SPACE STATION FREEDOM ATTITUDE DETERMINATION AND CONTROL SYSTEM OVERVIEW

For Presentation at the NASA/MDSSC Workshop on Fuzzy Control Systems and Space Station Applications

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INTRODUCTION

- SS Freedom is a highly variable system which requires a general, robust control system
  - Mass properties vary orders of magnitude during assembly
  - Vehicle orientation for normal operations changes significantly during assembly

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- Operational environment
  - Disturbances typically 0-2 times orbit frequency
    - — Aerodynamic, gravity gradient, gyroscopic torques
  - Sensors sampled at 5 Hz, effectors commanded at 2.5 Hz

- Vehicle is controlled using two different systems
  - CMG's (Control Moment Gyroscopes)
  - RCS (Reaction Control System)

HIGHLY DYNAMIC PLANT

- Vehicle changes significantly after each assembly stage
  - Mass properties variations
    - — Mass varies from 60,000 - 800,000 lb
    - — Center of Mass (cm) location moves over 100 ft.
    - — MOI's (Moments of Inertia) vary by 2 orders of magnitude
    - — Delta MOI's (Ixx - Izz etc) can change sign during planned operations resulting in the gravity gradient torque derivatives changing sign
  - RCS system variations
    - — Number and location of thrusters changes depending on assembly stage
    - — Blowdown ACS thrust varies from 25 - 9 lbf.
    - — Reboost varies from 50 - 20 lbf.

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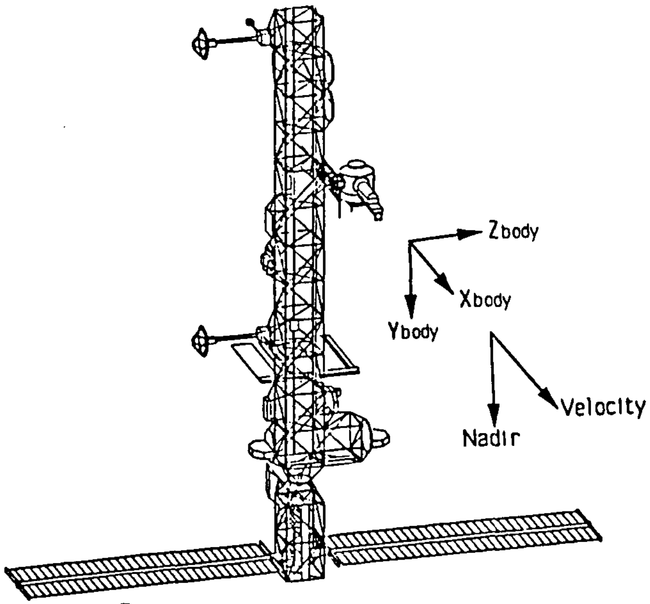
HIGHLY DYNAMIC PLANT (cont.)

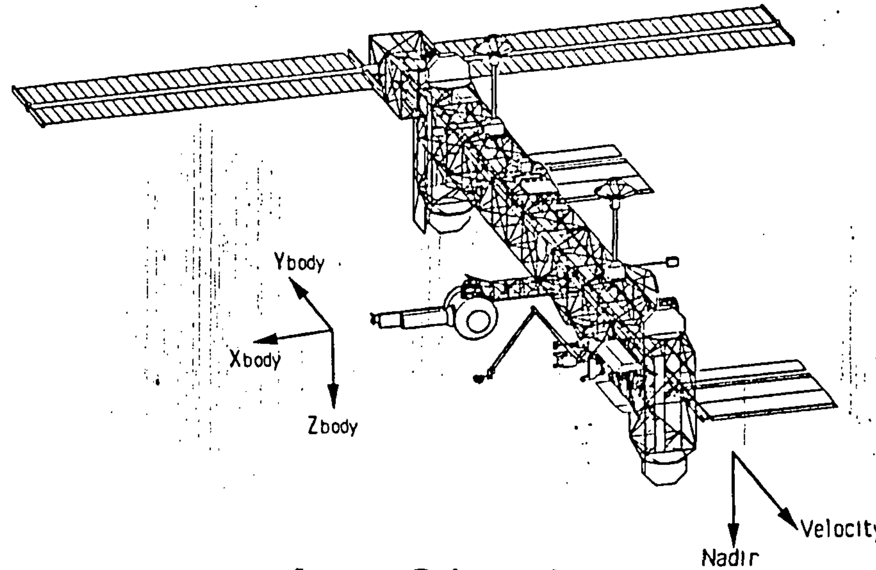
- Mass properties change significantly <u>during</u> each assembly phase
  - Orbiter docking adds approximately 220,000 lb and causes significant changes in cm and MOI's
  - Arm motion with heavy payload attached causes continually varying mass properties during operations

- Vehicle orientation during normal operations changes during assembly flights
  - Assembly flights 1-6
    - Nominal attitude is gravity gradient stable with the truss aligned with the local vertical
    - During reboost 'Arrow' orientation is maintained with the truss aligned with the velocity vector
  - After assembly flight 6 vehicle maintains TEA (Torque Equilibrium Attitude) during normal operations, LVLH (Local Vertical Local Horizontal) during reboost

SS FREEDOM FLIGHT ATTITUDES



Gravity Gradient Orientation



Arrow Orientation

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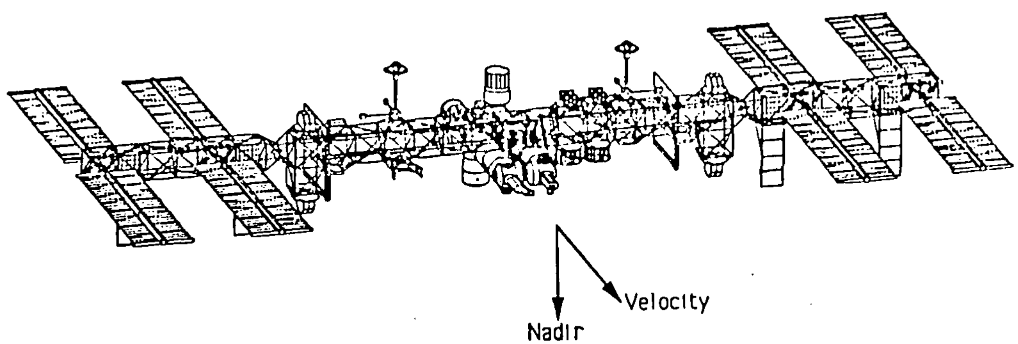

Normal Orientation

EFFECTORS

- **CMG (Control Moment Gyroscopes)**
  - Dual Gimbal, constant speed rotors store angular momentum (3500 ft-lbf-sec each)
  - Provide torque to the vehicle by changing the net angular momentum vector of the CMG(s)
  - Linear actuator
  - Relatively small angular momentum storage capacity (4 CMG's in current design)

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- **RCS (Reaction Control System)**
  - Uses small, rocket thrusters to provide vehicle attitude control & reboost
  - Requires consumable propellant
  - Non-linear actuator

SENSORS

- Inertial Attitude Sensors
  - ISA (Inertial Sensor Assembly)
    - Three axis ring laser gyroscope
    - Provides body rate information
    - 3 ISA's on the Attitude Reference Assembly
  - Star Tracker
    - Provides inertial attitude based on star catalog
    - Software provides 'deadstart' capability
    - 2 star trackers on Attitude Reference Assembly
- CMG angular momentum measured via sensed gimbal angles

CONTROL SYSTEM PERFORMANCE REQUIREMENTS

- Attitude control
  - TEA must be within ± 5° of LVLH (currently not doable)
  - Attitude variations from TEA of less than 2.5°/orbit

- Minimize propellant consumption during program lifetime
  - Requires a CMG momentum management system
    - Manages CMG momentum using gravity gradient torques
    - Can fly TEA and consume no propellant
  - RCS must use minimum propellant
    - TEA seeker minimizes propellant consumption
    - Use of fuel optimal jets for every firing

CONTROL SYSTEM FUNCTIONAL REQUIREMENTS

FUNCTION	CMG	RCS	COMMENTS
Primary Attitude Control (Normal operations)	X		Orbit at TEA using momentum manager
Backup Attitude Control		X	Orbit in TEA seeker mode
Attitude Maneuvers		X	CMG's in reset mode
Reboost attitude control	X	X	CMG's in reset
Large Transient Disturbances	X	X	Cooperative CMG/RCS control - RCS assists CMG's to prevent saturation
Adequate Flex Stability Margin	X	X	No active damping of structural vibrations. Controllers must not excite significant flex-body modes.
LVLH Attitude Hold	X	X	
Inertial Attitude Hold	X	X	
Failure Accomodation	X	X	CMG controller must handle failed CMG(s) RCS must handle failed thruster(s)

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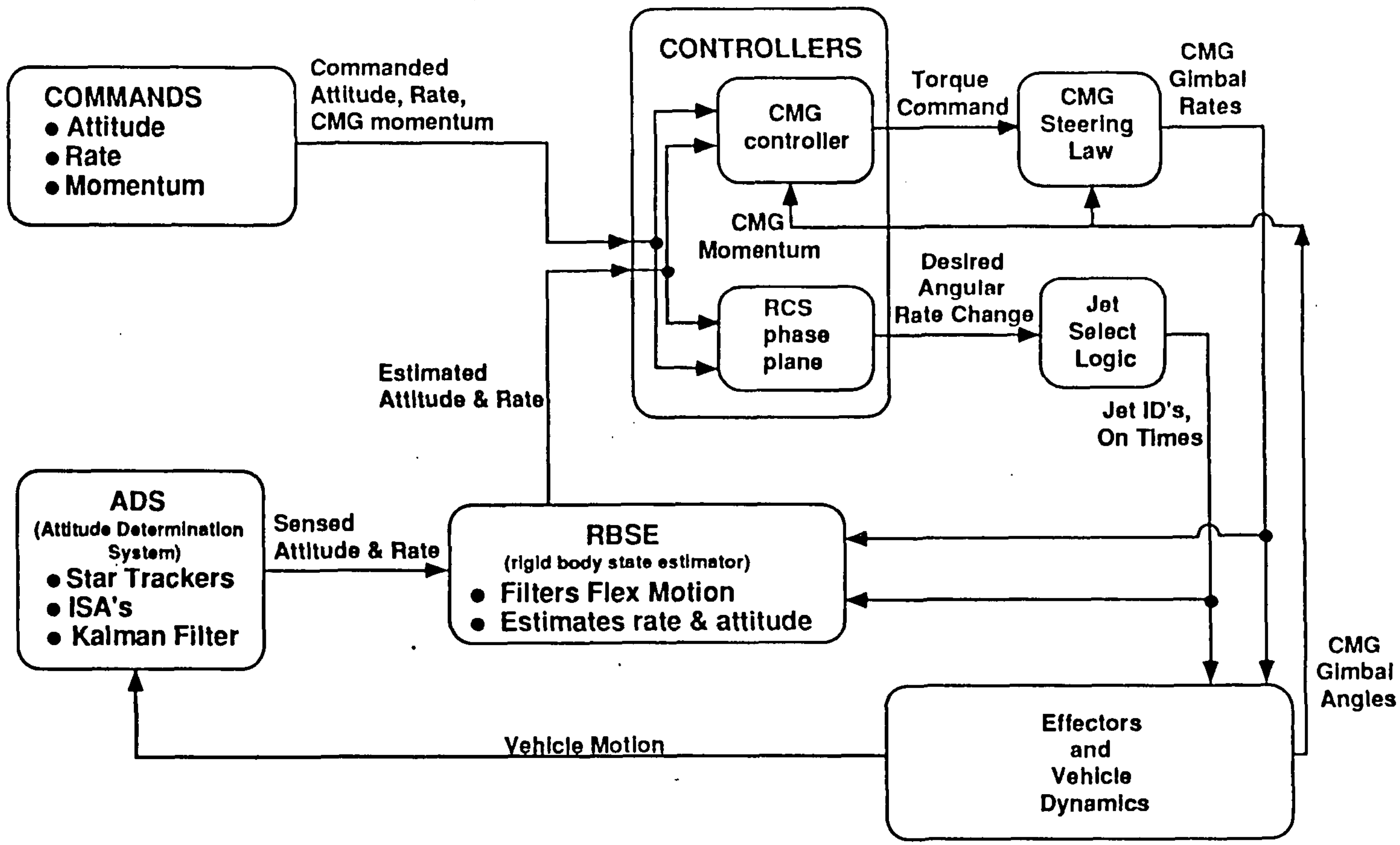
CONTROLLER ARCHITECTURE



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CONTROLLER OVERVIEW

- **Momentum Manager/CMG Controller**
  - Maneuvers the vehicle to generate time-varying gravity gradient torques to manage the CMG momentum and thus use no consumables
  - Gravity gradient torques about roll and pitch axes only. Yaw momentum must be dissipated via roll maneuvers 1/4 orbit after momentum buildup occurs
  - Low Bandwidth (poles are .3-10 times orbit frequency), continuous controller

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- **RCS Controller**
  - Generates control torques using pre-processed fuel optimal sets of jets
  - 50 millisecond minimum on-time
  - Bang-off-bang controller with variable phase plane parameters
- **Structural flex-body mode filters used**

SUMMARY

- Robust, multi-variable stable control system is required for SS Freedom attitude control due to dramatic variations of the vehicle mass and aerodynamic properties
- CMG controller requires a guidance momentum management algorithm so no consumable is required during normal operations
- RCS system must minimize propellant consumption by using sets of fuel optimal jets for maneuvers
- Both systems must be fault tolerant and operate with failed components (thrusters and individual CMG's)
- Multiple opportunities for fuzzy logic controllers, particularly the RCS if fuel use can be reduced below current levels

BLOWDOWN THRUST PROFILE PREDICTION

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Outline

- Introduction
- Thrust Prediction Problem
- Solution Approach
- Limitations of Current Approach
- Summary
- Panel Discussion

BLOWDOWN THRUST PROFILE PREDICTION

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(Continued)

■ INTRODUCTION

- Space Station Freedom propulsion system consists of a blowdown (non-constant thrust) hydrazine system. The thrust depends on the tank pressure which "blows down" as the thrusters are fired.
- The station is periodically reboosted to maintain orbital lifetime and reduce orbital eccentricity. Due to the low thrust to mass ratio available, typical reboost maneuvers can require hours of continuous thrusting.
- Computation of the burn on/off times for a reboost require accurate prediction of the thrust profile for the length of the burn.
- Computation of the burn on/off times onboard require a means of generating a predicted thrust profile without resorting to a 6-dof simulation.
- Prediction of the thrust profile is complicated by the following:
  - — Thruster cycling to maintain attitude control.
  - — Both reboost and attitude control thrusters are cycled for attitude control depending on the relative thrust miss-match on the modules.

BLOWDOWN THRUST PROFILE PREDICTION

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(Continued)

- **Introduction (continued)**
  - Thruster cycling is frequency limited due to structural constraints.

BLOWDOWN THRUST PROFILE PREDICTION

by
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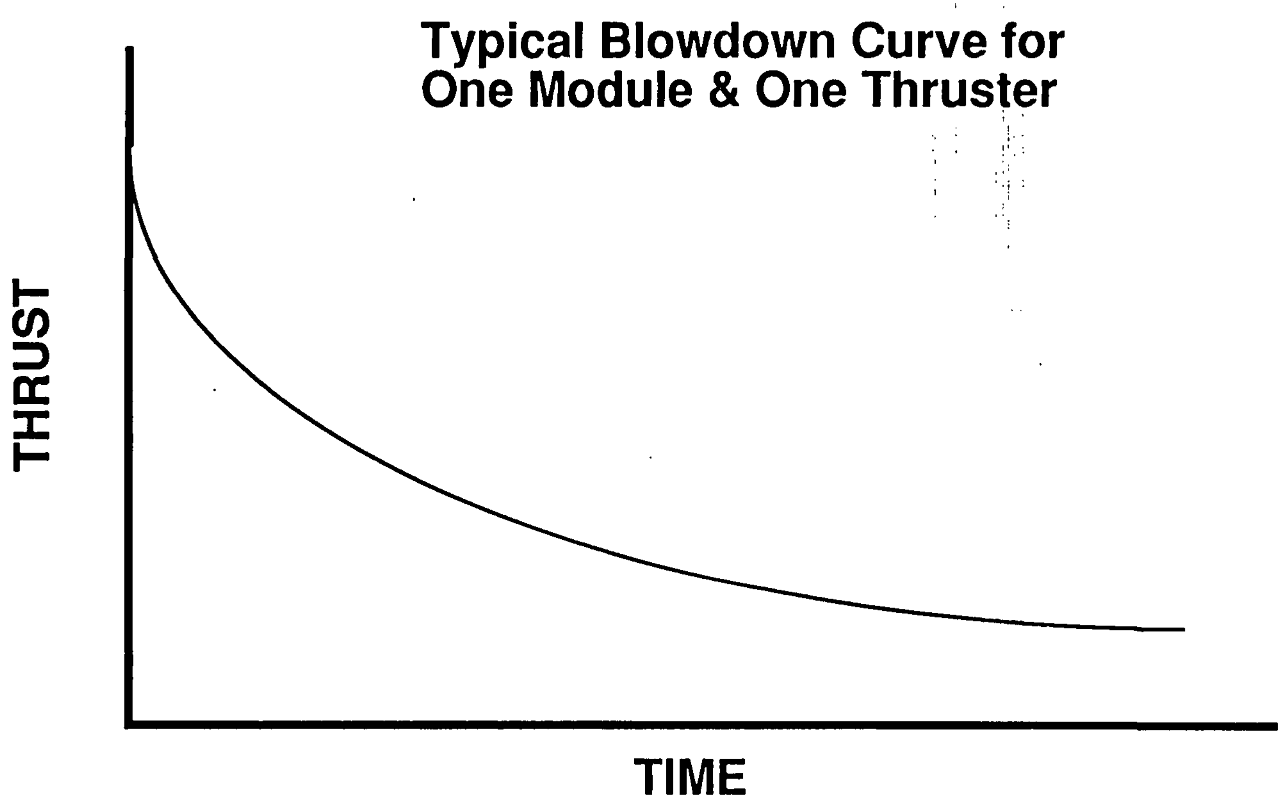
(Continued)



BLOWDOWN THRUST PROFILE PREDICTION
by
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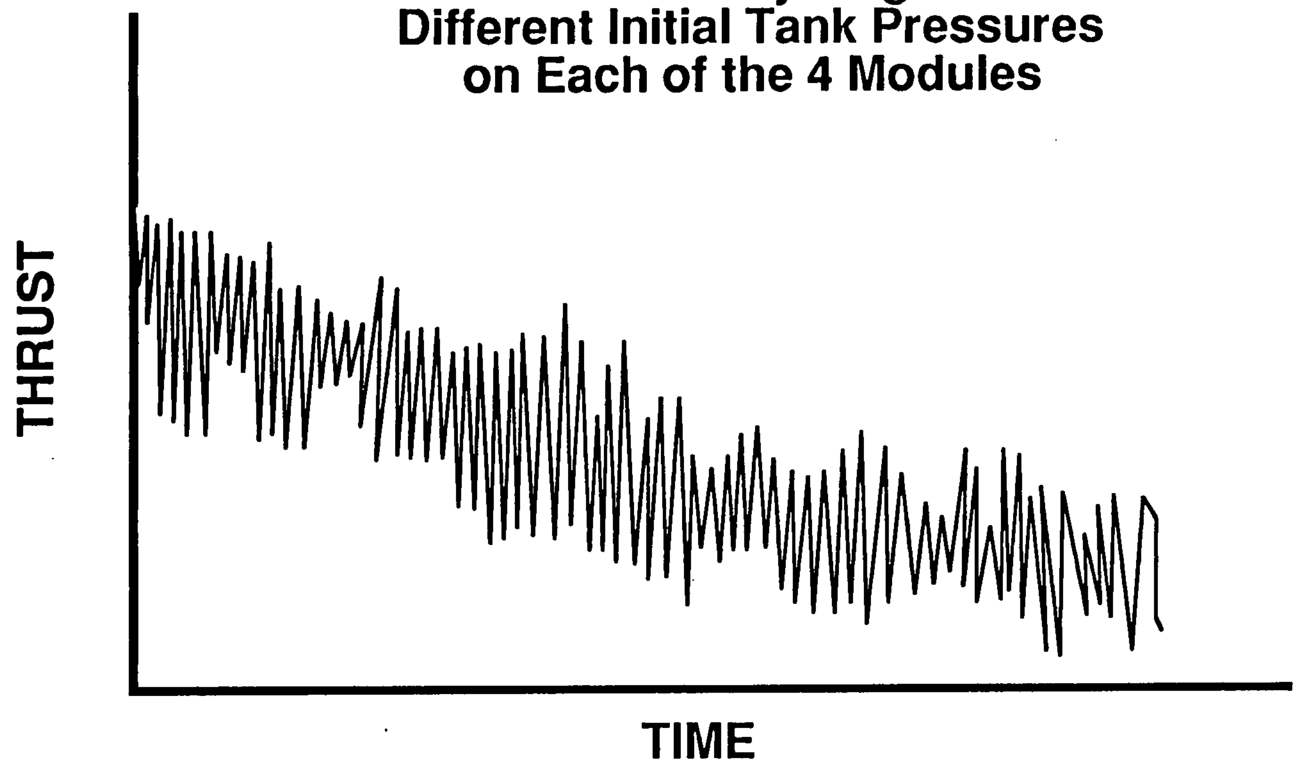
(Continued)

Typical Total Thrust Profile With Thruster Cycling & Different Initial Tank Pressures on Each of the 4 Modules



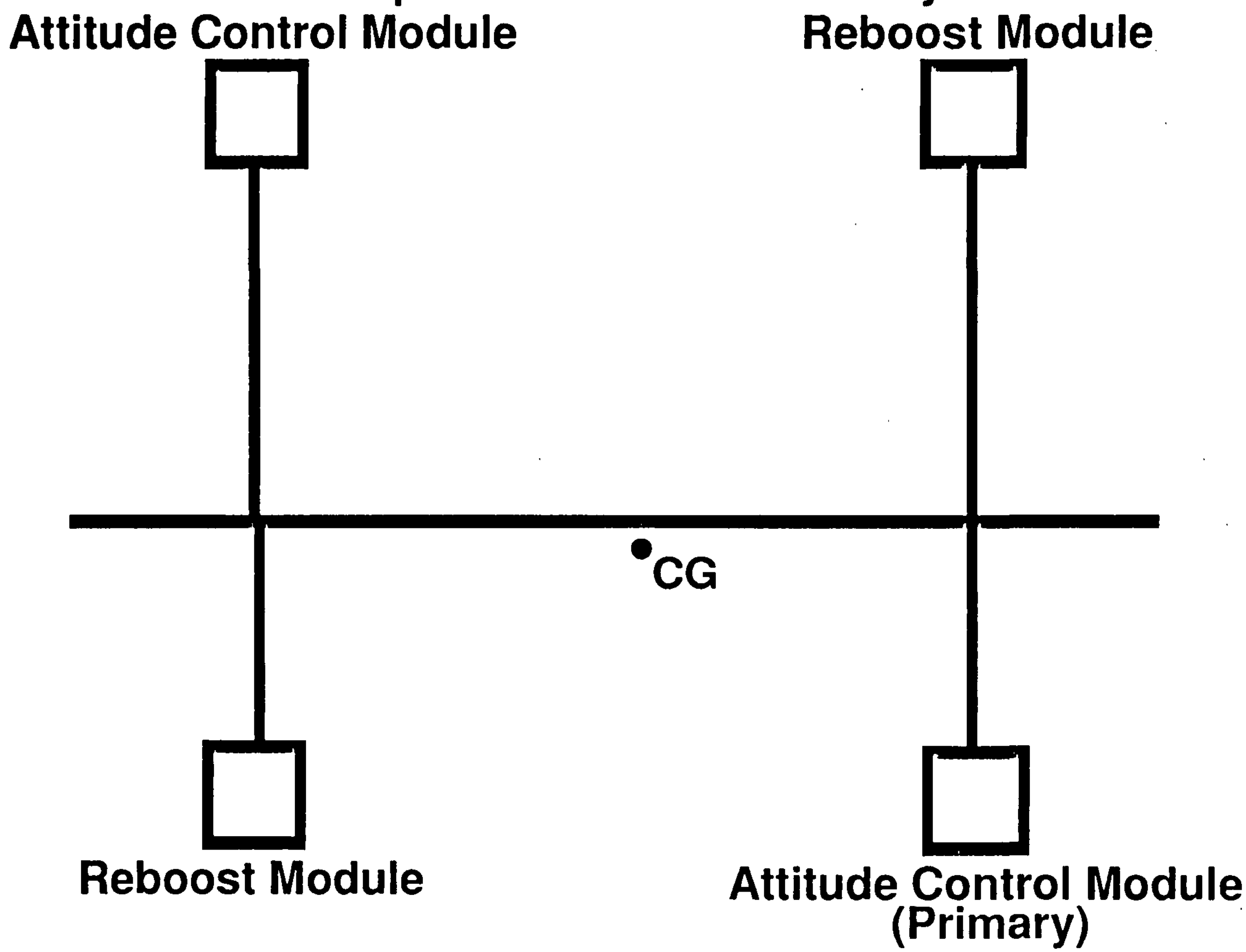
BLOWDOWN THRUST PROFILE PREDICTION

by

Kelly D. Murdock

(Continued)

Propulsion Module Geometry



BLOWDOWN THRUST PROFILE PREDICTION

by
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(Continued)

- **Solution Approach**
  - The current solution approach seeks to determine an approximation to the average thrust curve representing the blowdown thrust profile. The curve is smooth and does not contain the spikes associated with thruster cycling.
  - The algorithm for determining the thrust curve runs as follows:
    - — Determine whether attitude can be maintained by pulsing attitude control jets only with both reboost jets on full or whether one reboost jet must be cycled with the other reboost jet on full. This can be determined by considering the geometry.
    - — Select a burn duration for the full-on reboost jet.

BLOWDOWN THRUST PROFILE PREDICTION

by
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(Continued)

- **Solution Approach (Continued)**
  - Form the equation for the static moment of the two reboost and single attitude control module. This provides two equations (one each in pitch and yaw) in two unknowns (scale factors on the burn times of the attitude control module and the reboost module that has the pulsing jet). Mathematically this is expressed as:

$$\int_0^T \left\{ \vec{r}_1 \times \vec{f}_1(t) + \vec{r}_2 \times \vec{f}_2(\alpha t) + \vec{r}_3 \times \vec{f}_3(\beta\, t) \right\} dt = 0$$

    where the $\vec{r}_i$ are the position vectors (relative to the truss center) of the full on reboost module, the pulsing reboost module and the attitude control module respectively. The $\vec{f}_i$ are the thrust vectors of the respective modules (all in the +X body direction) and the α and β are time scale factors.
  - Solve the above system of equations for the time-scale constants.

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BLOWDOWN THRUST PROFILE PREDICTION

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(Continued)

— Iteration on the burn time for the full-on module provides time-scale factors for the other two modules over the length of the reboost.
— The total thrust profile as a function of time is then given by:

$$\text{Thrust}(t) = \vec{f}_1(t) + \vec{f}_2(\alpha t) + \vec{f}_3(\beta t) \quad 0 \le t \le T$$

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BLOWDOWN THRUST PROFILE PREDICTION

by
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(Continued)

- **Limitations of Current Approach**
  - Although full numerical evaluation of the algorithm has not yet been completed the following points can be made:
    - The predicted thrust curve is more accurate towards the end of the reboost time T than it is at the beginning. This is a drawback since the predicted curve is used for maneuver performance monitoring as well as targeting.
    - The thrust profile is also more accurate in predicting the integrated thrust the longer the time span chosen. Once again though, the accuracy of the curve near the start of the burn is reduced.

BLOWDOWN THRUST PROFILE PREDICTION

by
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(Continued)

- **Summary**
  - A means of generating an estimate of the total thrust curve encountered during a reboost using a blowdown propulsion system has been developed.
  - The algorithm is straight forward and does not involve a large amount of code.
- **Question for Panel Discussion:**
  - Can a fuzzy logic algorithm be developed that would provide a thrust profile curve that would predict the integrated thrust of the propulsion system over time spans of a few hundred seconds rather than over 1000's of seconds with equal accuracy over all regions of the curve?

Topic: Blowdown Thrust Prediction
Presenter: Butch Stegall

Comment: (Stegall) Environment on the ground is worse than in space. They currently have an analytical math model (running in Fortran and Ada). GN&C experts are available at JSC, Marshall, JPL, etc.
- Highly dynamic system during assembly & operation – opinion is that this is a good area for uncertainty management
- The largest criteria for deciding which method to use is the minimization of the code size.

Question: (Stegall) What can be done? Current algorithms are simple, but they are approximations – large amount of uncertainty and many combinations

Q (Berenji): Why is source reduction a goal?
A: $450. per line of code for development for manned flight software systems; Large life cycle costs; 30 year program (SSFP); software maintenance

Q (Lawler): Over suite of combinations, is it still fuel optimal?
A: Yes, 98% optimal.

Q (Lawler): If fuzzy logic came up with an algorithm to match curve (see figure from presentation of "typical" thrust profile with thruster cycle), how much precision will they gain?
A: Don't know; full blown Monte Carlo simulations have not been run. This is not a "large" software application – contains less than 40 lines of code. The tradeoff is in performance and MIPS.

Q (Lawler): What is the value added?
A: in MIPS – any reduction in MIPS is a value. Right before reboost, they are predicting crunch (reboost --> every 90 days).
C (Stegall): Reboost case is a long-term high fuel utilization.

Q (Lawler): Why can't this be done on the ground?
A: Zone of Exclusion, tank management, attitude control – need to be onboard in order to run closed loop and to deal with errors.

Q (Kosko): On control system, what kind of sensitivity studies have been done and what will the benchmarking be done against?
A: 5 out of 21 Shuttle flights are being looked at in detail for standardized set of disturbances; The main concentration is using analytical verification. Example: Verified shuttle aero-variables have some range. In test and verification, GN&C does Monte Carlo simulations; destructive testing, trying to break it.
C (Lea): There is a good deal of work on phase plane control attitutde using forty for attitude hold. Also, we have used fuzzy logic on pre-editing of filtering rate attitude data from sensors (sensor data preprocessing).
On the attitude control we are still testing but have seen a significant decrease in fuel usage (over 1/3) for an attitude hold. Propellant consumption is propulsion metric.

C (Sugeno): If the flight control system is controlled on the helicopter, you have also succeeded in controlling Space Station (less complicated control sequence).

Topic: Rendezvous Guidance
Presenter: Andy McGuire

Q (Berenji): The LQT assumptions – which one can you make with confidence?

Comment: (Lea) What fuzzy gain functions don't require reinitialization.
A candidate is to attack the drawbacks.

Comment: (McGuire) The software is still in preliminary design phase.

Comment: (Berenji) observation - no restriction combining fuzzy logic with detailed domain model; use the fuzzy logic application as a high level controller.
Possibility --> use fuzzy logic for doing reinitialization.
Gain --> Adaptability, flexibility

Q (Lawler): How "bad" off are they? Computational? i.e. can traffic control use it's own SDP; what's throughput; sizing problem? What are the metrics? [All systems need to answer this].

A: Fuel Performance. Run against performance using existing information.