Critical Orbit Control Issues for Fractionated Spacecraft

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Agenda

• **Issues**
  – What are the important issues related to orbit control?

• **Experience**
  – What experience do we have in these areas?

• **Examples**
  – Passive collision avoidance with “safe formations”
  – The effects of navigation uncertainty
“Engineers like to solve problems.
If there are no problems handily available, they will create their own problems.”

– Scott Adams
Motivation

• This fractionated paradigm is motivated by the ideals of:
  – Flexibility
  – Robustness
  – Economy

• While the paradigm itself is a solution to many problems, it also brings new challenges.

• Success depends on several technologies:
  – Distribution of power and actuation
  – Docking and resource transfer systems
  – Relative navigation
  – **Orbit control**
Orbit Control Issues

Now that we’ve broken it into all of these pieces...
How do we control the orbit?

- We must consider **ALL** aspects of orbit control:
  - **Collision Avoidance**
  - **Relative orbit control**
    - Formation Flying
    - Cluster-Maintenance
  - **Absolute station-keeping**
    - About 55 m/s annual delta-v for GEO
    - Fewer, larger maneuvers
    - How to do this with a distributed system?

*Delta-V Requirement?*
Orbit Control Issues

Requirements Flow:

- Relative Orbit Control
  - Formation Flying
  - Cluster-Maintenance
**Orbit Control Issues**

**Requirements Flow:**

- Relative Orbit Control
  - Formation Flying
  - Cluster-Maintenance
Orbit Control Issues

Requirements Flow:

Must Close the Design Loop to Ensure Feasibility
Important Questions:

• What is the propulsion capability at each node?
  – Fully distributed vs. Partially distributed with a fuel tug

• What are the tracking requirements for the mission?
  – Precise formation flying vs. Loose cluster control

• What are the range constraints?
  – Range limits imposed by communication systems

• What are the primary differential disturbances?
  – Earth oblateness, atmospheric drag, solar pressure

• What is the relative navigation uncertainty?
Orbit Control Issues

Some Specifics:

- Even loosely controlled clusters must combat secular drift
  - Differential disturbances, Earth oblateness (J2), Navigation error

- Heterogeneous spacecraft bring differential disturbances
  - Atmospheric drag (LEO)
  - Solar pressure
  - Geometry and Attitude

- Effects of Earth oblateness (J2) depend on the orbit
  - Creates secular drift, linear with time
  - Some effects can be neutralized with choice of relative orbit

- Navigation error
  - Leads to an error in semi-major axis
  - Energy differential → Secular drift
Experience

1999

• **TeamAgent Formation Flying**
  – Phase 1-2 SBIR with AFRL Kirtland, TechSat 21

• **Autonomous Rendezvous and Docking**
  – Phase 1-2 SBIR with AFRL Kirtland

• **Autonomous Control of Formation Flying Spacecraft**
  – 3 Year CETDP with MIT, Cornell

• **Integrated Multi-Range Rendezvous**
  – Phase 1 SBIR with NASA Marshall

• **Defensive Counter Space - Escort Satellites**
  – Phase 2 SBIR with AFRL Kirtland

• **Decentralized Formation Flying Control System**
  – Phase 1-2 SBIR with NASA Goddard

• **PRISMA**
  – CRADA with Swedish Space Corporation, Launch 2008

Present
Experience

• We focus on **practical implementation** of formation flying technology:
  – How to achieve autonomy with efficiency and robustness?
  – How to scale effectively to large clusters?
  – How to deal with disturbances and hardware constraints?
  – How to develop a fault management plan for the cluster?

• **Capabilities:**
  – Real-time fuel optimal maneuver planning
  – Model Predictive Control
  – Decentralized Guidance and Control Methods
  – Scalable Architectures
  – Autonomous Cluster Management
  – Collision monitoring using set membership theory
  – Safe guidance methods for collision avoidance (PRISMA)
• Decentralized Formation Flying
  – Phase 1-2 SBIR
  – NASA Goddard

• Scope and Objectives:
  – Guidance and Control
  – Scalable to large systems
  – Extensible to different orbit regimes and spacecraft designs
  – Autonomous Initialization
  – Autonomous Reconfiguration

• Fractionation:
  – Hierarchical team framework
  – MANTA middleware
• PRISMA Rendezvous Robots
  – CRADA
  – Swedish Space Corporation (SSC)
  – 2 Spacecraft in LEO
  – Launch 2008
  – GNC Demonstrations:
    • Formation Flying
    • Rendezvous
    • Proximity Operations

• PSS Developing Algorithms for:
  – Safe Orbit Guidance
  – Collision Monitoring
Safe Orbit Guidance

- Passive collision avoidance
  - Minimum level of effort for relative orbit control

- 2 Guidance Modes
  - Separation
  - Nominal

- Avoidance Region
  - 2x1x1 Ellipsoid
Safe Orbit Guidance

Objectives

• Separation Guidance
  – Single burn
  – Exit region by time T
  – Monotonic separation
  – Passively safe - never reenter region

• Nominal Guidance
  – Achieve and maintain safe ellipse
  – Fuel efficient
Safe Orbit Guidance

• Safe Ellipse:
  – T-Periodic, or passively stable trajectory
  – Lies outside a “nominal boundary”
  – Coordinated in-plane and cross-track motion
  – Prevents collisions while allowing along-track drift

• Fractionated Missions?
  – Can be applied to large clusters, but increases the maximum range
  – A challenge is to combine safe orbit designs with mission objectives

Orbit-Plane
Along-Track
Safe Orbit Guidance

Drifting Safe Ellipse
Drift due to Navigation Error
Safe Orbit Guidance

Deformation
Due to J2
42 Day Period
LEO

- Along-Track Drift
- Radial Growth
- In-plane / Cross-track Phase Shift

1 Week Trace:

3 Week Animation:
Navigation Error

• Common to all missions, all orbits

• Significant impact on performance and safety
  – Annual Delta-v
  – Collision Probability

• How does it impact cluster-maintenance?
  – Monte Carlo Analysis

• Model predictive control
  – Maneuver planned when position error exceeds deadband
  – Parameters:
    • Deadband
    • Maneuver duration
Navigation Error

- **Parameters of the Monte Carlo Simulation**
  - No disturbances, Zero Eccentricity
  - Each case is simulated for 2 weeks
  - Random noise
  - Results are **averaged** from 150 runs

- **Altitudes**
  - LEO
  - GEO

- **Deadband**
  - 25 m
  - 50 m
  - 100 m

- **Noise Levels**
  - Position: 1.0 to 10 cm
  - Velocity: 0.5 to 5 mm/s

- **Maneuver Duration**
  - 30 min
  - 60 min
  - 120 min

(CDGPS Level)
Navigation Error

Annual Delta-V (m/s)

LEO
Navigation Error

Annual Delta-V (m/s)

GEO
% Time Outside Deadband

LEO
Navigation Error

% Time Outside Deadband

GEO
Navigation Error

Trajectory
- LEO
  - Low Noise
  - High Noise

Deadband
Navigation Error

Trajectory

GEO

Deadband

Deadband

Low Noise

High Noise
Concluding Remarks

• Orbit Control for Fractionated Spacecraft
  – Relative Station-Keeping
  – Absolute Station-Keeping
  – Collision Avoidance

• Important questions:
  – How to perform large-scale station-keeping maneuvers with whole cluster?
  – How to best distribute propulsive capabilities to cluster elements?

• Propulsion Requirements
  – Derived from Mission Req’s and Spacecraft Design
  – Even “loose” clusters will require moderate delta-v capability
  – Are these requirements feasible for fractionated missions?
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