The Location-Scheduled Control Architecture as Applied to Interplanetary CubeSats

Matt Sorgenfrei\textsuperscript{1}, Sanjay Joshi\textsuperscript{1}, & Elwood Agasid\textsuperscript{2}

\textsuperscript{1}Department of Mechanical and Aerospace Engineering  
University of California, Davis

\textsuperscript{2}Mission Design Division  
NASA Ames Research Center

May 30, 2012
CubeSats for Scientific Research

- Past missions developed by NASA Ames have demonstrated efficacy of CubeSats for science operations
  - GeneSat-1, PharmaSat-1, NanoSail-D, O/OREOS
- Payloads studied fundamental space biology, space weather
- Introduction of 6U form factor and miniature sensors/actuators is expanding the field of candidate missions
Passive Stabilization

- Substantial flight heritage for passively stabilized spacecraft from prior NASA Ames missions
- Made use of permanent magnets and hysteresis rods to provide approximately 40° pointing accuracy
- Sufficient for down-link to groundstations but little else

Active Attitude Control

- Increasingly wide field of 3rd party companies developing control sensors and actuators specifically for CubeSats
- Torque coils/rods, reaction wheels/momentum wheels, and even thrusters have been demonstrated in a 1U - 3U scale
- Sun sensors, magnetometers, Earth horizon sensors, and star trackers all now available COTS
Previous CubeSat Attitude Control Implementations

**Passive Stabilization**
- Substantial flight heritage for passively stabilized spacecraft from prior NASA Ames missions
- Made use of permanent magnets and hysteresis rods to provide approximately 40° pointing accuracy
- Sufficient for down-link to groundstations but little else

**Active Attitude Control**
- Increasingly wide field of 3rd party companies developing control sensors and actuators specifically for CubeSats
- Torque coils/rods, reaction wheels/momentum wheels, and even thrusters have been demonstrated in a 1U - 3U scale
- Sun sensors, magnetometers, Earth horizon sensors, and star trackers all now available COTS
What Heritage Can We Leverage?

Bridging the Gap from LEO

- Interplanetary spacecraft traditionally use different sensors and actuators than spacecraft in Low Earth Orbit (LEO)
  - e.g., magnetometers and magnetic torquers don’t work at the Moon, asteroids
- Basic operations are also different: power generation, communications, and science operations all result in different system dynamics and thus different control strategies
- Existing CubeSat ADCS hardware has varying degrees of testing/on-orbit verification, all of it limited to LEO
- The case for interplanetary CubeSats can only be made if they ultimately follow a cost/schedule model that is analogous to that established for LEO
  - At NASA, that means under $5 million and less than 2 years...what is the interplanetary analog?
Interplanetary CubeSat Representative Example

In-Situ Resource Utilization

- Consider exploratory mission to a Near-Earth Object (NEO) for the purpose of in-situ resource utilization (ISRU)
- ‘Mothership’ responsible for the majority of surveying operations, but substantial additional data could be contributed by a secondary spacecraft
- Assume 6U CubeSat with approximately 4U of volume allocated for sensing equipment baselined as the secondary
- Mission operations include approach/recede from Mothership, approach to NEO, and surveying operations
- In general, the attitude knowledge and control requirements for this mission would be much greater than for a traditional LEO CubeSat mission
Implications for CubeSat ADCS

Major Operating Requirements

- Want to maximize science return of secondary spacecraft while minimizing risk (collision?)
- ADCS responsible for detumble after tip-off, approach to NEO, posturing for science, communication, and power generation
- Possible touchdown/retrieval similar to Hayabusa?

Figure: Visualization of a candidate CubeSat for NEO exploration
The Location-Scheduled Control (LSC) Concept

Creation of a Family of Designs

- Under LSC a stand-alone ADCS module would be created to satisfy as many missions as possible
  - Module is reused in a range of spacecraft layouts corresponding to a specific CubeSat form factor
- ADCS location and controller gain values optimized and controller gain values optimized for each possible layout a priori
- “Pre-tuned” configuration selected as required for a given mission
- Previously studied for LEO missions, simple extension to interplanetary operations

Figure: A specific 6U layout to which LSC could be applied.
First Fix Hardware and Controller

- Choice of sensors and actuators influences dynamic response of spacecraft and informs control law choice
- Volume footprint of ADCS defines nature of spacecraft layouts to be tested (e.g. 0.5U vs. 1U)
- Nature of control law strongly impacts complexity of overall design space

Then Search Design Space

- User creates a fitness function that reflects the requirements of the science payload under study
- Genetic algorithm searches for combination of ADCS location and control law gain values that result in highest fitness score
- Allows for rapid study of a large field of candidate designs
First Fix Hardware and Controller

- Choice of sensors and actuators influences dynamic response of spacecraft and informs control law choice
- Volume footprint of ADCS defines nature of spacecraft layouts to be tested (e.g. 0.5U vs. 1U)
- Nature of control law strongly impacts complexity of overall design space

Then Search Design Space

- User creates a fitness function that reflects the requirements of the science payload under study
- Genetic algorithm searches for combination of ADCS location and control law gain values that result in highest fitness score
- Allows for rapid study of a large field of candidate designs
Application of LSC to Interplanetary CubeSats

**Traditional ADCS Design**

- Science Requirements → Pointing Requirements → Mission Specific Sensor/Actuator Selection → Control Algorithm Selection/Verification

**Location-Scheduled ADCS Design**

- General Purpose ADCS Development
  - General Sensor/Actuator Suite Selection → Control Algorithm Selection
    - Science Payload Layout #1 → ADCS Location & Gain Values #1
    - Science Payload Layout n → ADCS Location & Gain Values n

- Mission Specific ADCS Selection
  - Science Requirements → Pointing Requirements → Configuration Selection → ADCS Verification

**Figure**: Comparison between traditional ADCS design and ADCS design via location-scheduled control.
Further Considerations for Interplanetary Operations

- Need to determine a structure for the algorithm fitness function that yields optimal system performance
  - What are the driving performance factors: power consumption? settling time? steady-state error?
- Perform genetic algorithm search process using multiple ADCS modules—only thing that changes is spacecraft model within the algorithm
  - Still unclear what the optimal combination of sensors and actuators is for CubeSats beyond LEO
- Also test multiple control laws—proximity operations could well require a control methodology beyond PID
- Include a high-level metric which assesses the survivability of hardware combinations—much greater possibility for exposure to radiation
- All of these various combinations can be tested quickly thanks to the genetic algorithm approach
Questions?

Thank you for your attention!


Figure: Two candidate configurations for a 6U CubeSat in which the science payload is green, the bus is grey, and the ADCS module is red.
Design Approach: Genetic Algorithm

LSC Requires Multi-Variable Design Optimization

- Genetic Algorithms (GAs) have been widely used for complex optimization problems (Cage et al. 1994, Krishnakumar 1992)
- Allow designer to rapidly search a large portion of the design space in parallel—\( n \) designs evolved for \( m \) generations
- Driven by ‘natural selection’ and randomized evolutionary operators of crossover and mutation
  - Selection methodology and evolutionary operator probabilities controlled by user
- Figure of merit is user-defined fitness function
  - For ADCS design, fitness function comprised of ‘typical’ performance metrics (settling time, tracking error)
- ADCS designs that are deemed more fit as per the fitness function are more likely to ‘reproduce’ during algorithm execution