two and a half to 3 degrees per second. As the degrees per second go up, the fuel consumption goes up, proportionately and violently.

Eisele: I think we hit every mode in there except those high rates - -

REP: The TVC's, DELTA-V's, RCS and SPS interface; any problem there?

Schirra: No.

REP: Okay.

Schirra: I believe we were right in our preflight decision of not checking out the command module RCS thrusters, both from a time-line basis and from a real-time observation that we had propellant right up to the thruster solenoids. There's no doubt in our minds that that even occurred.

[...]

Eisele: Just discuss the rotation hand controller.

Schirra: We did try direct/direct, and the technique there is to take the stick all the way out to the soft stop and just blip from that, and you can get a short pulse of about one tenth of a degree per second which is sufficient to back up a pulse mode, or I think it is usable for a re-entry, but as you get g on, it's a very difficult task. This is merely coming up with the feeling that the soft stop is tough and then just go along a little bit and watch the result of this, rather than feel it or hear it.

[...]

REP: We were talking about control ... rotation, translation, different modes here.

Cunningham: Well, our preferred mode was PULSE and an occasional ACCEL COMMAND input and, on very rare occasions, using RATE COMMAND.

Schirra: [...] Another problem we found was switching from PULSE to ACCELL COMMAND. Unless we switched rapidly through RATE COMMAND position, which is between the two, you get RATE COMMAND lock-up, meaning that you would stop the rates you had, either from ACCEL back to PULSE or PULSE to RATE COMMAND. This would waste your fuel, but you could set up a rate you wanted, and maybe you'd want to stop it with PULSE or ACCEL COMMAND, just reversing the modes. Going through RATE COMMAND, if you went slowly, you'd stop at RATE COMMAND; that got expensive. You might not want to stop it; you might want to increase it. Ideally - and that's for future design; I wouldn't change it in any of the command modules - RATE COMMAND should be on either end, not between the two modes. It's not a major crisis; it's just something that technique hasn't been thought out too well. [...]

[...]

Eisele: Translator seemed to work fine; we didn't have any problems with it.

Schirra: Never.

Eisele: In both G&N and SCS. I don't know what this means, automatic.

We didn't do any automatic maneuvers in SCS; all it can do is attitude hold. It does that very satisfactorily. That minimum deadband is a very nice type deadband. It's very useful for things like line-of-sight measurements in rendezvous and also holding a precise attitude just before an SPS burn, but it's also a very expensive mode. One thing we noticed - this is to a degree subjective because it was kind of hard to measure on board, but it seemed that the limit cycle switch didn't really help all that much, particularly in this tight deadband configuration. The limit cycle is supposed to cut down the number of firings, the frequency of them. It didn't seem to make much difference whether it was in or out because the thing in tight deadband would cycle rather rapidly and roll back and forth. You'd get a pulse every few seconds, and it would drive to the opposite side of the deadband, fire another one, and come back. You could get around this partly by trying to set up a single jet configuration. If you push and pull the right combination of circuit breakers -

Schirra: Can't do that. You have to go into ACCEL COMMAND to do it.

Eisele: Yes.

Schirra: The only way you can do that is to turn the roll attitude hold off and use PULSE in that mode, in that attitude, in ROLL. That's what I was complaining about in flight. It's very expensive to hold attitude in SCS minimum deadband, limit cycle OFF, minimum deadband, low rates. The roll would - well, attitude very technically would pulse back and forth at the rate of two tenths of a degree per second, holding this very tight deadband on a two-tenths of a degree roll attitude. That's terribly luxurious.

6.6.6 Waste Management System

[...]

Schirra: I know on Mercury I wanted less than a 1 pound thruster, for example. We didn't have pulses as such, but we used a small thruster. They were great. I'd say that in Mercury, we got about two tenths of a degree per second for a minimum fly-by-wire thrust in a 1-pound thruster. I bet you get more than that out of these overboard dumps. Although the acceleration is not there, you are getting the rate by letting it build up over a period of possibly a minute.

[...]

J.3.2 Apollo-9

4.1.2 Separation, Transposition, Docking, and Extraction

Scott: [...] Separation from SLA: We started the DET at the time we separated from the S-IVB. The plan was to thrust for 4 seconds which should have given us about 0.8 ft/sec separation velocity. I noticed on the EMS, which had been set up at 100 ft/sec to compensate for the drift, that after 4 seconds we only had approximately 0.4. I continued thrusting until we had approximately 0.6 on the EMS which took approximately 6 seconds. At the time I attributed this to a difference between the simulator and the actual vehicle.

We started the pitch around at 15 seconds at approximately 2 deg/sec. I guess the first indication I had that we were doing alright was when Jim saw the S-IVB. As I recall, it was well before we pitched 90 degrees that Jim saw it through the hatch window. His comment was that we were in the proper position for the turn around. When we completed the 180-degrees pitch maneuver, I noticed that the alignment was somewhat off in pitch and that to get the needles nulled, I would have to pitch up approximately 10 degrees. At that time, I became suspicious of our angles that we had gotten in preflight because we previously had so much trouble with them.

A summary of the transposition and docking is contained on the onboard SONY tape. Upon looking back at the indications we had on accelerations and pitch attitude after the separation and during the transposition, it is obvious that quad C was not working, because we got less than the nominal amount of acceleration. Also, we were in the improper pitch attitude when we turned around which might justify the technique of accelerating out at a greater-than-necessary velocity to compensate for a quad failure, which is, incidentally, one of the things we did not have time to simulate very much other than the procedures. Another significant thing that we noticed was that the venting of the S-IVB caused a somewhat greater acceleration than what we had expected from reading the preflight data and also, from observing the vent model in the simulator. You could visually see the venting take place from the side of the S-IVB. It is a continuous vent, but you can see the pulses as the system vents. We did not get any indication from the ground as to what the vent model was – whether it was a high vent model or a low vent model.

[...]

The control systems worked very well once we got the quad problem squared away. Both the SCS and CMC DAP were good solid control systems, and the docking task was relatively easy as far as the aligning with the standoff cross and doing the actual contact.

4.2.8 Performance of Burns 2, 3, and 4

McDivitt: Prior to starting the stroking test, we had been maneuvering the spacecraft; and with the tremendous mass of the vehicle, the minimum impulse was almost imperceptible on the rate needles. We had used the acceleration command on a number of occasions, and when we did, I felt that there was coupling between a pitch input and a vehicle response of some sort – an oscillatory response in both pitch and yaw. It felt as if it were coupling the same way that the SPS stroker test coupled on the MEI04 simulations that we ran at North American. Frankly, I had expected to see some tremendous oscillations when we did the first stroker, and I didn't expect that we'd even get into the second stroker because of the way the spacecraft combination responded to just the RCS thruster inputs.

Scott: Yes, I agree with that; and it seemed that with a good acceleration pulse, the whole combination would bend. You could almost feel it bending; but when we actuated the stroker, we didn't get this same bending sensation physiologically that we had experienced with the acceleration command RCS. The feeling was not so much like a loose joint between the two vehicles but more like there was a flexible rod that would couple pitch and yaw because of the bending.

[...]

SPS number 3 was a G&N burn of 4 minutes and 42 seconds, with a 100-percent amplitude stroker after 1 minute and an MTVC SCS rate command for the last 45 seconds of the burn. The start was the same as SPS number 2. When we initiated the full amplitude stroker, the response was similar to the mission evaluator at North American, except that the amplitude was not as high as we had experienced there. The pitch rates during the first 3 seconds were approximately 0 to minus 0.2, 0 to peak, and then at damp to plus 0.2 and oscillated around the plus 0.2, coupling in yaw as it did on the mission evaluator. There would be an oscillation cycle in pitch; then it would couple to an oscillation cycle in yaw and then back to pitch, with amplitudes about one-third the values that we saw in the mission evaluator. On the mission evaluator, we saw an oscillation of plus or minus 0.2 degree per second, approximately a minus 0.2 in pitch; whereas, in flight, it was just an oscillation from 0 to 0.2. Therefore, it was about half the amplitude that we saw in the mission evaluator.

It appeared that all the oscillations damped within approximately 10 seconds after the completion of the stroker. After the stroker damped, the DAP again drifted over to the minus 5-degree roll deadband and sat at that point until we initiated the MTVC by switching the spacecraft control from CMC to SCS. When we performed the switchover, the SCS TVC brought the spacecraft back to zero roll with a noticeable transient. In fact, the main transient that we noticed was in roll. This was noticeable physically and on the FDAI. By the time the rates stabilized after the switchover, the G&N error needles were almost full-scale yaw left and pitch up, which required a manual control back to null the error needles, since we were using those for our display. The GPI indications at the time of switchover were at pitch of approximately 1.9 degrees and a yaw of approximately minus 0.6. The trim values were set at a pitch of plus 1.1 and a yaw of minus 0.2. Thus, there was a noticeable difference in the gimbal trim settings relative to the actual position of the gimbals when we switched over.

The rotational hand-controller response seemed more sensitive than on the mission evaluator at North American. However, the needles could be nulled without difficulty but tended to start moving immediately after reaching a null position.

McDivitt: It was more difficult to stop the needles and have them remain at some fixed position than it had been in the simulator. The stick integrator appeared to work alright; it just seemed as if the c.g. was changing more rapidly than we had experienced in the simulator. The residuals on shutdown were plus 2.7, minus 2.1, and minus 2.6.

[CSM LM Undocking, Proximity Operations, and Separation]

McDivitt: When the command module began his RCS separation burn, I began tracking him in PGNS RATE COMMAND. PGNS RATE COMMAND provides a very good control system. I was in fine scaling. I was able to track him as he moved away; the rates went to about 1 deg/sec, and he was easily tracked in this mode. When we got to some distance where the 1-deg/sec rate looked like it was going to hold, Rusty inserted a VERB 76, ENTER, which put us in PULSE. I then tracked him in PULSE for the remainder of the time and PULSE CONTROL provided an excellent control mode, even with the descent stage still attached.

[...]

Scott: At the completion of the inspection of the LM, I prepared to do the automatic maneuver to the separation burn and P41. When Jim took over stationkeeping, I went to MINIMUM IMPULSE or free drifting mode.

There was very little effect, and it's obvious that you could stationkeep in MINIMUM IMPULSE with no problem at all. The separation burn was performed on time and the DSKY read 5.0 and the EMS was 5.2 feet-per-second. It took approximately 12 seconds, which was the same time required during the simulations.

[CSM LM Rendezvous and Docking]

Scott: Formation flying: After the completion of braking phase, the LM pitched over so that the CSM could visually observe the ascent engine. Everything looked as if it were intact with no pieces missing or insulation torn off, and it was easy to look into the engine nozzle and even see the injector and the chamber, apparently because of the sunlight reflection at that particular time. The nozzle was black, the chamber was still silver, and everything looked clean and smooth. The pulsing of the RCS jets was visible. It looked as if the particular control modes used were very active. During the terminal part of the docking, it seemed as if the jets were firing almost at intervals of 0.2 or 0.3 second. The final approach to the contact by the ascent stage looked very smooth. There were no overshoots or oscillations in attitude. It appeared, even though it was a very slow closing rate, to be a very stable closing rate.

Docking and pressure integrity: At the point of contact, when the LM got into the probe/drogue contact point, it was well within the boundary as indicated by the diamond on the target on the LM relative to the CSM COAS; and I would have estimated the contact velocity at about 0.1 ft/sec. Approximately 7 seconds later, I got the barber poles on the capture latches and then proceeded to stabilize and align by using a minimum impulse. As before, it was effective to align the two vehicles by using the CSM COAS and the LM target. We had decided prior to the contact that we would not do an automatic retract because of the questions we had on the EXTEND RELEASE switch.

[...]

Docking and integrity checks: From the command module side, there was never any question about being able to perform the final docking. The only problem was that the COAS again faded on a white docking target on the LM, and it was very difficult to see the COAS even though it was visible. We do need a brighter, sharper COAS.

McDivitt: After we got close to the command module and began station keeping, we did an auto maneuver at one-half deg/sec, narrow deadband, and another one 2 deg/sec in wide deadband. Once again, the DAP performed very well with no problem at all.

[...]

Maneuvering to docking attitude and translating to capture latch: We installed the COAS in the overhead window, and it was apparent as we were in close that the COAS on the command module and the command module sunlit completely faded out at any kind of range at all, and that we would have to use a little intuition in the docking. I pitched around to the 90-degree point and then, looking through the overhead window, I found that the upper part of my helmet was all scarred up and I was having a little bit of difficulty seeing the command module through the top of my visor and the COAS. When the COAS is superimposed on the command module, it is impossible to see any portion of it whatsoever. I started to dock and thought that I'd better make sure that the whole thing works. Therefore, I maneuvered to one side and looked to see if it was still all there and got a pretty good idea of where it should be by looking through the overhead window. I moved back in, and as I closed, it was still almost impossible to see the COAS. I had to maneuver my head around and try to see the docking target and the COAS together, neither one of which was very bright. After some manipulation, we were able to get in close enough where the COAS did appear on the docking target, which was back inside the shadow of the command module window. As I got in close (about 4 or 5 feet), I began to see the COAS appear against the darker background of the window, when the window began to fill up a little more of the COAS. At that time, I could tell what my attitude was with respect to the docking target, and I could see what my translational position was with respect to the docking target. I maneuvered around at this fairly close range until I was in a proper attitude, and I went ahead and docked. During this particular time, Dave was telling me that I was inside of the safe boundary, outside of it, or whatever my position was, and gave me a good GCA until I got down where I could see the whole thing. I think that the COAS brightness has to be increased manyfold so that it can operate in a bright environment like this; and I think it also would be worthwhile to brighten up the docking target, if at all possible.

[...]

I'm not sure what the closing rate was. It was very low because of the proximity at which I finally located the COAS and the docking target. The light weight of the ascent stage made it so that I never really did stop the translation left/right and the horizontal components with respect to the docking probe and drogue. I had to thrust continually left and right and fore and aft, or whatever that other direction is, to keep myself within the boundaries of where I wanted to be prior to contact.

Docking: We got in close, and the standoff cross on the docking target filled the 2-degree mark on the COAS. I went ahead and started thrusting. This indicated that we were at just about the point where we were captured. It clunked in, and I could feel the drogue and the probe make contact very gently; and Dave called a couple of barber poles. Dave said it took 7 seconds of thrusting from the time I started until the time we got the barber poles. At contact, when Dave called the barber poles, Rusty inserted the VERB 76 ENTER, which put us in a free mode, or a PGNCS pulse mode. We were at the end of the probe, captured, but not latched up with the two tunnels together. Dave then damped whatever residuals rates we had because it was very difficult to see these rates from the LM side.

[...]

McDivitt: IMU coarse and fine align: When we completed the radar check and opened up the radar circuit breakers, we began the first alignment of the IMU using the LM-only data. We maneuvered, AUTO maneuver, to Sirius prior to sunset, and when we got there, I was able to see Sirius without any problem at all. It came right into the center of the AOT.

[...]

The technique that we had worked out for alignments was for me to watch the star and call the pulses left, right, up, and down to Rusty, who put them in. It seemed to work even better in actual practice than it had in the simulator. The simulator provides an additional problem in that it's very difficult to see near the center of the telescope because of the mirror configuration in the simulator. In the actual spacecraft with actual stars, we were able to maneuver through the X and Y lines much closer to the center of the telescope. It was much more easily done and done a lot quicker, too.

We did the maneuver over to the next star, Acrux. As the maneuver took place; I could see the stars coming up and the spacecraft pointed essentially at Acrux, which indicated our docked alignment was once again quite good. Here again, we had no problem aligning on Acrux and made the 10 marks that we were going to use there. I might add that at the completion of this, we had five zeros, which was something that we had never even come close to in the simulator. It's much easier to do it in the spacecraft than it was in the simulator. The star angle difference was five zeros.

While looking through the. telescope at the stars, the spacecraft was being maneuvered in PULSE mode, and the flash of the thrusters could certainly be seen as an orange cloud, but didn't in any way affect the ability to see the stars.

[...]

On the completion of the alignment, we did a star check using the COAS. This was not as easily done as I had hoped. Unfortunately, we had the moon in the view. We were using Spica as the star. We had the moon and a very bright planet, and Spica by comparison was quite dim. However, we were able to identify it, and when we did, the COAS calibration showed that the star was 0.5 degrees to the right and zero up and down, which was certainly within the bounds that we expected.

Schweickart: From the LMP's side of the cockpit, the alignment went very smoothly. The mode 2 error needles gave me an excellent picture of how the star was behaving in the AOT, and the callouts that Jim would give - one or two pulses right or left, up or down - corresponded exactly with what was displayed on the mode 2 error needles. And this, of course, enabled me to keep track very easily of where the star was with respect to the center of the X-Y lines.

[Post-Separation Maneuvering]

McDivitt: Maneuvering of LM: At this time, we enabled the flight control system, and rather than do all the maneuvers that we had anticipated, we eliminated some of them.

We enabled the flight control system as planned and did our 120-degree yaw maneuver. Then, instead of doing the 180-degree pitch maneuver, where we show the descent engine bell to the command module, we decided to eliminate that and just do the 90-degree pitch maneuver, so that we could find ourselves in a position where we were looking at each other and still have enough time to prepare for the seperation maneuver. We did this under AGS control. After we'd done the 90-degree ptich-down, we maneuvered to an attitude that put us in plane. We were still somewhat off in pitch attitude. We then started our 360-degree yaw maneuver using pulse control. We were back on the timeline at this time. We were at minus 18 minutes from the separation maneuver.

Formation flying in AGS and PGNS: The pulse modes, both the ones that we had used so far, operated fine. The ATTITUDE HOLD mode on the AGS operated fine, but the RATE COMMAND mode of the AGS for orbital flight is a very poor flight control mode. It's impossible I believe, to command a desired rate at low rates using AGS rate command. The stick is no more than displaced from neutral when we had rates in the order of 1.5 deg/sec or so. On the simulator, I displaced the stick and established a rate, and then Rusty would move the switch to the pulse position to establish a rate. We had a considerable amount of difficulty getting the rate established at some relatively low rate, and getting the pulse switch thrown so that we could continue on around at this lower rate. I think the AGS RATE COMMAND mode may be alright for landing, but it's certainly a very poor control system for orbital flight.

After completing the yaw maneuver, we went to PGNS ATTITUDE HOLD to stop the rate. We then went to AGS control and did some stationkeeping in AGS. As I mentioned, the ATTITUDE HOLD mode is fine. It doesn't limit-cycle excessively, it attitude-holds properly; it's just that whenever you try to do any rate commanding, it's very poor. The station-keeping in AGS was no problem at all and the same with PGNS. We did some station-keeping in PGNS and it was also very easy to do. It's worthy to note, though, that there were very few inputs required for stationkeeping. It was easy in either control mode.

[...]

McDivitt: Preparation for phasing burn: The maneuver to the burn attitude was done manually using pulse mode, which was the flight control mode used during almost 99 percent of the flight. We operated in PGNCS pulse. We flew to local vertical attitude and it was a good chance to see how the spacecraft really performed in this semi-heavyweight configuration. There was a fair amount of fuel left in the descent stage and the ascent stage. I think that this mode is certainly adequate for the kind of maneuvers that take place in orbit. As we got down close to the burn time, we switched to AGS pulse and again this control mode is very good, very good.

[...]

McDivitt: Preparation for the CDH burn: [...] With the ascent stage only, the pulse mode was still a very effective mode. It gave a little snappier response than it did when the descent stage was hooked on. It compared quite favorably with the response of the simulators, but at this point, I began to notice even more the lack of fidelity in the rate needles that we had onboard. Earlier when the pulse input was causing a lesser DELTA rate change, I could watch the needles and see how the spacecraft was actually behaving. If I saw the thing deviating, I had plenty of time to stop it. With the higher rate changes per pulse without the descent stage, I really got so that I had a stronger and stronger desire for a set of accurate rate needles. I finally had to give up almost completely on the rate needles. I went to the radar error needles and upon watching the rate with which they changed, I used them as my rate indicators. I just almost completely forgot about the rate needles as displayed on the FDAI. It's unfortunate that they weren't more sensitive and more accurate, because we did a lot of pulsing back and forth across the correct attitude trying to get these needles to stop when we could have used the rates; and with that information, we probably could have stopped it a little better.

[...]

McDivitt: Operation of the PGNCS and AGS: I'd like to review the control systems again. I felt that the pulse modes, both PGNCS and AGS, were very good modes. We used them predominantly through the orbit periods, the nonthrusting periods. The DAP operation was smooth with no overshoot. It appeared to be a very fine control system, both for attitude holding, automatic maneuvers, and manually commanded RATE COMMAND. The AGS appeared to attitude-hold properly, and I felt that the RATE COMMAND just had too much authority and could not be used without overcontrol. During our coasting phases between burns, I noticed no tendency of the LM to trim to any particular attitude, and there didn't appear to be any drag or any external effects influencing our attitude. When we put it some place, it stayed there. I think that the rate needles in the LM certainly need improving. I think that we could have saved a considerable amount of fuel if we had just known what our rates were. I doubt seriously if we ever get them to be comparable to the 1-deg/sec rate read-out that we have in the command module with its accurate gyros; but if we could, it would certainly be a worthwhile effort.

[...]

McDivitt: Formation flying; attitude control: When the command module broke out into the sunlight, it appeared as a little white silver blob and then sort of formed a crescent shape. The sun was shining from my right, and I could see the right side of the spacecraft first. As I got in closer, the sort of crescent became larger and larger until I could see the command module very well at approximately 1500 feet. We had no trouble stopping. We just coasted right up in front and stopped at about 25 or 30 feet; and at the time, we had something like 60 percent fuel remaining.

Braking: We arrived at 6000 feet at just about 30 ft/sec, and this was our first braking gate. No braking was needed. We coasted right on through. At 3000 feet, we braked to 20 ft/sec, and I felt that it took just a little bit longer to take out the Delta-V in actual practice than it did in the simulator.

We then braked to 10 ft/sec at 1500 feet and 5 ft/sec at 500 feet.

Docking: While we have demonstrated that you can dock with the LM as the active vehicle, which was one of the DTO's that we were supposed to accomplish in this particular mission, I personally recommend that all the dockings be performed command module active because of the much better visibility and the much better target that the command module has and because of the sort of standard configuration where you are thrusting in the direction in which you are looking and where you don't have to make a coordinate transformation before you hit the control handle everytime. I think that we have demonstrated a backup system here, and I personally feel that in the future all the dockings ought to be command module active and the LM used only as a last ditch kind of thing. In the lunar orbit mode that we were supposed to be demonstrating, I think that when the command module has accomplished the docking, has the probe inside the drogue, and there has to be some thrusting, he can call thrust and have the LM do the thrust maneuvering and let that be its part of the docking maneuver.

[...]

Schweickart: [...] LM closeout and APS interconnect: [...] The maneuver to the final attitude for ejection was done in the LM again by using the ACA for yaw control and the TTCA for pitch and roll. This proved to be no particular problem as far as maneuvering was concerned. When we arrived at the LM attitude for the burn, the CSM was informed and took over attitude holding at that point in narrow deadband. The LGC was configured to wide deadband ATTITUDE HOLD. At this time, the AGS was updated, aligned, and put into configuration to support the APS burn to completion. During the docked alignment, the second star that was selected was occluded by the earth before we were able to take marks on it, and a third star had to be selected mark on. Unfortunately, the way the alignment program is set up, there was no way to get the mode 2 error needles for this star. As a result, there was no assistance for the maneuvering other than calling for pitch up/down or yaw left/right by the commander who was looking through the AOT. This did make attitude control more difficult during that alignment.

[...]

Preparation for LM jettison and LM jettison: In preparation for the AGS burn to depletion, we received from the ground a P30 update which was inserted. Prior to pressing on with the checklist, we did a docked alignment, active from the LM side. For this alignment, we used LM attitude control for yaw. For pitch and roll control, we used the horizontal thrusters with the

TTCA to keep from firing the vertical thrusters toward the CSM. This made the rates of the vehicle during alignment a bit higher than was experienced using pulse mode with the LM alone. However, the star angle difference came out to be all zeros again, and the torquing angles hopefully are recorded on a tape somewhere. I don't happen to have them here now, but as I recall they are all quite low.

[Landmark Tracking]

McDivitt: We performed landmark tracking a number of times. Overall, it proved to be successful; however, it was significantly more difficult in earth orbit than it will be in lunar orbit, primarily because of the rates at which the spacecraft goes across the ground.

We used the standard in-plane alignment for all the landmark tracking, even though the spacecraft ended up being pointed perpendicular to the plane of the orbit. After we received the pad messages, we determined whether the landmarks were going to be to the left of the track or the right of the track. I'll discuss only one direction. If the landmark were going to be to the left of the track, I would align one of the balls with the orbit rate torquing on it, yaw the spacecraft around to the left, and position the X-axis so that I was just outside of the red circle on the FDAI which indicated gimbal lock. Then I would bank the spacecraft so that the telescope would be looking in the direction in which the spacecraft was actually traveling. It took constant looking after the spacecraft because the spacecraft tended to trim back into the plane of the orbit. Therefore, after I had maneuvered around into a position where I was pitched down approximately 20 degrees, I would be banked to the left approximately 60 degrees. I would hold the spacecraft in this attitude until Dave said that the optics had tracked up to the horizon and then started tracking down on the part of the land mass that he could actually see. As Dave had mentioned earlier, the PAD was changed from the initial PAD times, when we received only the time when the landmark would appear on the horizon, to include the time when it would be directly underneath us or when we would have our point of closest approach. I set the digital event time up so that it counted down to this moment of closest approach and then called the times to Dave and tried to establish a slow roll rate so that, when we arrived at the time of closest approach, the spacecraft would be essentially wing's level pointed directly out of plane, to the left and pitched down approximately 20 degrees. As the target passed underneath us, I would continue to roll around so that we could track it out the rear. The roll rate had to change as the target approached us when it was out near the horizon. It was very low, and as it passed underneath us, it required about 0.6 deg/sec if we had the time of closest approach correct and had maneuvered properly. The time of closest approach was very critical, and if we were off by approximately 30 seconds, so that I still had the spacecraft rolled to the left waiting for the time of closest approach and the target actually passed underneath us, it required a very high rate (almost more than 1 deg/sec) to keep the optics off the stops. It took a little bit of coordination between the man in the optics and the man guiding the spacecraft to make sure that the roll rates were such that the optics drive modes did not have to be continually changed. It was possible to make two landmarks, and I think we could have made three landmarks across the dayside pass.

It required approximately 10 minutes to do one landmark tracking – approximately 7 minutes prior to the time of the landmark and approximately 3 minutes after the point of closest approach to get set up for the next one. I did all of these landmark trackings with only six jets operating, two for pitch, two for yaw, and two for roll. Even though I had only two for roll, I still had plenty of roll control. I do believe that some of the attitude excursions that occurred in pitch and yaw were the result of firing only one jet in roll, because as the c.g. moved back and forth, we were contributing some pitch or yaw by firing the roll thrusters. I did not have any trouble at all establishing the roll rates and maintaining the ones that I wanted with only one thruster firing in each direction. I used minimum impulse throughout the entire time; In placing the spacecraft out of plane, it was necessary for us to pitch down rather than pitch up because some of the landmarks were fairly close to track; but we did pick up some landmarks as far out as 78 miles, I believe. We were still able to handle landmarks directly underneath us and out to a range of approximately 80 miles by pitching the spacecraft down 20 degrees. We never seemed to have any problem with the landmarks being too far out. I think that if they go out at distances greater than that, it may be necessary to pitch up above the gimbal-lock point rather than down below it.

[CM/SM Separation]

McDivitt: [...] Everything went according to the checklist. There wasn't any problem. We yawed right to 45 degrees, got everything set up, and boomed off the service module which went off with a big bang. There wasn't any doubt about the fact that it was gone. We set the switches up single ring – number 1 on MAIN A, maneuvered back around to the zero yaw attitude, rolled over and pitched up to put the horizon on the window at the right spot (-32.5 degrees), and tracked around. That part of the checklist and that part of the maneuver went just the way it was supposed to go. I used single ring pulse, maintaining the -32.5 degree attitude line near the horizon until we got down near 0.05g. As we approached 0.05g I tightened up the control of the attitude and put the line right on the window as I was supposed to do. The attitude errors were down to practically zero at 0.05g. Dave points out that, as we went around, the G&N needles were driving us to a point that did indeed put the 32.5 degree line on the horizon and that we had a real good confirmation that the G&N was steering us in the proper attitudes through this portion of pre-reentry.

One thing that might be worth pointing out is that the single ring pulse is a real nice control system; it is snappy. You can really hear the thrusters banging, and it gives you real fine control of the spacecraft. It is not an over-control situation, but you do not have to wait there very long for it and it will bring you right where you want to go.

[Reentry]

McDivitt: When we handed over the control of the spacecraft to the CMC at 0.05g, it performed just the way I had seen it do in simulations; and just the way I had expected it to do. There wasn't a single anomaly.

[...]

McDivitt: We flew all the way down in G&N attitude control mode. I had the rates scale set to 55. There was no problem.

[Stabilization and Control System]

Scott: [...] I did find that when the spacecraft was in full-up configuration (full command module, full LM), it was sometimes better to go to the ACCELERATION COMMAND to get a reasonably sized rate.

[CSM Control]

Scott: I found that the MINIMUM IMPULSE was the most used motor control for the spacecraft. We used this because it was a fuel saver.

[CSM Thrust Vector Control]

Scott: The MTVC on SPS number 3 was as expected with the exception of the difficulty in stopping the error needle movement. It was easy to fly and easy to hold the error needles in a position, but the needles didn't appear to stay in a fixed position as long as they had in the simulations.

[LM PGNCS]

McDivitt: I'd like to comment a little on spacecraft attitude control system here. We used PGNCS in PULSE, ATTITUDE HOLD and AUTO. In each one of these modes the digital auto pilot performed up to my greatest expectations. There was no unnecessary limit cycling and I think that it's an excellent control system. The only reason I'm mentioning it here is I'm sure there was a lot of interest in finding out how it performed. Rather than just skip it and say it's nominal, I want definitely to say that I think it was a good control system.

J.3.3 Apollo-10

5.0 TLI THROUGH S-IVB CLOSEOUT

5.7 TRANSPOSITION AND DOCKING PHOTOGRAPHY

Cernan: As soon as we separated from the SLA, we could see SLA panes start to go. As we started to turn around, we picked up probably three of the four SLA panels.

Young: There's no indication on the EMS or anything that we got any DELTA-V out of that separation.

Cernan: It's a good solid klonk.

Young: We applied 0.6 ft/sec velocity to about 40 seconds and nulled the velocity to zero, essentially. We then started our pitch-around at about a degree and a half per second. When we got around, we were about 150 feet away from the S-IVB (which is not a bad place to be). But that's about 100 feet further away than we should have been. I don't have any explanation for this. It took us a little more gas to get back there. Better to be safe than sorry. We were still moving away from the vehicle when we turned around. It took three different positive translations of 0.2 to 0.3 ft/sec to start closing on the vehicle.

Stafford: We used the exact same procedure we used in the simulator. In the simulator, when we turned around, the vehicle would be out there 40 to 50 feet. And in real life, we got more DELTA-V.

Young: I don't understand it, but it didn't cause any problem. If you're going to be safe about it, why not do it that way?

Stafford: I thought that the total transposition and docking was done with a very minimum amount of fuel. There was very little thruster firing.

Young: We didn't do any formation flying; we just turned around and went back into docking. Transposition was a degree and a quarter per second to turnaround. We were doing 0.2 ft/sec and we docking in CMC AUTO. It was easy. There were no vehicle oscillations. Alignment, as for as I was concerned, was absolutely perfect – a piece of cake.

Stafford: To show how accurately John had it aligned, we looked at the docking tunnel for the LM activation, and he had the roll aligned to a tenth of a degree. As for the capture latches, both the barber poles went grey. As the same time, you could feel just a little clunk.

Young: The CSM handled perfectly. The handling characteristics are just exactly what they were in the simulator. It's easy to fly in AUTO control. There was nothing to it.

J.3.4 Apollo-11

5.17 Transposition

Collins: Transposition and docking, in general, worked in flight just as it worked a couple of times in the simulator. I went MANUAL ATTITUDE PITCH to ACCEL COMMAND, and I started to pitch up. After 10 or 20 degrees of pitch-up, when it was definitely established that the attitude error needle in pitch was full scale high (indication that the DAP wished to continue the maneuver in the same direction in which I had started it), then I went PROCEED and MANUAL ATTITUDE PITCH to RATE COMMAND. Then, just as in the simulator, the DAP rolled itself out. It ceased its pitch rate. I don't understand that. At the time, Buzz said that I had forgotten one PROCEED. As I recall, I went through this turnaround procedure exactly as the checklist was written. In the simulator; sometimes it worked like magic and other times it wouldn't. In flight, it worked just exactly like a bad simulator did. MIT or G&C people should check and see what if anything is wrong with this procedure. If I were going to fly this flight over again, I would say it doesn't matter if you pitch up or down. You ought to put those NOUN 22 values in there, hit PROCEED twice, and let the spacecraft turn itself around. You're going to get around within 30 or 45 seconds anyway. It's such a neat, simple, clean, easy procedure to do that way. The way we've got it designed, to make sure that we go pitch-up instiad of pitch-down, sort of mixes apples and oranges. Let the DAP do it, then you take control away from the DAP, then you give it back to the DAP; and, for reasons unknown to me, sometimes it works and sometimes it doesn't.

Armstrong: I'd say that the manual procedure is probably the best. That would be my preference.

Collins: This is something that I'm sure Apollo 12 and other flights will want to massage. I'm firmly convinced that the way to save gas on that maneuver is to let the DAP do it. Make it a totally automatic DAP maneuver.

The price you pay for that is that you never know whether it's going to pitch up or down. This is not important. In an effort to save gas and to assure that we always pitched up, I ended up wasting some gas.

5.18 Stabilization & Alignment at 50 ft

Collins: My procedure was worked out so I'd be 66 feet away from the booster at turnaround. Because of these delays and because of the fact that the DAP kept trying to stop its turnaround rate, I would say that we were about 100 feet away from the booster when I finally turned around. This cost extra gas in getting back to it. I don't know how much extra gas, they said 12 to 18 pounds over. I don't know how much they allocated. I think it was 60 or 70 pounds. That whole maneuver probably cost 80 pounds. In the simulator, doing it completed automated, I can probably do it for 30 to 35 pounds. The difference between 30 to 35 pounds and probably 80 pounds was just wasted gas.

5.19 Docking

Collins: Docking, as in the simulator, was very easy. I did have a slight roll misalignment. I knew I had a slight roll misalignment, but everything else was lined up. Rather than diddle with it and make a last-minute correction, I just accepted it. It turned out later to be 2 degrees in the tunnel.

5.21 CSM Handling Characteristics During Docking

Collins: Absolutely normal. I docked in CMC, AUTO, NARROW DEADBAND with a 2-deg/sec rate. I went to CMC, FREE, at contact. Docking alignment was fine.

8.1.13 Undocking

[...]

Armstrong: After separating for a distance of 30 to 40 feet then taking the DELTA-V out in P47 we asked Mike to choose his own separation distance for watching the gear. He stopped his relative motion with respect to ours; and the intent was, at that point, both vehicles would have exactly the same state vector that they had prior to undocking.

Collins: Any error we had in there might well have been the reason why you might have been long.

Armstrong: Possibly, it may have contributed to that.

Collins: I don't know how much error we had in there. I did have to fire lateral thrusters several times and pitch thrusters once or twice. As near as I can tell, those things should have just about compensated for each other.

Armstrong: It was our intention to try and keep the command module from firing any thrusters once he had killed the relative rate. We didn't quite accomplish that.

Collins: I didn't have to fire any toward you or away from you, but I had slow drift rates back and forth across you and up and down while you were doing your turnaround maneuver. I had to kill those rates. I don't know how they developed.

Armstrong: The resultant station-keeping was one that was very good. The vehicles wer pretty much glued together, 50 to 70 feet apart. [...]

[...]

8.2.33 Formation Flying

Armstrong: Formation flying was considerably less difficult than our simulation would lead us to believe. We were able to maintain position with respect to the other vehicle. It was less trouble than in simulations and used less fuel. At separation, we thought we had relative velocity nulled to less than 0.1 ft/sec in all axes. This was based on the size of the translational inputs required to maintain a constant position over past 10 or 15 minutes before separation.

Aldrin: We did add 20 degrees to our pitch attitude after undocking, so that we'd get better high gain during the yaw maneuver. That, I think, is peculiar with the particular landing site, but we were able to get high gain lock-on. As a matter of fact, I could have gotten it before we made the pitch maneuver, but it didn't look like there was too much point in doing that. As soon as we finished the pitch maneuver, we had high gain lock-on and had it throughout the yaw maneuver. I was going to take some pictures with the 16-mm camera mounted on the bracket, but it looked like it was canted off to the side. No comment at all on using the AGS for this versus the PGNS. We made a change from MAX deadband to MIN deadband. This to me is an open area.

Armstrong: We were in AGS, ATTITUDE HOLD, MIN deadband, and PULSE in the axis that we were maneuvering in. The separation attitude was not the attitude we had expected to be in as a result of some changes to the ephemeris at this point. In other words, Mike was separating on the local verical, but that was not at the same inertial pitch angle that we expected to be at. It was off by about 10 degrees as I recall.

[...]

9.2.25 Manual Control/Pitchover

Armstrong: We then went into MANUAL and pitched the vehicle over to approximately zero pitch and continued. I was in the 20 to 30-ft/sec horizontal-velocity region when crossing the top of the crater and the boulder field. I then proceeded to look for a satisfactory landing area and the one chosen was a relatively smooth area between some sizeable craters and a ray-type boulder field. I first noticed that we were, in fact, disturbing the dust on the surface when we were at something less than 100 feet; we were beginning to get a transparent sheet of moving dust that obscured visibility a little bit. As we got lower, the visibility continued to decrease. I don't think that the altitude determination was severely hurt by blowing dust, but the thing that was confusing to me was that it was hard to pick out what your lateral and downrange velocities were, because you were seeing a lot of moving dust that you had to look through to pick up the stationary rocks and base your translational velocity decisions on that. I found that to be quite difficult. I spend more time trying to arrest translational velocities than I thought would be necessary. As we got below 30 feet or so, I had selected the final touchdown area. For some reason that I am not sure of, we started to pick up left translational velocity and a backward velocity. That's the thing that I certainly didn't want to do, because you don't like to be going backwards, unable to see where you're going. So I arrested the backward rate with some possibly spastic control motions, but I was unable to stop the left translational rate. As we approached the ground, I still had a left translational rate which made me reluctant to shut the engine off while I still had that rate. I was also reluctant to slow down my descent rate anymore than it was or stop because we were close to running out of fuel. We were hitting our abort limit.

9.2.28 Touchdown

Armstrong: We continued to touchdown with a slight left translation. I couldn't precisely determine touchdown. Buzz called lunar contact, but I never saw the lunar contact lights.

Aldrin: I called contact light.

Armstrong: I'm sure you did, but I didn't hear it, nor did I see it. I heard you say something about contact, and I was spring loaded to the stop engine position, but I really don't know whether we had actually touched prior to contact or whether the engine off signal was before contact. In any case, the engine shutdown was not very high above the surface. The touchdown itself was relatively smooth; there was no tendency toward tipping over that I could feel. It just settled down like a helicopter on the ground and landed.

Aldrin: We had a little right drift, and then, I guess just before touchdown, we drifted left.

Armstrong: I think I was probably overcontrolling a little bit in lateral.

I was confused somewhat in that I couldn't really determine what my lateral velocities were due to the dust obscuration of the surface. I could see rocks and craters through this blowing dust. It was my intention to try and pick up a landing spot prior to the 100-foot mark and then pick out an area just beyond it such that I could keep my eyes on that all the way down through the descent and final touchdown. I wouldn't, in fact, be looking at the place I was going to land; I would be looking at a place just in front of it. That worked pretty well, but I was surprised that I had as much trouble as I did in determining translational velocities I don't think I did a very good job of flying the vehicle smoothly in that time period. I felt that I was a little bit erratic.

Aldrin: I was feeding data to him all the time. I don't know what he was doing with it, but that was raw computer data.

Armstrong: The computer data seemed to be pretty good information, and I would say that my visual perception of both altitude and altitude rate was not as good as I thought it was going to be. In other words, I was a little more dependent on the information. I think I probably could have made a satisfactory determination of altitude and altitude rate by eye alone, but it wasn't as good as I thought it was going to be, and I think that it's not nearly so good as it is here on Earth.

Aldrin: I got the impression by just glimpsing out that we were at the altitude of seeing the shadow. Shortly after that, the hoizon tended to be obscured by a tan haze. This may have been just an impression of looking down at a 45-degree angle. The depth of the material being kicked up seemed to be fairly shallow. In other words, it was scooting along the surface, but since particles were being picked up and moved along the surface, you could see little rocks or little protuberances coming through this, so you knew that it was solid there. It wasn't obscured to that point, but it did tend to mask out your ability to detect motion because there was so much motion of things moving out. There were these few little islands that were stationary. If you could sort that out and fix on those, then you could tend to get the impression of being stationary. But it was quite difficult to do.

Armstrong: It was a little bit like landing an airplane when there's a real thin layer of ground fog, and you can see things through the fog. However, all this fog was moving at a great rate which was a little bit confusing.

Aldrin: I would think that it would be natural looking out the left window and seeing this moving this way that you would get the impression of moving to the right, and you counteract by going to the left, which is how we touched down.

Armstrong: Since we were moving left, we were yawed slightly to the left so I could get a good view of where we were going. I think we were yawed 13 degrees left; and, consequently the shadow was not visible to me as it was behind the panel, but Buzz could see it. Then I saw it in the final phases of descent. I saw the shadow come into view, and it was a very good silhouette of the LM at the time I saw it. It was probably a couple of hundred feet out in front of the LM on the surface. This is clearly a useful tool, but I just didn't get to observe it very long.

Aldrin: Here's a log entry: 46 seconds, 300 feet, 4 seconds after the next minute. Watch your shadow, and at 16 seconds, 220 feet. So I would estimate that I called out that shadow business at around 260 feet, and it was certainly large at that point. I would have said that at 260 feet the shadow would have been way the hell and gone out there, but it wasn't. It was a good-size vehicle. I could tell that we had our gear down and that we had an ascent and a descent stage. Had I looked out sooner, I'm sure I could have seen something identified as a shadow at 400 feet; maybe higher, I don't know. But anyway, at this altitude, it was usable. Since the ground is moving away, it might be of some aid. But of course, you have to have it out your window.

9.2.23 LPD Altitude

Armstrong: The LPD was not used until we were below 2500 feet, and it was followed for some number of computation cycles. The landing point moved downrange with time as evidenced by successive LPD readings.

FCOD Rep.: Do you recall when you proceeded?

Armstrong: It was very shortly after we were going into P64.

Aldrin: We got P64 at 41 minutes 35 seconds; then you went MANUAL, ATTITUDE CONTROL.

Armstrong: I can't say whether that was before or after proceeding.

Aldrin: It wasn't too long after that, 41:35-P64, 42:05-manual attitude control is good, 42:17-program alarm. What I'm wondering is did the proceed have anything to do with maybe generating some more activity which would cause the program alarm? We weren't in 1668 at that point.

Armstrong: I have no recollection of that area.

12.1 APS Lift-Off

Aldrin: We had another update from the ground instructing us not to go to AGS in the event that the LM engine didn't ignite and not to make a manual start. We agreed that we would wait a REV. Everything worked according to the checklist. We just emphasized that we did use the lunar align mode in the AGS and did not align the AGS to the PGNS, so it lifted off with its own reference system. It did have a PGNS state vector instead of the manual one that we could have given it in the LM slot. Lift-off, or at ignition, we waited until the last 2 or 3 seconds, or almost simultaneously, Neil depressed the abort stage and threw the engine arm switch to ascent and I proceeded on the computer.

It might have been a second after the T-zero that any motion was detected. There was, as I recall, an appreciable bang of the PYRO's and a fair amount of debris that was tossed out at the same time that we did detect first motion. It was a fairly smooth onset of lifting force. There wasn't any jolt to it. Yaw started gradually; it was not abrupt either in starting or ending. As a matter of fact, I really didn't notice it. I was looking more at some of the gauges and the altitude rate, both in the PGNS and the AGS. It seemed to take quite a while before we accumulated 40 or 50 feet per second.

The pitch maneuver, as seen from inside the cockpit, was not in any way violent or very rapid as we were expecting. We seemed to have a good altitude margin looking down on the surface. It wasn't something that you'd describe as a particularly scary maneuver. I felt that we had adequate altitude rate at the time for that type of a maneuver. Right after the pitchover, I could still look out to the side and see the horizon. We could verify out the window what our pitch angle was.

12.4 Velocity and Altitude

Armstrong: Velocity, altitude, altitude rate, and attitudes were consistent with the ascent table that we were monitoring. AGS and PGNS were consistent in attitude as frequent crosschecks on the attitude indicators showed and also in altitude rate, which was being read off the DEDA and compared with the PGNS value of H-dot.

Aldrin: A couple of years ago, we had a simulation rigged up that tended to give us the sensations in the cockpit that you were liable to experience during LM ascent. We did this in DCPS and they rotated us back and forth. Based upon this and many ascent simulations in the simulator, watching the rate needles pop back and forth, and the arrow needles wipe back and forth, I expected quite a roller coaster ride of whipping back and forth. Nothing could have been further from the way it actually turned out. I was a very smooth wallowing type of an ascent with far less excursions. Maybe the total rates were approximately the same, but the physical effort of them was not at all objectionable.

Armstrong: The rates and attitude errors and attitude changes were consistent with the simulations. The physiological effect of these was much more akin to the description presented by the Apollo 10 crew of their ascent engine burn. It was very pleasant. It had a Dutch roll mode and relatively low frequency. It was not at all distracting toward your ability to monitor the ascent quantities that were significant. It was a very pleasant and unusual trajectory.

[...]

12.5 Attitude

Aldrin: We got the attitude hold and balance couple on. I don't think we reset abort stage and engine stop immediately. We held off on those, disabled the TTCA's, and designated the radar down out of the field of view in preparation for the alignment. We configured the switches, stopped the camera, and progressed on with aligning the platform.

12.15 RCS/CSI Burn

[...]

Speaker: How about the handling?

Aldrin: The nulling of residuals with the thrusters, even with two jet operations, produced a pronounced difference in translating with just the ascent stage. Each time you hit the thrust controller, the vehicle behaved as if somebody hit it with a sledge hammer, and you just moved. There is no doubt about the fact that the thrusters were firing.

Armstrong: It's a very light, dancing vehicle, and this is true in attitude also. It's very unusual, and the fact that we got five zeros on that alignment, I think, is just a matter of being consistent with all the other good luck we had that day. It certainly was more difficult to do than the upstaged alignment where the vehicle was a lot steadier, and we didn't get results that were that good.

Aldrin: It was sporty; there's no doubt about it. It appeared that with the automatic tracking and the wide deadband of the radar that it was not bouncing all over the sky. I guess I anticipated that it might have been even sportier than it turned out to be, even though it was a difficult job doing precise aligning with it. I think the 10 mission indicated that. They thought that they had a light weight vehicle, but, of course, they had much more fuel on board than we did.

Armstrong: We did not find as severe a reaction to operating in PGNS AUTO as had been earlier reported. I can't confirm just what their configuration was in terms of the DAP and vehicle inertial, but our combinations made the vehicle fly quite comfortably in PGNS AUTO. We used that mode more or less intermittently with PGNS PULSE. We almost did all the manual flying in PGNS PULSE, and the remainder of the time, we were in PGNS AUTO. Burns in PGNS attitude holds were generally done with VERB 77.

Aldrin: That lightweight a vehicle did appear as though it was not an easy task to make either X- or Z-axis burns. Of course, all burns were Z-axis burns. To make them, and at the same time avoid having residuals of a fairly sizable number (at least less than 1 ft/sec) is quite difficult. We did end up with minus 0.2, plus 0.7, minus 0.1. The AGS agreed fairly close again, showing the greatest difference in Z, which I think is attributable to the rotation of the burn when loaded into the AGS. The radar stayed locked on throughout the maneuver. [...]

12.31 Braking Gates

Armstrong: Braking was pretty much on the braking schedule; no problems there. The line-of-sight rates were small and easily controlled. The line-of-sight rate indicator gave us proper indications of line-of-sight rates. [...]

12.36 Docking

Armstrong: We stopped braking phase at 50 to 100 feet, insured that both vehicles were in a docking configuration, and at this point, we ran into a problem that we wouldn't have anticipated preflight. Our procedure was for the LM to get into station-keeping position 40 feet out in front of the command module plus X-axis, pitch over 90 degrees so that the X-axes are colinear, then yaw left 60 degrees so that we are in the docking attitude with the command module. It was obvious when we got to this point if we pitched the LM over 90 degrees, we would be looking directly into the Sun. We knew that would be an unsatisfactory lighting condition for docking. So the alternative would be to roll the LM 60 degrees, pitch down, and then you'd be in the same attitude and would have prevented the Sun coming into the window. After arriving at that attitude a discussion between the LM and the command module indicated that we weren't quite far enough, so I rolled a little farther, pitched over, and waited looking through the top window. We were asked to rotate a little farther by the command module to line up the docking aids and get the proper alignments. We complied and promptly maneuvered the vehicle directly in the gimbal lock. I wasn't aware of it because I was looking out the top window. No doubt, we were firmly ensconced in gimbal lock. We had all the lights on, the DAP was not operating anymore, we had no control outputs, clearly no CDU outputs were being processed, so we just put it in AGS and completed the docking in AGS.

Aldrin: And I don't think the AGS is a good system to dock in, or PGNS either.

Armstrong: This was just a goof on our part. We never should have arrived at the conclusion from any series of maneuvers. However, that's how it happened. It wasn't significant in this case, but it certainly is never a desirable thing to do. There's nothing catastrophic about it here, but I'm sorry that somehow or other we hadn't studied the docking maneuver a little bit more carefully and recognized that there might be some attitude constraints in the maneuver that we hadn't considered.

Aldrin: The few times that we'd done that previously we ended up approaching docking with the Sun more along the line of sight to the two vehicles. This was more our concern, arriving at the docking point a little bit late. If you arrive there a little late and the line-of-sight motion happens to be such, the Sun is going to be pretty close to where the command module was. In this particular case, it was about 90 degrees away. After getting in that attitude (or getting docked), to have a PGNS operating, I aligned it to zero and went through the quick alignment procedure. I got the PGNS back in operation again and figured it was not a known REFSMMAT. There were no post-docking maneuvers planned by the LM, so to get both systems the same, I then aligned the AGS to the PGNS. Both of them lost their reference, but both of them were 00 and as far away from any future gimbal lock as they could be. That might have been a better way to operate anyway.

Collins: The rendezvous procedures from the command module view point were about as well worked out, I thought, as they could be with the existing command module computer structure and with the degree of participation necessary by the CMP. I have always felt, and I still feel, that the system is designed in such a fashion that the CMP is too busy during the rendezvous procedure. Although I was able to keep up with the timeline quite well, I felt that I was devoting too large a percentage of my time to the job and that I really was poorly placed to cope with any systems problems or any other difficulties or abnormalities that might have come up. I don't propose any sweeping changes from mainline Apollo. It would be fruitless to do so, but I really think that for future vehicles the rendezvous should be something that is relatively straightforward, something which does not require literally hundreds of simulator hours to master the procedural aspects of. I think, as we get into these lunar-exploration flights, the crew is going to be forced to devote more and more of their attention to what they're going to do once they've arrived, not just to working out the procedures for how to arrive. I really think that. From the command module viewpoint, with one man inside the command module, I think the procedure should be simplified, and if that requires a greater degree of automation, then I think we ought to have more automation. I had a solo book which combined features of various other publications, the idea being I wouldn't have to chase around the cockpit; I would have everything under one cover. This concept worked well. I recommend it highly. [...]

[...]

Collins: Midcourses were very small. Braking was done entirely by the LM. I was completely passive, and that's all I have to say about the rendezvous.

Docking we did in CMC, AUTO, narrow deadband under DAP control. Neil made the crude alignments to get the correct side of the LM pointed toward the COAS. Then I made the final adjustments. I estimated that I contacted the LM just about exactly dead center and at a slow but adequate closing velocity. I would guess slightly in excess of 0.1 ft/sec. Despite this fact, I couldn't tell the instant of contact. The empty ascent stage is light enough relative to the command module that when the two vehicles touch, it's just sort of like pushing into a piece of paper. The LM recoiled enough that they could feel it in the LM, but I couldn't really feel it in the command module. I thought I was getting there, and I thought I was getting there, and finally was fairly sure I had contact. I looked up for the third or fourth time, and I did have two barber-poles indicating that the capture latches had made. At this time, I looked out the window, and the situation appeared static. I threw the switch from AUTO to FREE, so that I was in CMC, FREE. I looked out the window again this was all going pretty fast now I would say this was 3 seconds after contact. The situation looked like it had previously, that is, the two vehicles were statically joined together with no motion. At that time, I fired the bottle. No sooner did the bottle fire than a yaw gyration started between the two vehicles. I'm not sure whether it was a result of the retract cycle beginning or whether it was a result of the LM firing thrusters toward me. At that time, this static situation became very dynamic, and a fairly large yaw excursion took place. I would say that relative to the LM I rapidly went to about a 15-degree yaw right angle. I put the CMC, FREE switch back to CMC, AUTO. This enabled the hand controller in rate command and minimum deadband. I made manual inputs to yaw back over towards the centerline, and there were a couple of other oscillations en-route. I can remember thinking, “I don’t think we’re going to get a successful hard dock this time. I’m probably going to have to let the LM go and try again.” About that time, the docking latches fired, and we were hard docked. I would guess that the time interval from firing the bottle to hard dock was about 6 to 8 seconds. This is probably a pretty normal retract time. Things were happining fairly rapidly, and the oscillations had built up almost exactly at the time I fired the bottle which was primary 2.

Armstrong: I can add a few comments here from the other side. At the time we felt the contact which really was difficult to feel it was a very low bump sound, or touch in the tunnel we fired plus X RCS in the LM as per the preflight plan. Shortly thereafter, we also observed significant attitude oscillation. I guess it would be primarily right roll as observed in the LM. We were in AGS RATE COMMAND minimum deadband and, in addition, plus X. As soon as the attitude deviation started, I left the plus X off and called for Buzz to give me MAX deadband in the thrusters so we wouldn’t be firing a lot of attitude thrusters. Then I took control and manually maneuvered the vehicle back toward colinear status. About that time, it snapped us in there and locked the latches.

Collins: I didn’t like the idea of these two vehicles being joined together just by these two little capture latches. I was in the habit of firing the bottle the first time it appeared; the two vehicles had been joined together and the situation was static. I never gave these oscillations a fair chance to develop. Maybe a better thing to do is delay firing the bottle until you are sure the oscillations are not going to develop. Although it was sort of alarming there for a second or two, this way did work and it was within the envelope. I’m not sure if I had it to do over again that I would do differently. It depends on what caused the oscillations to get started. It could be the thruster firing of the LM or it could be some other cause. If it’s the thruster firing of the LM, then you ought to delete the thruster firing on the LM. I’m not really sure you need that thruster firing on the LM.

Aldrin: I’m not either.

Collins: If it’s some other cause, then the thruster firing of the LM is probably not a bad thing.

Aldrin: It should tend to give some stabilizing effect to the LM. You’d like to have some control system that’s holding the LM fairly close to where you want it to be. I think automatic is probably able to catch sooner than manual. Because you’re looking up this way, it’s pretty darn hard to maintain a close position. That argument says that you ought to be in some kind of automatic rate command system.

Armstrong: I think we have to admit that this was one area, in retrospect, that we gave less thought to than it probably deserves. During simulations, none of our simulators is able to duplicate this kind of dynamics. We saw some film that had been taken of a McDonnell study. We saw these and observed what their recommendations were. That's what was incorporated in our docking plan.

That really was devised to get the capture latches in. I really suspect that everything we experienced happened after the capture latches were engaged. The results of that study really weren't pertinent to this particular phenomenon. We hadn't experienced any trouble at all on your previous docking. That was just as smooth as glass.

Aldrin: It seems to me that it's not too good a mode to be working in. You're tempted, if the thing starts to move on you, to touch the stick. As soon as you do that, you have now reset a new attitude that may not be what the combined systems are going to be happy with; and if it's not, it's going to fire.

Armstrong: That's right. I'm not sure that a lot of thought on our part in this area would have made the situation any better.

Collins: No. That's right.

Aldrin: I don't think we got a tremendous amount of guidance out of the AOH or anybody. It seemed to be, however you want to do it. You can do it this way or that way. They are both acceptable means in the AOH. It seemed to me there were two ways to be acceptable, and this was with primary guidance control. We didn't have primary guidance control because of the gimbal lock problem. It seemed to me that the book treated that subject a little lightly. Wasn't it written for LM active?

Armstrong: Yes.

Collins: We gave the subject very little training time, but had we given it a lot of training time, I'm not sure we could have come to any different conclusions.

Armstrong: It did bite us a little bit.

Aldrin: It's worthy of concern because if you do prang something the consequences are time consuming and nasty to have to go through.

Armstrong: This one got to us and, for one reason or another, we didn't understand it well enough. I suggest that the next crew spend a little more time than we did in this area and try to improve on the procedures.

Aldrin: All other dockings were done in PGNS.

Collins: This was the same procedure from the command module. The only difference was that the LM ascent stage was considerably lighter.

Armstrong: The LM control configuration was different.

Collins: Yes, I meant from the dynamics of the command module viewpoint. I had the feeling that going to FREE under these circumstances was a mistake.

Aldrin: You don't have a good choice of deadbands. Half a degree seems to me to be too tight for this operation, and 5 degrees is much too loose.

Collins: Flag it as a problem. I don't have a solution.

14.42 CM/SM Separation

Collins: CM/SM SEP went normally. The water boiler was in operation during this period of time, which gave the spacecraft a left yaw. I was in MINIMUM IMPULSE a good percentage of this time, and thus it was quite noticeable. I yawed out 45 degrees left, jettisoned the service module, and yawed back in plane by yawing right. When I got a yaw rate started, the water boiler would fight me, the rate would reduce to near zero, and I would then have to make another input.

Having gotten back to zero yaw after jettisoning the service module, I noticed there appeared to be something wrong with the yaw-left thruster at this time. It had worked normally for a little while, but after several minutes of operation, it did not. That was command module RCS thruster 16, yaw left. It appeared to be functioning improperly using the automatic coils. When you yawed left, it made some noise, but it did not give the proper response. It would work properly if you'd move the hand controller all the way over to the hard stops and use the direct coil. At this late stage of the game, I didn't want to devote any time to troubleshooting or talking about it. I probably should have brought the number 2 system on the line in that axis, but I didn't; and everything else seemed to be working normally. I'm just flagging that as a possible systems problem; somebody should look at that thruster and its associated wiring after the flight and see if there's anything wrong with it.

15.6 Control Mode

Collins: We gave spacecraft control over to the computer after we passed all our pitch attitude cross-checks. We gave it to the computer shortly before 400,000 feet. I don't recall exactly when, but a matter of seconds before 400,000 feet. We stayed in CMC, AUTO for the rest of the entry. The computer did its usual brilliant job at steering. We just sort of peered over its shoulder and I made sure that the spacecraft was responding to the bank angles that the computer commanded, and that those bank angles made sense in light of what we saw on the EMS and through other bits and pieces of information. The computer did not fly the EMS the same way I would have flown the EMS. As soon as it got subcircular, it seemed to store up a lot more excess energy than I thought was reasonable. It was holding on to an approximate 250 miles downrange error. When the downrange distance to go was, say, 500 miles, it would have about 750 miles available at that particular g level we were seeing at the time. I thought this was probably a little excessive, but it hung on until very, very late in the game and then it decided all of a sudden to dump it. It sort of rolled over on its back and gave us a second peak pulse of 6g's getting rid of that excess energy. After that, everything was all cross-ranges and down-ranges, and everything made sense. It was essentially on zero error for the remainder of the run. Our first peak pulse was 6.5 as nearly as you can read that thing, and the second one was 6.0.

The EMS trace looked more like a roller coaster than a horizontal line. It really climbed for altitude after the initial pulse and hung way up there high. All of a sudden, it decided to dump it, and rolled over on its back and we came screaming back in. That is really a pretty gross exaggeration, but that was the trend.

24.22 Lunar Landing - LLTV, LLRF, LLTV's, and LMS

Armstrong: For the type of trajectory that was required for us to fly (with a long manual flight at the end), the LLTV was a most valuable training experience. Like all simulations, it's primarily a confidence builder to derive the required information from the information that's at hand. In the flight situation, the information that I used in the landing was primarily visual. It was augmented by information inside the cockpit that Buzz relayed to me. I did very little gauge monitoring during the final descent, that is, below 300 feet. It is primarily an out-the-window job, picking a suitable landing spot and getting into it. The full-scale simulations are the only ones that do this the LLTV and the LLRF. I would have to recommend continuing them both, at least until we have a few more landings under our belt.

I would suggest that more attention be given in the LLTV to changing your landing spot while you're in the trajectory.

Aldrin: And how to deviate from an automatic trajectory and smoothly pick up what you want to do in the way of deviations.

Armstrong: I believe the LLTV can do that job and do it safely. That means that you probably have to do a few more total trajectories than we did in preparation for this flight. I suggest that a dozen is a desirable number a dozen lunar trajectories in the LLTV. It takes about half a dozen before you're comfortably flying on a lunar trajectory, and after that, a couple of different deviations to different touchdown areas. The LLRF lighting simulation was quite interesting, but in retrospect, it's not a very good simulation of the lunar lighting situation.

In the flight, you see much more daylight, at least at our Sun angle (10-degree Sun angle). It was much more of a daylight landing situation than the simulation that was portrayed by the night lighting simulation at Langley Research Center.

Aldrin: They essentially set up a situation where there was no available horizon. That certainly was available in the actual case.

Armstrong: The LMS new model is really a fine addition to the simulator. If you could afford building a model for Apollo 12, so that their last 2 months of simulation would be going into the Surveyor site, then I think you would get a substantial improvement in your confidence level to get to the desired touchdown site.

Aldrin: I think this is particularly true if they stick to the objective of going to that specific area. We have enough available information from the Surveyor itself to build that model.

Armstrong: I know that's an expensive item to provide, but our experience with looking at the L&A of Site 3 indicates that you really can get a good understanding of that local area in your many landing simulations in the LMS.

Aldrin: In looking back on the choices that I made with regard to my participation in landing simulations, I think they were generally correct. I don't think that I suffered by not being exposed any more to the LLTV. I think one session at Langley was worth the effort. I concentrated on manual use of the throttle and I think that's probably what future LMP's should concentrate on, also. I think Neil agrees that if we did have to execute a complete manual landing, it would probably best be done by the Commander concentrating on attitude control and voicing to the LMP what rate of descent and what changes he wanted. It appeared to be a very difficult task for one person to accomplish all of these. Whereas, when the tasks were split, and use was made of the instruments to manually control the throttle, and a fair amount of practice was made, use of that good performance could be anticipated by a manual throttle landing. For the most part, this can be done in the LMS.

J.4 Shuttle

J.4.1 STS-41B

STS-41B was the first Shuttle mission equipped with Manned Maneuvering Units (MMUs). The MMUs were test flown to evaluate general performance and handling characteristics and to test the Trunnion Pin Attachment Device (TPAD). The TPAD was attached to the front of the MMU arms in order to provide a capture mechanism for satellites equipped with cylindrical trunnion pins as part of their structure. At the time this mission was flown, the MMU and TPAD were planned to be used to capture the Solar Max satellite on the upcoming STS 41-C mission. The following are excerpts from the STS 41-B Flight Crew Report [29]:

3.0 EVAs

McCandless was EV-1, Stewart was EV-2, and Brand was IV-1.

[...]

Early MMU operations went essentially as planned with only the following noteworthy items. [...] (2) When inputting a translational command, especially in the X and Y axes to the maneuvering unit with automatic attitude hold engaged, a chatter was noticed. Upon reflection it was realized that this was the normal, relatively high frequency, modulation of some of the translation thrusters "off" in order to assist in holding attitude with an offset center of mass. Based on post-flight comparison at the SOS in Denver the frequency of this chatter appeared to be about six and three quarters Hertz. It had not been seen on the simulators since they modelled the average response of the system owing to lags in the simulator servo dynamics; (3) The center of mass of the combined EMU/MMU system turned out to be several inches above the location of the center of thrust rather than nearly coincidental with it; and (4) subjectively, propellant consumption appeared to be higher than had been seen on the SOS, but relatively close to that shown on the SES or Shuttle Engineering Simulator in building 16. The checkout maneuvers were started with approximately 2800 psi of nitrogen in the MMU tanks and completed with about 2000 to 2200 psi of nitrogen remaining. The first series of long range translations was conducted by EV-1, leaving the payload bay promptly at sunrise. His impression was that the translations were more straightforward and less affected by "orbital mechanics" in the real world than in the manner that they had been modelled in the preflight simulations.

[...]

Upon completion of the long range translations by each crewman, the secondary TPAD assembly was donned and exercised against the trunnion pins on top of the CBSA and on the aft side of the SPAS-01. Function of the secondary TPAD assembly was satisfactory and essentially as advertised. One hard dock and numerous soft docks were accomplished.

[...]

Checkout of the second MMU closely parallelled that of the first with the two units functioning apparently Identically.

[...]

Owing to the failure of the helmet mounted TV, the failure of the Orbiter vernier RCS thrusters, and the failure of the RMS, which had been base!ined to provide elbow TV camera coverage of the maneuvers, the engineering evaluation procedures had to be redeveloped in real time. The gyro dead band test indicated a 1 degree MMU yaw dead band width compared with the 1.25 plus or minus 0.25 degree specification value The translation maneuvers showed that the center of mass of the crewman was high; that is, displaced in the MMU -Z direction from the geometrical center of the thrusters by 2 to 4 inches. Postflight evaluations on the simulator on the SOS in Denver indicate that similar response was obtained with a -Z CG displacement of about 1.34 inches. Roll, pitch, and yaw maneuvers without attitude hold revealed the presence of significant cross coupling between the roll and yaw axes which may have been caused, or at least aggravated, by the MMU crewman carrying his legs in an attitude further forward of the Y-Z thruster plane than anticipated. Aggravating factors on the center of mass shift included presence of the helmet mounted television camera, the weight increases associated with the addition of more stainless steel components to the EMU life support system, and the larger, higher capacity sublimator.

[...]

In terms of overall evaluation of the MMU, EV-1 awarded it a Cooper-Harper rating of 1 without the TPAD and using the automatic attitude hold control mode. In either the unstabilized mode or with the TPAD attached, stabilized or not, a Cooper-Harper rating of 3 would be assigned. EV-2 assigned the following Cooper-Harper ratings: 1 - with full up system during docking tasks; 3 - Without attitude hold during docking tasks; 5 - for long translations without attitude hold, with TPAD. It was found that the payload bay lighting comprised of the Xo “576” bulkhead floodlight and the four forward payload bay floods were more than adequate for manual EVA tasks as well as flying the MMU in and in the immediate vIcinity of the payload bay. Owing to the aforementioned RMS failure there was no significant excursion away from the payload bay during the nighttime periods. The helmet mounted lights worked quite satisfactorily, with the recent removal of the pitch stop allowing illumination of the installed TPAD by the MMU pilot. The commander noted, however, that the flash characteristics and intensity of the MMU locator light were inadequate to provide good tracking should an MMU have strayed off during a night pass.

J.4.2 STS-41C

The STS-41C mission's primary object was to rendezvous with, capture, repair, and deploy the Solar Max satellite. The following are excerpts from the STS-41C flight crew debriefing [30]:

7.4.6 MMU

Nelson: On the MMU, I thought the simulator did a good job of letting us know how it was going to fly. It flew very much like the simulator. The only surprise I had, which when I thought about it I guess wasn't a real surprise, was that the MMU seemed to put a pitching rate into the satellite as I flew up against it, even before making the docking attempt. All the systems on the MMU worked well. Thruster cuelights worked good for me. ! think they were good to have. When Ox [Van Hoften] had his flight, we didn't have them in the payload bay, so he flew without them. He thought it was adequate to fly without them, but he would've liked to have had them.

To mention the simulators, I thought the SOS was excellent as far as the flying and reaching around the satellite. And the SES was very good for the translation part of the flight.

As far as the docking attempts with the MMU and the TPAD, I made three attempts. First one, I would say the velocity was between 0.1 and 0.15 ft/sec. The alignment, the alignment was good on that. It might have been pitched down a little bit, but I doubt it, because I was still in ATTITUDE HOLD on pitch and roll. I bounced right back off the TPAD about the same rate I had gone in, put a little pitching moment into the satellite. The second attempt, I'd say was between 0.15 and 0.2 ft/sec, I did the second docking attempt with ATTITUDE HOLD on in both pitch and roll, and so I was probably pitched down a little bit on that attempt but still within limits. The third attempt, I flew without ATTITUDE HOLD on. I had a real good lineup on that one, and I went in at some rate above 0.2 ft/sec.

Again bounced out at about the same rate I went in. On examination of the trunnion pin, after we had the satellite in the bay, the pin that held the thermal blanket, I described the measurements before. It was very solid, seemed like it stuck out, I don't know, an inch or so off the satellite, and it had a washer on the end of it, and the washer on the end of it was firmly attached to the pin also. It was about 1/2 inch in diameter. One further comment on the grapple attempts - or on the docking attempts. I think that if there had been a manual release on the TPAD, that on any of the three grapples, I could have manually attached myself to the trunnion pin without any difficulty. One check we made was a COMM check while the MMU crewman was behind the satellite. So the satellite was between the Orbiter and the crewman, and we did a RF COMM check there, and there was no noticeable effect to being behind the satellite.

Van Hoften: One comment we made earlier is that Pinky [Nelson] and I had planned on always doing our MMU operations as a two-man task with one guy doing all that configuration of the cuelights and the TPAD and whatnot and the safety belt. It's an extremely helpful thing to do. It's a difficult task to do some of that alone, and it probably is four times faster when you have two people. The other thing is, translating with TPAD, there's really not an adequate handle on it. It, with the pins and whatnot, tended to flail around and I was afraid I was going to tear one off. And translating at the port slidewire with the RMS in position was awkward, but we were able to do it.

The following comments are from the STS-41C flight crew report [60]:

MMU OPS: All MMU OPS were nominal. As noted on STS 41-B, propellant usage was high during maneuvers with attitude hold engaged and while stationkeeping. During the checkout flight, EVA 1 noted that the CG offsets were more similar to the "old" valves used in the space operations simulator (SOS) model than the "new" valves used for the last training run. Both crewmen were impressed with the MMU flying characteristics. It was very stable and maneuverable. The limb motion filter was tested by both crewmen and neither noted excessive jet firings.

The thruster cue light extenders were used on EVA 1 but not on EVA 2. They were helpful during the docking and stabilization attempts on the Solar Maximum Satellite, and should be used on operational flights (R). MMU pre- and post- was nominal. The tolerances were too tight on the arm retention straps. They should be at least 1/4 inch longer (R). Tightening the two top launch bolts manually was a tedious, time-consuming task.

Solar Maximum Satellite Docking Attempts: The flyover to the Solar Maximum Satellite was nominal. A small pitch rate was imparted to the Solar Maximum Satellite from the MMU plume prior to any contacts. Three attempts were made to dock with the satellite at approximate rates of 0.1, 0.15, and >0.2 ft/sec. All resulted in an elastic bounce off the trunnion pin at a comparable rate. The first two attempts were done with attitude hold engaged in pitch and roll this resulted in a slight pitch down attitude on the second try, but still within the capture envelope of the Trunnion Pin Attachment Device (TPAD). The third attempt was accomplished without attitude hold due to the rates already on the Solar Maximum Satellite. Each docking attempt put a larger pitch rate into the Solar Maximum Satellite.

It was felt that a manual release capability of the TPAD would have allowed the MMU to dock with the Solar Maximum Satellite (R). Even then the thermal blanket standoff pin could have kept the expanding bolt from engaging the threads in the trunnion pin. One attempt was made to stabilize the Solar Maximum Satellite by holding onto a solar array and engaging MMU attitude hold in the satellite stabilization mode. During this attempt, the rates were reduced to a Solar Maximum Satellite roll in the opposite direction from the original rotation. After release from the solar array, the Solar Maximum Satellite roll rates coupled into the other two axes resulting in an unpredictable tumbling motion.

MMU Engineering Evaluation Flight: During EVA 2, the MMU was flown within the payload bay. The thruster cue light extenders were not available and were not required for these tests. To investigate the effects of CG offsets a series of maneuvers were flown without altitude hold.

(1) +X Translation

Chatter was not present. The +pitch rate induced was very similar to the last training run made in the SOS.

(2) ±Pitch

No cross coupling was noted.

(3) +Yaw

A small cross coupling into +pitch was noted.

(4) -Roll

Coupled into -yaw immediately at nearly the same rate.

J.4.3 STS-51A

STS-51A was a mission whose primary objectives included rendezvous, capture, and return of two failed communications satellites. The MMU was used with a device known as "the stinger" to capture the satellites. The stinger mounted to the MMU armrests and used an expanding probe inserted into the motor nozzle of the satellites to provide a rigidized capture system.

The following excerpt are from the STS 51-A Technical Crew Debriefing [31]:

Gardner: The next comment is the flying that I observed in SAT STAB. The MMU without the stinger, I thought, flew better than the SOS. It seemed even more stable than the SOS did; it just was rock steady. That's in NORMAL flight mode. When I put the stinger on and flew it in SAT STAB, it was much degraded as compared to the SOS. And my perception of it was that the c.g. was much further forward than anticipated. And what I saw was this: in the SOS, typically, when I'd ask for a Y translation, you'd see both lights come on, you'd see the translation start, and then sometime after that, you'd see attitude hold take over keeping you in the deadband caused by the Y translation. In flight, what I saw was immediately when I deflected the THC, attitude hold immediately took over, took priority over the translation, and started firing rotational correction jets such that I was hosing out gas in opposite directions and really not going any place. Looking at the pictures of the EVA postflight, I see that my legs were carried much further forward than I have observed Joe or any of the four crewmen in movies or stills from the previous two flights. So it's probably a c.g.-forward situation there that caused it to fly that way in SAT STAB, but that needs to be looked at.

The following excerpts from the STS-51A Flight Crew Report [77]:

Manned Maneuvering Unit (MMU)

Both operational MMU's were carried in order to assure the availability of a fully functional MMU for each satellite capture. Because of DISCOVERY's configuration, N2 service, power to, and data from the starboard-mounted MMU were not available. This did not substantially affect the MMU operation, and the power tool was used to remove the launch bolts on this side in lieu of N2 pressure.

The prep/don/doff and post procedures for the MMU were essentially identical to those practiced in the WETF training session and described in previous flight reports. Both crewmen left all waist tethers on the FSS arms before MMU flights to avoid any chance of snagging tethers in the stinger mechanisms. The tethers were then easily retrieved as part of the MMU doff procedure.

Upon leaving the FSS each crewman performed the standard flight checks of both A and B systems, as had been done on the previous MMU flights, and each tried to save as much propellant as possible while verifying the flying characteristics of the MMU as being those learned in MMU simulations. Even with the stinger attached and in both the "NORM" and "SAT STAB" modes of control the MMU was indeed as smooth and responsive to fly as simulations suggest. The one exception to this was the "SAT STAB" mode, stinger attached, for EV2 who found this configuration to be sluggish in control and inefficient in propellant usage. Post-flight examination of TV tapes of the EVA-2 MMU flyover show EV2's legs being held forward, resembling a sitting position rather than the standing position more frequently used. This body position results in the center-of-mass of the MMU-crewman-stinger being anomalously far forward which could cause, in turn, a decrease MMU control authority in the "SAT STAB" mode. Further analysis and simulation will be required to determine the exact cause of the MMU flying characteristics observed on EVA-2. Even with the decreased control authority during EVA 2 the MMU flyover and satellite capture were easily carried out, including flying the MMU with confidence right up to the MFR work stanchion to enable stinger attachment, in close proximity to the outstretched RMS end effector, and close enough to Orbiter structure that the MMU user could retrieve a tether from the FSS and, later, doff the stinger unaided and tether it to the Orbiter longeron.

In summary, the flying of the MMU with stinger attached, the capture of the satellites including soft dock, hard dock, stabilization and repositioning for grappling (or for grabbing) all occured as had been planned and simulated premission. The propellant usage was also very close to that expected. Since the satellite capture task was not particularly demanding in terms of MMU fuel required, the fact that about two-thirds of the propellant available was used underscores the need for more fuel capacity in future MMU devices.

Appendix K

Glossary of Acronyms and Terminology

3-DOF Three degree of freedom.

6-DOF Six degree of freedom.

ACME (Gemini) Attitude Control and Maneuver Electronics.

ADI Attitude Director Indicator. A flight instrument resembling a physical or virtual sphere used to display 3-DOF attitude information.

Agena (Gemini) An unmanned propulsion stage used as a rendezvous and docking target for Gemini spacecraft.

AGS (Apollo) Abort Guidance System. The backup navigation and control system used on the Apollo Lunar Module.

ALFA (Mercury) Air Lubricated Free Attitude.

ALT (Shuttle) Approach and Landing Test. A series of aerodynamic test flights in which a prototype Space Shuttle orbiter separated from a carrier aircraft to perform an approach and landing.

AOH (Apollo) Apollo Operations Handbook.

AOT (Apollo) Alignment Optical Telescope.

APAS Androgynous Peripheral Attachment System.

APS See *Ascent Propulsion System*.

APS (Apollo) Auxiliary Propulsion System. The attitude control and propellant settling system used on the Saturn S-IVB.

Ascent Propulsion System A system on the Apollo LM ascent stage consisting of an engine and associated tanks and support system used for lifting off from the lunar surface and ascending into orbit. This engine was fixed in place and did not gimbal.

ASCS See *Automatic Stabilization Control System*.

ASTP Apollo-Soyuz Test Project. A single mission program to rendezvous and dock an Apollo CSM to a Soyuz 7K-TM spacecraft in Earth orbit.

ATT Attitude.

ATT REF (Shuttle) Attitude Reference. The ATT REF pushbutton was used to direct the computer to record the current vehicle attitude for various purposes.

Attitude Hand Controller Gemini program nomenclature for what is now called the Rotational Hand Controller.

Automatic Stabilization Control System Primary system used to control attitude of the Mercury spacecraft. Designed to operate primarily in fully-automatic mode (ASCS NORM), it also included modes for rate damping only (ASCS AUX DAMP) and manual control of electronic RCS jet firing commands (ASCS FLY-BY-WIRE). The ASCS controlled the 'A' jets of the RCS, complete with separate fuel supply.

Bank Rotation about the velocity vector.

BEF Blunt End Forward.

BMAG (Apollo) Body Mounted Attitude Gyroscope.

CDH Constant Delta-Height.

CDR Commander.

CM See *Command Module*, also Center of Mass.

COAS Crew Optical Alignment Sight.

Command Module The conical Apollo spacecraft module containing habitable volume. It is normally attached to the Service Module until shortly before atmospheric entry. Also known as Crew Module.

CMC (Apollo) Command Module Computer.

CMP (Apollo) Command Module Pilot.

CSM See *Command and Service Module*.

Command and Service Module The combined Apollo vehicle consisting of Service Module (SM) and Command Module (CM) for long duration spaceflight.

CSI Coelliptic Sequence Initiation.

DAP See *Digital Auto-Pilot*.

DEDA (Apollo) Data Entry and Display Assembly. The user interface to the Apollo LM AGS.

Digital Auto-Pilot A software system that can control attitude and translation of a spacecraft. The term is somewhat mislead because although a DAP typically has true automatic control characteristics it can also act as part of the manual control system by interpreting pilot inputs and controlling the spacecraft accordingly.

DM (Apollo) Docking Module. This module acted as the adapter between the Apollo CSM and Soyuz spacecraft on the ASTP mission.

DM (Soyuz) Descent Module.

DPS (Apollo) Descent Propulsion System. The engine and associated support systems on the Apollo LM descent stage, used for descending from lunar orbit to the surface.

DRM Design Reference Mission.

DSKY (Apollo) Display and Keyboard Unit.

DTO Developmental Test Objective.

ECS Environmental Control System.

EMS (Apollo) Entry Monitor System.

ET (Shuttle) External Tank.

EV EVA Crewmember.

EVA Extra-Vehicular Activity. Activity outside of a spacecraft, spacewalking or working on the lunar surface.

FCSD Flight Crew Support Division.

FDAI (Apollo) Flight Director Attitude Indicator. The Apollo nomenclature for the ADI.

FDI (Gemini) Flight Director Indicator. The Gemini nomenclature for the ADI.

Free Free Drift. The spacecraft is allowed to drift in attitude.

FSS (Shuttle) Flight Support System. The storage and service system for the MMU.

GCA Ground Controlled Approach.

GDC (Apollo) Gyro Display Coupler.

GMS (Gemini) Gemini Mission Simulator.

G&N Guidance and Navigation.

GNC Guidance, Navigation, and Control.

GT (Gemini) Gemini-Titan. Titan was the launch vehicle used for all Gemini missions.

HQR Handing Quality Rating.

IMU Inertial Measurement Unit.

ISS International Space Station.

IV Intravehicular (Inside) Crewmember.

IVI Incremental Velocity Indicator. A flight instrument used to display velocity to be gained in each body axis.

J2000 An inertial coordinate frame. The origin is at the enter of the Earth, the X-axis is directed along the mean vernal equinox of epoch, the Z-axis is directed along the Earth's mean rotational axis of epoch, positive North, and the Y-axis completes the right-handed system. The epoch is 12:00 on 1 January 2000.

LEB (Apollo) Lower Equipment Bay.

LGC (Apollo) Lunar Module Guidance Computer.

LM (Apollo) Lunar Module.

LMP (Apollo) Lunar Module Pilot.

LLRF (Apollo) Lunar Landing Research Facility.

LLRV (Apollo) Lunar Landing Research Vehicle.

LLTV (Apollo) Lunar Landing Training Vehicle.

LMS (Apollo) Lunar Module Simulator.

LPD (Apollo) Landing Point Designator.

LVLH Local Vertical, Local Horizontal is a rotating coordinate system typically used for orbital flight near a primary body such as the Earth. The Z-axis lies along the geocentric radius vector from the vehicle to the center of the primary body. The Y-axis is normal to the orbital plane, opposite of the angular momentum vector. The X-axis completes the right-handed frame and is positive in the direction of vehicle motion. A orbiting vehicle holding an LVLH attitude can be thought of as fixed in rotation relative to the surface below like an airplane.

M1950 Mean of 1950 is an inertial coordinate frame. The origin is at the enter of the Earth, the X-axis is directed along the mean vernal equinox of epoch, the Z-axis is directed along the Earth's mean rotational axis of epoch, positive North, and the Y-axis completes the right-handed system. The epoch is 12:00 on 1 January 1950. In practice M1950 is used for legacy purposes only and new applications use J2000.

M50 See *M1950*.

MA (Mercury) Mercury-Atlas. Atlas was the larger Mercury launch vehicle used for orbital flights.

MAC McDonnell Aircraft Corporation.

Maneuver Hand Controller Gemini program nomenclature for what is now called the Translational Hand Controller.

Maneuvering Engine A spacecraft engine larger than RCS thrusters used for large translational maneuvers. Examples include the Apollo CSM Service Propulsion System (SPS) and Space Shuttle Orbital Maneuvering System (OMS) engines.

MFR (Shuttle) Manipulator Foot Restraint.

MMH Monomethyl Hydrazine. A common fuel used in hypergolic rocket engines in conjuction with N_2O_4.

MMU (Shuttle) Manned Maneuvering Unit. The propulsive backpack used on some early Shuttle missions.

MR (Mercury) Mercury-Redstone. Redstone was the smaller Mercury launch vehicle used for sub-orbital flights.

MTVC (Apollo) Manual Thrust Vector Control.

NASA National Aeronautics and Space Administration.

OAMS See *Orbital Attitude and Maneuvering System*

OM (Soyuz) Orbital Module.

OME Orbital Maneuvering Engine. See *Maneuvering Engine*.

OMS See *Orbital Maneuvering System*.

ORB Orbital.

Orbital Attitude and Maneuvering System Primary reaction control system used to control attitude and perform translational maneuvers for the Gemini spacecraft while in orbit. See also *Reentry Control System*.

Orbital Maneuvering System A system on the Space Shuttle consisting of two gimbaling maneuvering engines and associated tanks and support systems.

PAD Preliminary Advisory Data. Data voiced to a spacecraft crew usually written onto a specialized form to communicate data for an upcoming event such as a burn.

PDI (Apollo) Powered Descent Initiation. The point at which the Apollo LM descent engine is ignited to begin the descent from lunar orbit to the lunar surface.

PGNCS See *Primary Guidance Navigation and Control System.*

PGNS (Apollo) Primary Guidance and Navigation System. The primary guidance, navigation, and control system used on the Apollo Lunar Module.

PIO Pilot Induced Oscillation. A phenomenon in which the pilot inputs are out of phase with vehicle response causing instability.

PM (Soyuz) Propulsion Module.

PRCS (Shuttle) Primary Reaction Control System. A system of large RCS jets used for translation and rotation.

Primary Guidance Navigation and Control System The primary guidance and control system used on Apollo spacecraft consisting of a computer and inertial measurement unit.

PYR Pitch, Yaw, Roll Euler sequence.

Rate Stabilization Control System Secondary system used to control attitude of the Mercury spacecraft. Designed to operate in either of two modes: Rate Command (RSCS RATE COMD), in which the pilot electronically commanded attitude rates on a per-axis basis proportional to hand controller angular displacement, or Direct (RSCS DIRECT), in which the pilot mechanically commanded jet thrust on a per-axis basis proportional to hand controller angular displacement. The RSCS controlled the 'B' jets the RCS, complete with separate fuel supply.

RCS See *Reaction Control System*.

RCS See *Reentry Control System*.

Reentry Control System Reaction control system used to control attitude of the Gemini spacecraft during the deorbit burn and entry. Located in the nose of the spacecraft it consists of two identical redundant sets of RCS jets and propellant supplies known as 'Ring A' and 'Ring B'. See also *Orbital Attitude and Maneuvering System*.

Reaction Control System System of small thrusters used to control the attitude of the spacecraft and perform small translational maneuvers. Larger translational maneuvers are usually performed with a maneuvering engine.

REFSMMAT (Apollo) Reference Stable Member Matrix.

Rev Revolution. One trip in orbit around the central body.

RHC Rotational Hand Controller.

RMS Root Mean Square. The square root of the sum of the squares of the individual elements.

RMS (Shuttle) Remote Manipulator System. The Shuttle's robotic arm.

ROD (Apollo) Rate of Descent. The ROD switch directed the Apollo Lunar Module computer to change the rate of descent in $\pm 1\ ft/s$ increments as an alternative to manual descent engine throttle control.

RSCS See *Rate Stabilization Control System*.

SAFER (Shuttle) Simplified Aid For EVA Rescue. A small propulsive backpack attached to a spacesuit designed to allow a person who has become detached from a space station to self rescue by stabilizing rotation and translating back to structure. The SAFER is much simpler and very limited in capability as compared to the conceptually similar MMU.

SECO (Mercury) Sustainer Enginer Cut-Off.

SEF Small End Forward.

SCS See *Stabilization and Control System*

SMS (Shuttle) Shuttle Mission Simulator. The primary simulator used to train Space Shuttle crew and flight controllers. It had two cockpits, one with motion only simulated the forward flight deck, one without motion simulated the entire crew compartment.

Stabilization and Control System A system on the Apollo CSM that provides certain automated functionality to the PNGCS and a manual control capability that bypasses the PNGCS.

Service Module An uninhabited spacecraft module containing systems such as engines, power generation, and thermal control to support long duration spaceflight. When attached to the Apollo Command Module (CM) the combined vehicle is known as the Command and Service Module (CSM).

Service Propulsion System A system on the Apollo Service Module (SM) consisting of a large maneuvering engine and associated tanks and support systems.

SLA (Apollo) Spacecraft Lunar Module Adapter. The four panels that enclosed the Apollo LM and held the CSM during launch.

SM See *Service Module*.

SOS (Shuttle) Space Operations Simulator.

SPAS (Shuttle) Shuttle Pallet Satellite.

SPS See *Service Propulsion System*.

STS (Shuttle) Space Transportation System.

TAR Torque Advantage Ratio.

TCA See *Thrust Chamber Assembly*.

THC Translational Hand Controller.

Thrust Chamber Assembly Gemini program nomenclature for a Reaction Control System jet thruster.

THC Thrust Vector Control.

TPAD (Shuttle) Trunnion Pin Attachment Device.

TR (Gemini) Time of Retrofire.

TTCA (Apollo) Thrust/Translation Controller Assembly. The combined THC and descent engine thrust controller in the Apollo Lunar Module.

VRCS (Shuttle) Vernier Reaction Control System. A system of small RCS jets used for fine attitude control and slow maneuvers, also used to minimize loads on delicate payloads.

WETF (Shuttle) Weightless Environment Training Facility. A large pool used to train for EVA.

YPR Yaw, Pitch, Roll Euler sequence.

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14. ABSTRACT
This document describes work to determine a proposed set of concise design requirements for manned spacecraft to yield satisfactory handling qualities when the pilot is performing manual control. This is done primary via the analysis of various historic spacecraft. Partial requirements verification is performed via the creation of a simulated pilot used to determine limits of satisfactory vehicle performance. Partial requirements validation is per-formed via example conceptual design of a spacecraft that is compliant with all relevant proposed requirements.

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