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

Sensors
- QUEST
- EKF
- B-dot

Actuators
- Fine pointing
- Desaturation

Operation → Scenario → Simulation

Space (Zenith)

Earth (Nadir)
ADCS Design Process

**Requirement Definition**
- Desired attitude
  - LVLH frame
- Pointing accuracy
  - Error range define

**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
  - Command Strategy
- Finite-State Machine
  - QUEST/B-dot
  - EKF/B-dot
  - Desaturation
  - EKF/Pointing

**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.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Actuators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetometer</td>
<td>Reaction wheel</td>
</tr>
<tr>
<td>Sun sensor (Photodiode)</td>
<td>Magnetorquer</td>
</tr>
<tr>
<td>Gyrosopes</td>
<td></td>
</tr>
<tr>
<td>Star tracker</td>
<td></td>
</tr>
</tbody>
</table>

Each device has pros and cons.

For magnetometer and photodiode, specific calibration algorithm is implemented.
Sensors and Actuators

- Device install position and angle are important for the performance of ADCS

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**Angular Uncertainty over attitude sphere**

**Azimuth (deg)**
- -150
- -100
- -50
- 0
- 50
- 100
- 150

**Elevation (deg)**
- -80
- -60
- -40
- -20
- 0
- 20
- 40
- 60
- 80

**Uncertainty (deg)**
- 0
- 0.2
- 0.4
- 0.6
- 0.8

---

**5 degree**

**0 degree**
Embedded System Design

- ADCS middleware is implemented to manage sensors and actuators

<table>
<thead>
<tr>
<th>STAMP</th>
<th>Orbit Estimator (SGP4)</th>
<th>Hybrid ADCS</th>
</tr>
</thead>
</table>

**MSP 430**

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

<table>
<thead>
<tr>
<th>RW</th>
<th>MT</th>
<th>MM</th>
<th>Gyro</th>
<th>Photo</th>
<th>Star</th>
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<table>
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<table>
<thead>
<tr>
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<th>Task #3</th>
<th>Task #4</th>
<th>Task #5</th>
<th>Task #6</th>
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</thead>
</table>

- **Semaphore**

- **Communication Task**

- **1 sec**

- **Semaphore**

<table>
<thead>
<tr>
<th>UART</th>
<th>I2c</th>
<th>I2c</th>
<th>SPI</th>
<th>I2c</th>
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<tbody>
<tr>
<td>RW</td>
<td>Mag Torquer</td>
<td>Magnetometer</td>
<td>Gyro</td>
<td>Photodiode</td>
<td>Star tracker</td>
</tr>
</tbody>
</table>
Estimation algorithm

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

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

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

**Pointing** 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

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

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

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

- Muti-algorithmic hybrid system is implemented for an active ADCS of CubeSat
Simulation : Structure

Lie group variational integrator of Spacecraft with reaction wheel assembly

SO(3)

Sensor Calibration

$\dot{S}_B$

$\mathbf{B}_B$

EKF

$\dot{q}_{B/1}$

$\dot{\omega}_{B/1}$

Control Algorithm

$\mathbf{m}_{MT|B}$

Magnetorquer

IGRF

Emulation

Algorithm

Photodiode

$\mathbf{I}_B$

Sun + Eclipse

$\mathbf{O}_{B/1}$

ECEF + IGRF

Star tracker

$\dot{q}_{B/1}$

Gyroscope

$\dot{\omega}_{B/1}$

Orbit Dynamics

$\mathbf{O}_{B/1}$

Disturbances

$\mathbf{\tau}_{RW|B}$

$\mathbf{\tau}_{MT|B}$

Reaction Wheels

$\mathbf{\tau}_{\text{dis}|B}$

Gravity gradient

Solar pressure

Aerodynamic drag

Residual dipole

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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_yzOqYAJe

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.