Multi-algorithmic Hybrid Attitude Determination and Control System of the CubeSat "CADRE"

Dae Young Lee, Prince Kuevor, and James W. Cutler

Presenter: Dae Young Lee (daylee@csr.utexas.edu)
University of Texas at Austin,
Center for Space Research
Introduction

• CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE)
  – Payload: Wind Ion Neutral Composition Suite (WINCS)
  – WINCS monitors the response of the Earth’s upper atmosphere to auroral energy inputs

• ADCS requirement
  – WINCS requires 1 degree pointing accuracy

How to satisfy the requirement?

Hybrid Strategy ADCS

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Actuators</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUEST</td>
<td>Fine pointing</td>
</tr>
<tr>
<td>EKF</td>
<td>Desaturation</td>
</tr>
<tr>
<td>B-dot</td>
<td></td>
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</tbody>
</table>

B-dot

Operation → Scenario → Simulation

Space (Zenith)

Earth (Nadir)
ADCS Design Process

**Requirement Definition**
- Desired attitude
  - LVLH frame

**Device Selection**
- Actuator
  - Reaction Wheel
  - Magnet Torquer

- Sensors
  - Magnetometer
  - Photodiode
  - Gyroscope
  - Star tracker

**Algorithm Selection**
- Estimation
  - Extended Kalman Filter (EKF)
  - Quaternion Estimation (QUEST)

- Control
  - Attitude Control (Reaction Wheel)
  - Momentum Control (Magnetorquer)
  - B-dot Control (Magnetorquer)

**Hybrid Strategy**
- Operation Strategy
  - After Deployment

- Finite-State Machine
  - QUEST/B-dot
  - Desaturation
  - EKF/B-dot

**Numerical Simulation**
- SO(3) based

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Sensors and Actuators

- Each device has pros and cons.
- For magnetometer and photodiode, specific calibration algorithm is implemented.

### Sensors

- **Magnetometer**
  - Accuracy
  - Price

- **Sun sensor (Photodiode)**
  - Accuracy
  - Price

- **Gyroscopes**
  - Drift
  - Price
  - Accuracy

- **Star tracker**
  - Delay
  - Price
  - Accuracy

### Actuators

- **Reaction wheel**
  - Price
  - Saturation
  - Accuracy

- **Magnetorquer**
  - Accuracy
  - Price
  - Good
  - Bad
• Device install position and angle are important for the performance of ADCS
Embedded System Design

- ADCS middleware is implemented to manage sensors and actuators.

### Diagram

- **STAMP**
  - Embedded Linux

- **Orbit Estimator (SGP4)**

- **Hybrid ADCS**
  - I2C
  - 1 sec

### MSP 430

- **Salvo (Soft RTOS)**
  - Total Manager
  - ISR (Timer based semaphore distribution)

### Tasks

<table>
<thead>
<tr>
<th>Task #1</th>
<th>Task #2</th>
<th>Task #3</th>
<th>Task #4</th>
<th>Task #5</th>
<th>Task #6</th>
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</thead>
<tbody>
<tr>
<td>RW</td>
<td>MT</td>
<td>MM</td>
<td>Gyro</td>
<td>Photo</td>
<td>Star</td>
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<td>Time +1</td>
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</tbody>
</table>

- **Semaphore**

- **Communication Task**

- **I2C**

- **UART**

- **RW**
  - Mag Torquer
  - Magnetometer
  - Gyro
  - Photodiode
  - Star tracker
Extended Kalman Filter developed by Crassidis & Junkins is implemented

- Propagations and Updates
- Initial value is important for the convergence of filter estimation

QUaternion ESTimation (QUEST) suggest the initial estimation for EKF

- For valid estimation with low cost sensor, de-tumbling is required.
Control algorithm

B-dot is effective for de-tumbling of spacecraft and unified with Bang-Bang control
- One magnetometer’s measurement is required
- De-tumbling make a primitive estimation be exact

\[ m_k = -\frac{k_B}{h} (b_k^{avg} - b_{k-1}^{avg}) \quad b_k^{avg} = \alpha b_k + (1 - \alpha) b_{k-1}^{avg} \]

PD control on SO(3) developed by McClamroch et al. is implemented
- Exact attitude and body angular velocity estimation is required
- Disturbance make the reaction wheel saturated

\[ u_k = -K_v (\omega_k - \omega_d) - K_p \Omega (R_k) \]
\[ \tau_k = u_k + (\omega_k) \times \pi_k, \]
\[ \Omega_a(R) \triangleq \sum_{i=1}^{3} a_i e_i \times (R_d^\top R e_i) \]

Wheel desaturation developed by Lovera et al. is unified with Bang-Bang control
- Exact attitude and body angular velocity estimation is required

\[ m_k = -\frac{k_{mag}}{\|b_k\|^2} (b_k) \times \pi_k \]

Magnetometer

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Hybrid ADCS development

- Muti-algorithmic hybrid system is implemented for a active ADCS of CubeSat
Lie group variational integrator of Spacecraft with reaction wheel assembly

- Gravity gradient
- Solar pressure
- Aerodynamic drag
- Residual dipole
Simulation : Control results

- Disturbance torques increase the wheel speed
- Bang-Bang control is enough for B-dot and Desaturation control
- During desaturation, ADCS might lose pointing accuracy
Simulation: Estimation results

- Uncertainties are smaller when spacecraft has low angular velocity

Y axis uncertainty has lower average because of the star tracker delay
Hardware-in-the-loop simulation

- The test in MXL

- The test in Naval Postgraduate School - With Professor Romano and Dr. Park

https://youtu.be/lm_yzOqYAJC

https://youtu.be/qTDsV8Fm69g
Conclusion

• An active attitude determination and control system (ADCS) with a hybrid control strategy is proposed and applied to CADRE.

• To accomplish 1 degree pointing accuracy, pre-developed control and estimation algorithms are modified and unified into a hybrid strategy based on a finite-state machine.
  - Each state and the transition conditions of the finite-state machine are also defined and verified through simulations.

• To demonstrate accurate simulation results, we develop a dynamic satellite simulator that implements a Lie Group Variational Integrator of a spacecraft with the reaction wheel assembly.
  - The simulation library will be opened to cubesat developers and students

• Simulation results demonstrate that the active ADCS successfully performs the specified fine pointing control.