On-Orbit Propulsion and Methods of Momentum Management for the International Space Station

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Overview

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Background

- Since the first documented design of a space station in 1929, it has been a dream of many to sustain a permanent presence in space.
- Russia and the US spent several decades competing for a sustained human presence in low Earth orbit.
- In the 1980’s, Russia and the US began to openly collaborate to achieve this goal. This collaboration lead to the current design of the ISS.
ISS Propulsion Design Concepts

- Must perform momentum management and debris avoidance.
- Minimize propellant consumption.
- Ensure the ISS is flown within the design limits and capabilities of the on-orbit hardware.
Architectural Overview

- Based on heritage designs from both Russia and the US
- Lessons learned from previous space stations.
- A Torque Equilibrium Attitude (TEA) approach was selected.
  - TEA is a specific ISS Yaw, Pitch, Roll sequence selected so that the cumulative effect of all torques experienced by the vehicle during an orbit is approximately zero.
  - This lead to the need for an active momentum management system.
Architectural Overview

- Designed to allow temporary service vehicles to provide the bulk of the propulsive support while also providing the capability of resupplying propellant.
- Control Moment Gyroscopes (CMGs) are integrated to maintain attitude control between propulsive events.
- Russian hardware provides the bulk of propulsive elements.
- US hardware provides non-propulsive momentum management.
Architectural Overview

- Combination of permanently attached modules and transient vehicles.

- **Propulsive Segment**
  - Permanently attached modules:
    - Functional Cargo Block (FGB, Zarya or “Sunrise”)
    - Service Module (SM, Zvezda or “Star”)
    - Docking Compartment (DC1)
    - Mini Research Module 2 (MRM2)
    - Multipurpose Logistics Module (MLM) – not yet in orbit
    - Mini Research Module (MRM1) – not yet in orbit
  - Transient vehicles:
    - Progress
    - European Automated Transfer Vehicle (ATV)
    - Soyuz
    - US Space Shuttle

- **Non-Propulsive Segment**
  - 4 US Control Moment Gyroscopes (CMGs)
Architectural Overview – Permanently Attached Modules

- **FGB**
  - First module of the ISS
  - Main propellant storage facility
  - Thrusters permanently disabled once SM arrived

- **SM**
  - Located at the FGB-aft port
  - Command and control hub using three internally mounted computers
  - Also holds a smaller amount of propellant
  - Provides ISS attitude and altitude control

- **DC1**
  - Currently located at the SM-nadir port
  - An adapter for visiting vehicles to dock to the ISS
  - Provides no propulsion control, but supports propellant resupply operations
SM with a Progress vehicle docked to the Aft port
Architectural Overview – Permanently Attached Modules

- **MLM**
  - Not yet in orbit, will replace the DC1
  - Permanent vehicle for ISS roll control
  - More propellant storage space
  - ISS roll control thruster pack
  - Visiting vehicles will be able to dock to the MLM.

- **MRM1**
  - Not yet in orbit, will be berthed to the FGB-nadir port.
  - Will not provide attitude control, but it will support propellant resupply operations.

- **MRM2**
  - Docked to SM Zenith on November 12, 2009.
  - An adapter for visiting vehicles to dock to the ISS
  - Provides no propulsion control, but supports propellant resupply operations
Architectural Overview – Transient Vehicles

- **Russian Progress and European ATV**
  - Commanded by the SM
  - Can control attitude and altitude
  - Resupply on-orbit propellant storage tanks

- **Russian Soyuz**
  - Provides crew supply and return
  - Technically capable of providing propulsive support, but carries no consumable margin for integrated attitude control

- **US Space Shuttle**
  - Independent from Russian segment
  - Can control ISS attitude and altitude during its docked missions
  - Has no ISS propellant resupply capability
Soyuz docked to the DC-1 Nadir Port
Soyuz in free-flight departing from ISS
Progress docked to the SM Aft Port
ATV docked to the SM Aft Port
ISS Russian Segment

- Progress M/M1
- SM
- MRM2
- FGB
- DC1
- MLM
- MRM1
- Soyuz
Propulsion System – Attitude and Altitude Control

- **ISS Attitude Control (yaw, pitch and roll)**
  - Pitch and yaw are provided by a Progress or ATV docked to the SM-aft port.
  - Roll control is provided by a Progress docked to the DC1-nadir port or an ATV docked to the SM-aft port. The MLM attitude control thrusters will primarily control roll once it is docked to the SM-nadir port.
  - SM thrusters can control attitude if vehicles are not available.

- **ISS Altitude Control (debris avoidance and phasing maneuvers)**
  - Performed by either the aft vehicle or SM orbit control thrusters.
  - A Progress docked to the DC1-nadir port can also provide orbit reboosts.

- **Both ISS attitude and altitude can be controlled by the US Space Shuttle Vernier Reaction Control System (VRCS) thrusters.**
Propulsion System – ISS Propellant Resupply

- Critical for long term support of the ISS.
- Serviced by the Progress and ATV vehicles.
  - Propellant levels can also be managed between the permanent modules.
- Bellows and diaphragm tanks allow multiple refills and prevent vapor entrainment in the pressurization systems.
- Compressors are used to reduce the FGB and SM tank pressures to allow propellant transfers.
Momentum Management

- Uses a combination of Control Moment Gyroscopes (CMGs) and Russian Segment (RS) Thrusters

- Quiescent Operations
  - Momentum Management (MM) Controller uses 4 CMGs to maintain a specific momentum vector
  - ISS attitude allowed to deviate slightly (3-4 degrees)

- Dynamic Operations
  - Requires RS thruster propulsive control if CMGs cannot maintain desired momentum vector or a tighter attitude threshold is required (<1 degree).
  - Many handovers between the Russian propulsion system and the US MM Controller.

- Cooperation and innovative operational strategies have helped minimize propellant consumption and keep ISS operation efficient.
Momentum Management – CMG Saturation

- Saturation occurs when the CMGs lose control of the momentum vector due to external torques because they can only absorb a certain magnitude of momentum.
  - CMGs saturate when all angular momentum vectors are parallel and ISS momentum vector still exceeds their combined magnitude.
  - ISS will either go into “free drift” or RS thrusters will assume control of the station.
  - CMG desaturation is utilized when angular momentum vector reaches its threshold. Uses RS thrusters firings to realign the set of CMG spin axes in opposing directions.
Momentum Management – Torque Compensation Method

- Previously during extended RS attitude control, the ISS would need to maneuver to a Minimum Propellant Attitude (MPA) to minimize excess propellant consumption.
- It was determined that the CMG gimbals could be positioned to create a beneficial torque to compensate for expected external torques. Thus eliminating the maneuvers to and from the MPA.
- Propellant Consumption Savings
  - 50% to 75% savings has been seen for Progress undockings
  - Up to 80% reduction during ISS software uplinks
  - Savings of hundreds of kg per year
Momentum Management – Zero Propellant Maneuver (ZPM)

- CMG only maneuver
- Developed by Draper personnel
- First executed in November of 2006
- Manually uplink time-tagged commands and attitude updates
- Significantly slower than maneuver under RS thruster attitude control
- To date, only a few have been executed
- Continued success may prompt this method to be standardized
Momentum Management – New Processes

- **CMG Thruster Assist (CMG TA) mode.**
  - This is currently the primary mode for ISS.
  - CMG TA consists of using the CMGs until momentum gets too high, then the thrusters will pulse to help re-align ISS momentum. Direct handover to thruster control is also an option if large perturbations are observed.

- **Orbiter Deadband Collapse**
  - Involves reducing the associated error in attitude produced by Orbiter VRCS thrusters such that it is within the acceptable controllability range of the CMGs.
  - Allows for direct handover from Orbiter VRCS control to CGM momentum management instead of handing over from VRCS to RS thrusters and then back to CMG control.
Momentum Management – New Processes

- **110% CMG Controller**
  - When CMGs saturate, angular momentum reaches 100%, indicating the maximum allowable attitude error has been reached.
  - Some torques experienced by the ISS are considered partially conservative, meaning that they will eventually exhibit an opposite torque.
    - Robotic and solar array motions tend to be conservative
    - Changes in mass properties, atmospheric density, surface area and venting are not conservative
  - By relaxing the allowable error on the CMGs beyond 100%, this allows for larger perturbations in ISS attitude before losing control and going into drift.
Propellant Accounting

- Essential to track and monitor propellant quantity within each individual tank

- Measuring devices
  - Linear Translation Transducers – measures propellant volume
  - Radio Frequency Quantity Gauging – measures propellant volume
  - Flowmeters – measures propellant flow

- Analytical methods
  - Burn Time Integration (BTI) – calculate propellant consumed with thruster firing times and flow rates
  - Pressure, Volume, Temperature (PVT) Method
    Use measured pressures and temperatures
    Calculate tank ullage volume with ideal gas law: \( PV = zmTR/M \)
  - Proven to be most accurate and long term
RS Vehicle Configuration Tracking Tool
Propellant Budgeting

- Difficult to gauge how much propellant consumed for various activities
- Recent operations flight rule implemented that defines for propellant management categories
  - “Category 1” – ISS Program “Reserve”
  - “Category 2” – Nominally planned ISS attitude control activities
  - “Category 3” – Activities not essential for ISS operations
  - “Category 4” – Required for ISS altitude maintenance
- Categories have been defined, but actual process is still in work.
- Once finalized, this will be a reference guide
Propellant consumption timeline for FGB and SM

- **STS 127/2JA Docking**
- **34P propellant transfer to FGB ТБГ/О tanks**
- **HTV1 capture**
- **33P propellant transfer to FGB БНДГ/О tanks**

Timeline:
- **7/1/09** to **9/30/09**

Key Events:
- **18S Thruster test**
- **STS 128/17A Docking and N2 venting**
- **34P propellant purge**
- **SM Thruster and Solar Array Efficiency Test**
- **34P dock to SM Aft**
- **34P propellant transfer to FGB БВДГ/О tanks**
- **FGB БВДГ/О feeding SM**
- **FGB ТБГ/О 1-4 feeding SM Manifolds**
- **FGB БНДГ/О 1 feeding SM**
- **18S Relocate to DC-1 Nadir**
- **33P rendezvous**
- **33P propellant purge**

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Propellant Budgeting – Results

- Continuous improvement of procedures for controlling the ISS have lead to more efficient propellant management over the years.
- Improved efficiency combined with the steady use of cargo vehicles has kept ISS propellant levels well above their defined thresholds in all categories.
- The continuing evolution of propellant and momentum management operational strategies demonstrates the capability and flexibility of the ISS propulsion system.
Conclusion

- The hard work and cooperation of the international partners and the evolving operational strategies have made the ISS safe and successful.
- The ISS’s proven success is the foundation for the future of international cooperation for sustaining life in space.