13th Annual Summer CubeSat Developers' Workshop

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

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AEROSPACE ENGINEERING
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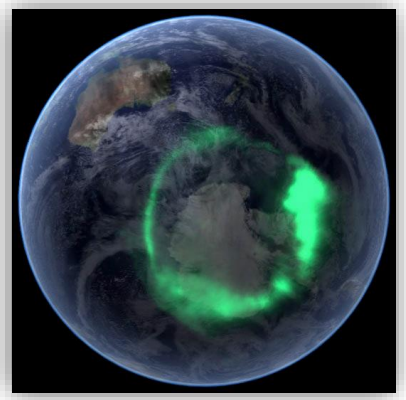
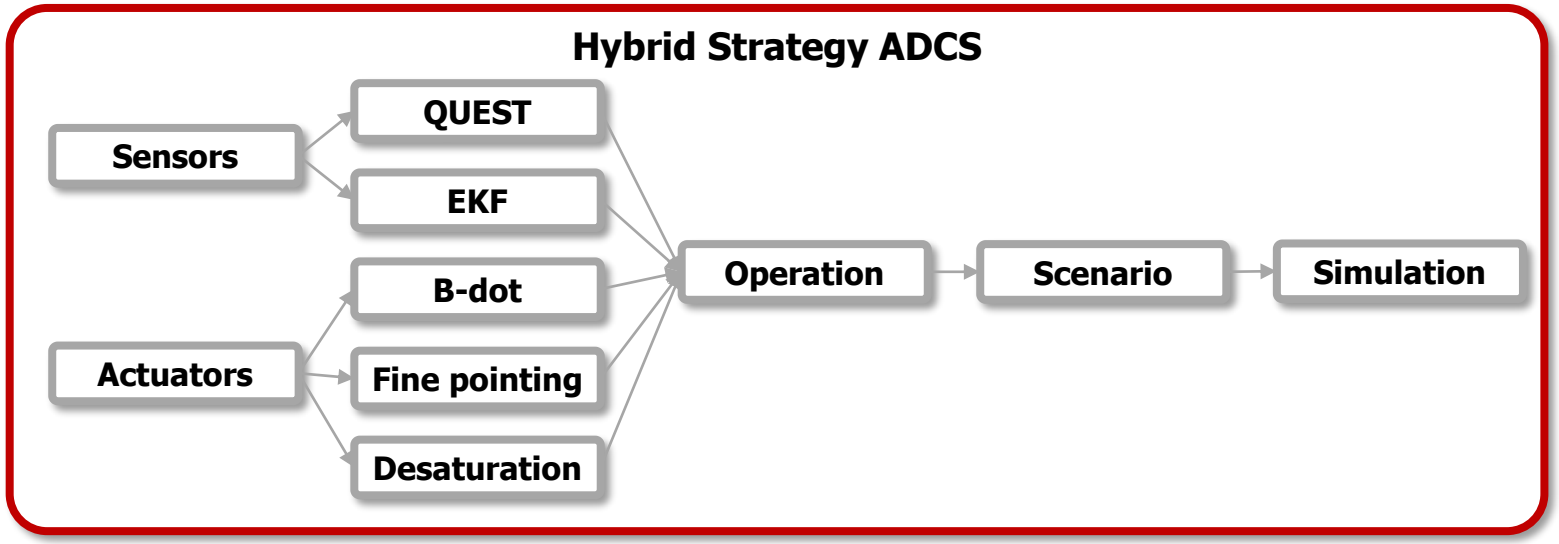
Introduction

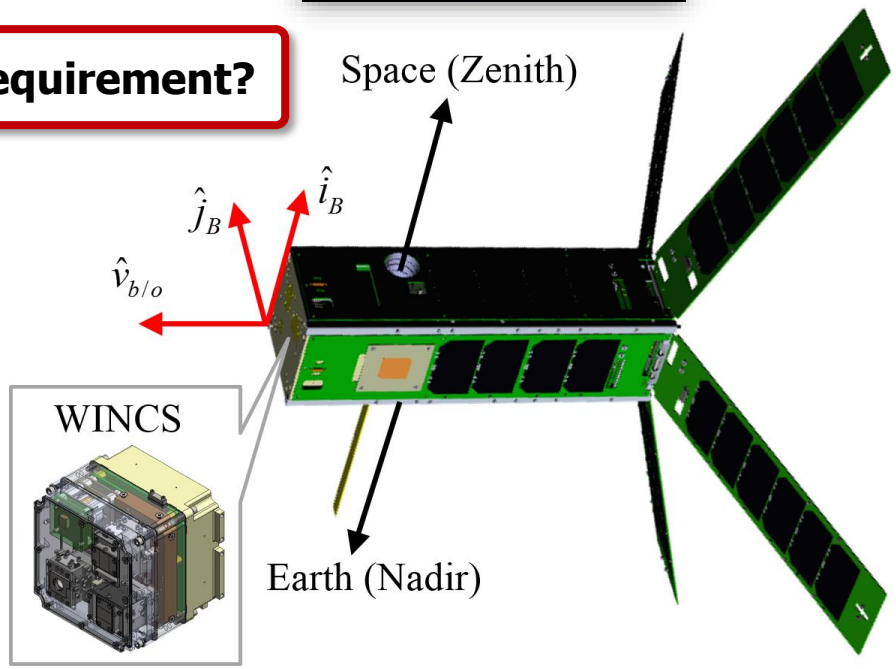
- **CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE)**
  - **Payload : Wind Ion Neutral Composition Suite (WINCS)**
  - **WINCS monitors the response of the Earth's upper atmosphere to auroral energy inputs**



- **ADCS requirement**
  - **WINCS requires 1 degree pointing accuracy**

How to satisfy the requirement?

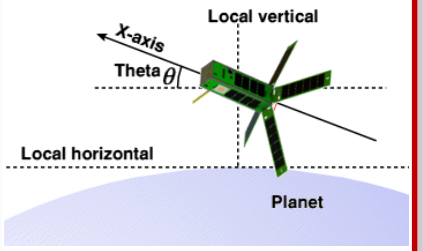




ADCS Design Process

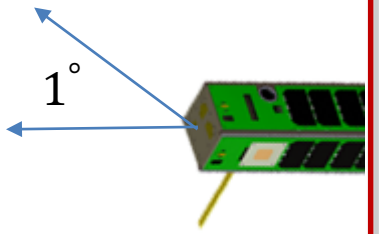
Requirement Definition

Desired attitude



LVLH frame

Pointing accuracy

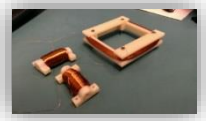


Error range define

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)

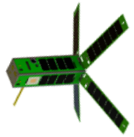
+

B-dot Control (Magnetorquer)

Hybrid Strategy

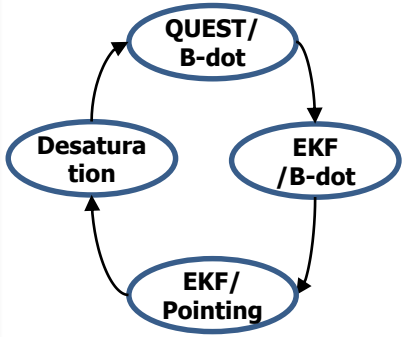
Operation Strategy

After Deployment



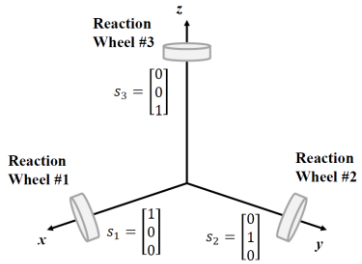
Command Strategy

Finite-State Machine

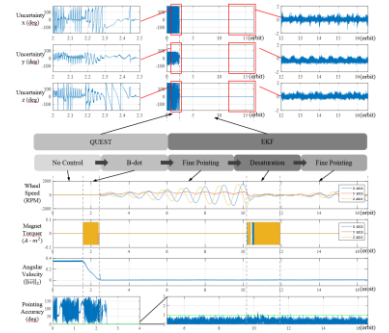


Numerical Simulation

SO(3) based



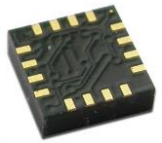
Simulations



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

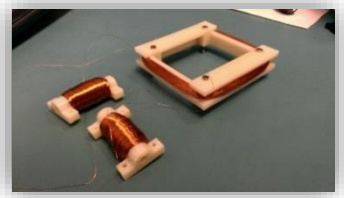
Star tracker

Delay | Price | Accuracy

Actuators

Reaction wheel

Price | Saturation | Accuracy



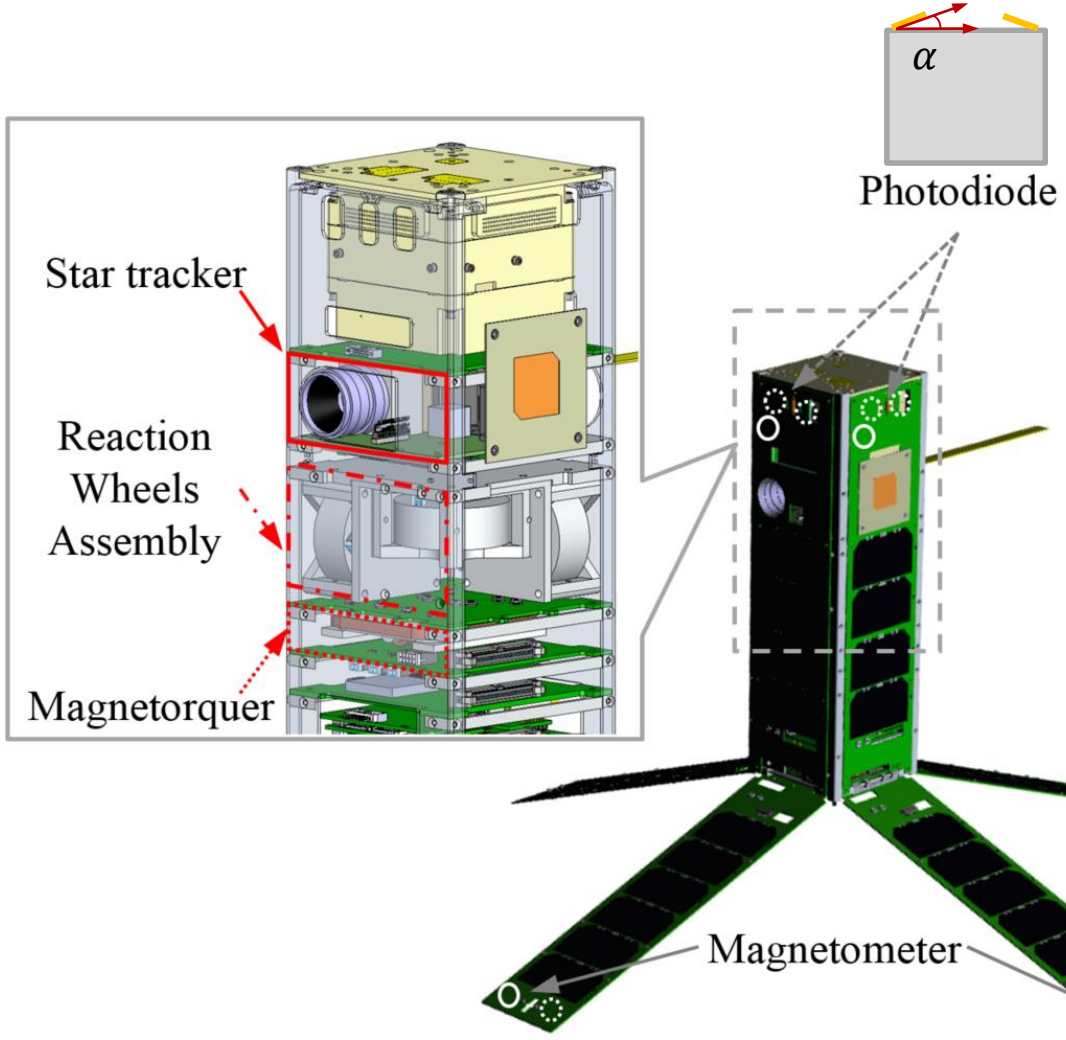
Magnetorquer

Accuracy | Price

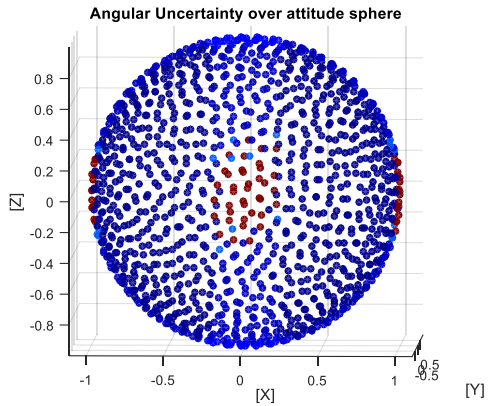
Bad | Good

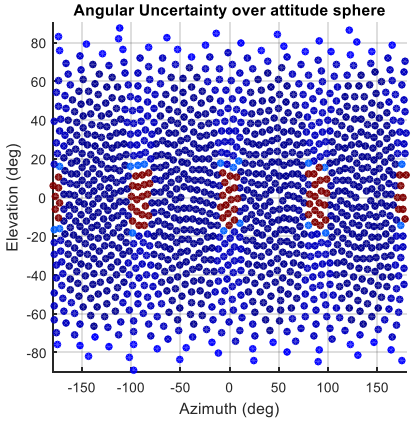
Sensors and Actuators

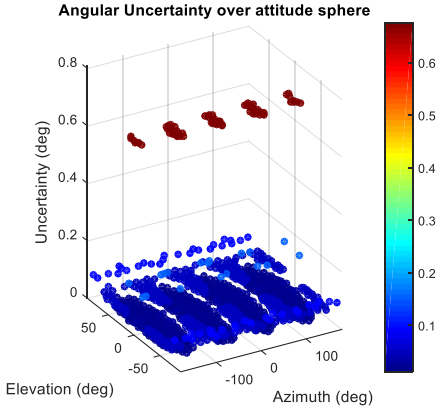
- **Device install position and angle are important for the performance of ADCS**



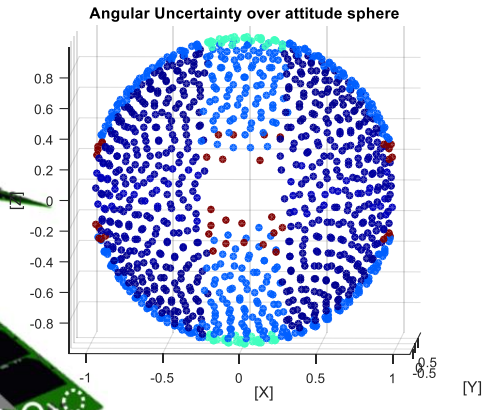
– **5 degree**

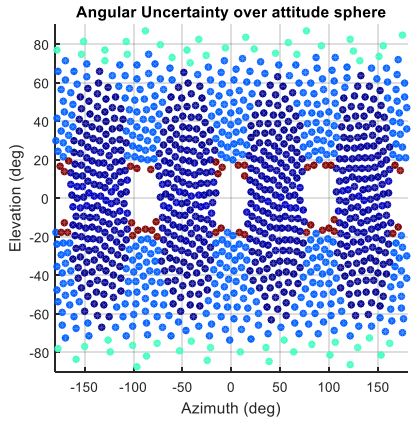


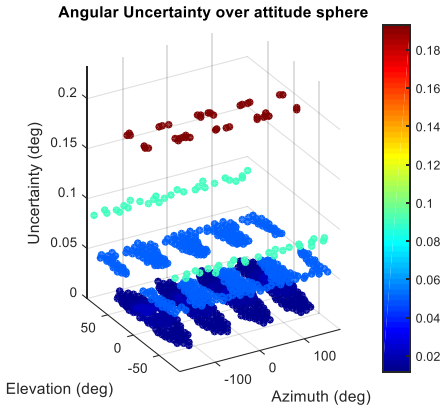




– **0 degree**

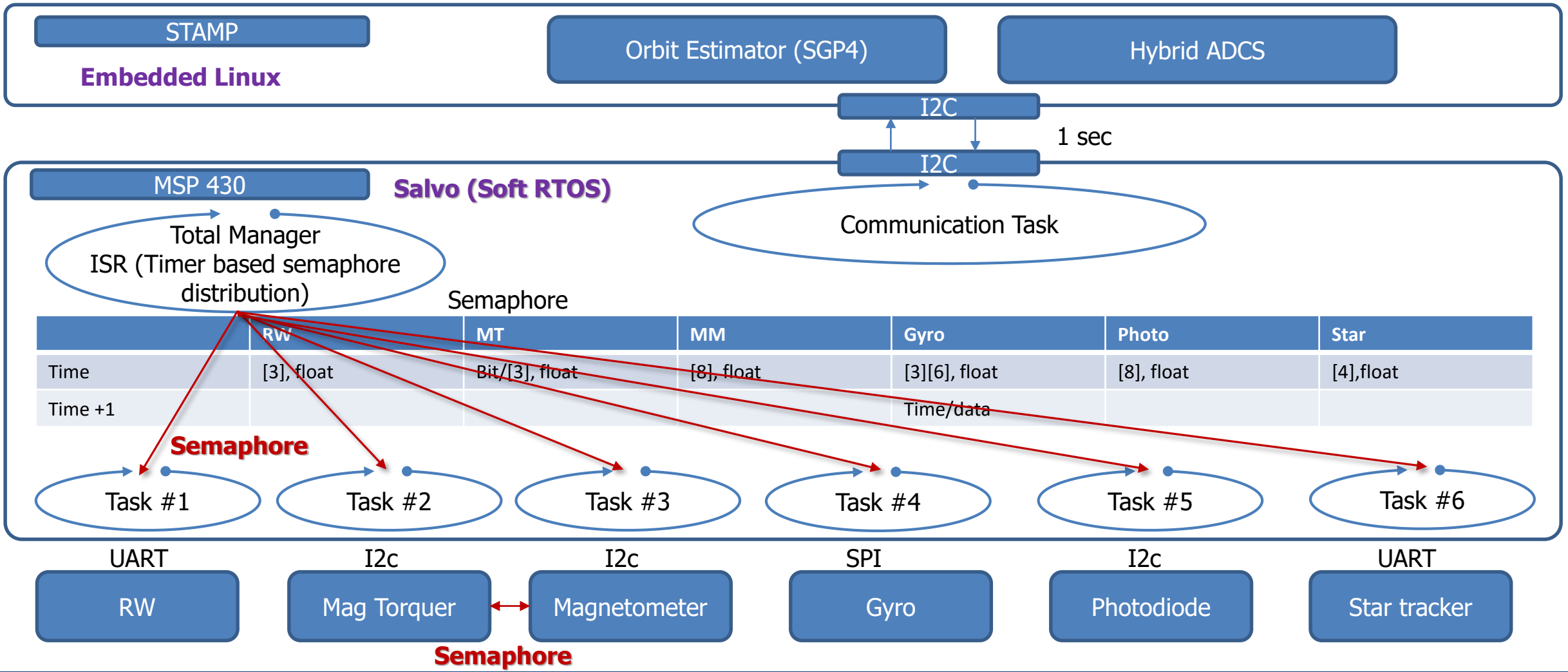






Embedded System Design

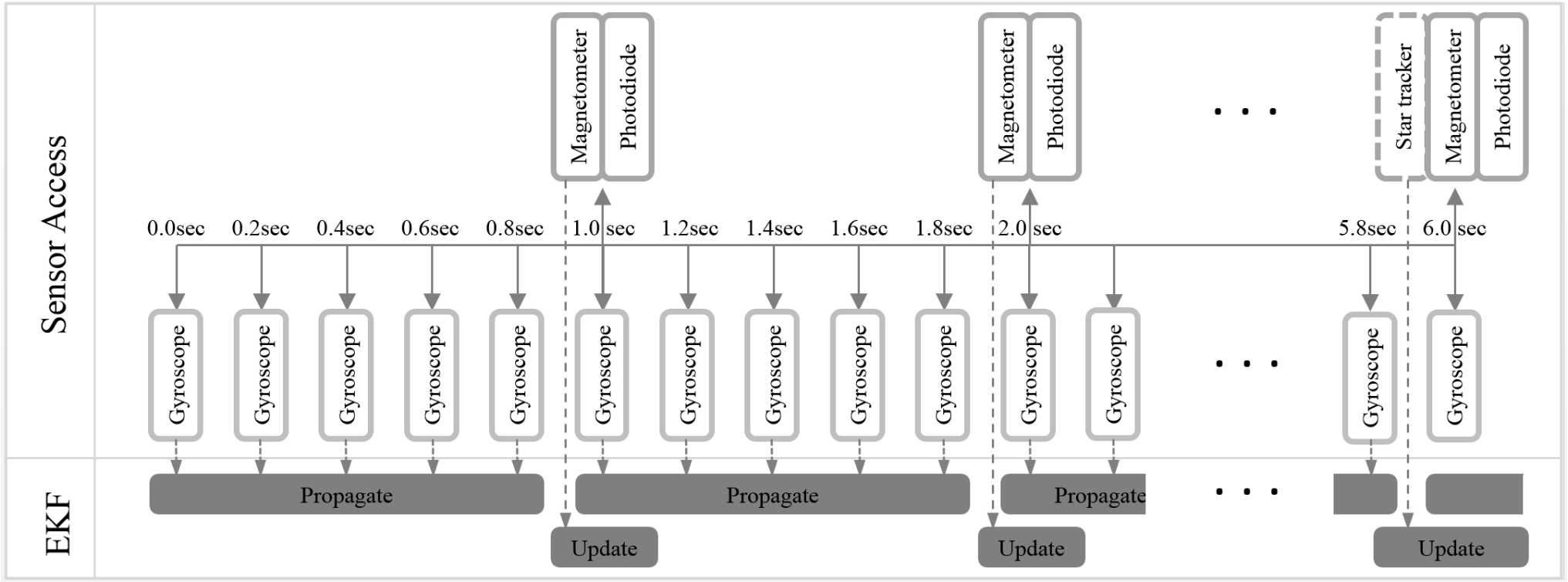
- **ADCS middleware is implemented to manage sensors and actuators**



Estimation algorithm

EKF **Extended Kalman Filter developed by Crassidis & Junkins is implemented**

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



QUEST **QUaternion ESTimation (QUEST) suggest the initial estimation for EKF**

- **For valid estimation with low cost sensor, de-tumbling is required.** → **B-dot**

Control algorithm

B-dot 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

QUEST

$$m_k = -\frac{k_B}{h}\left(b_k^{avg} - b_{k-1}^{avg}\right) \longleftarrow b_k^{avg} = \alpha b_k + (1-\alpha) b_{k-1}^{avg}$$

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

EKF

Rotation rate, Desired Rotation rate, Desired orientation, Current orientation

$$u_k = -K_v\left(\omega_k - \omega_d\right) - K_p \Omega_\alpha\left(R_k\right),$$
$$\tau_k = u_k + \left(\omega_k\right)^\times \pi_k,$$
$$\Omega_{\mathbf{a}}(R) \triangleq \sum_{i=1}^{3} a_i e_i \times \left(R_{\mathrm{d}}^\top R e_i\right)$$

Desaturation Wheel desaturation developed by Lovera et al. is unified with Bang-Bang control

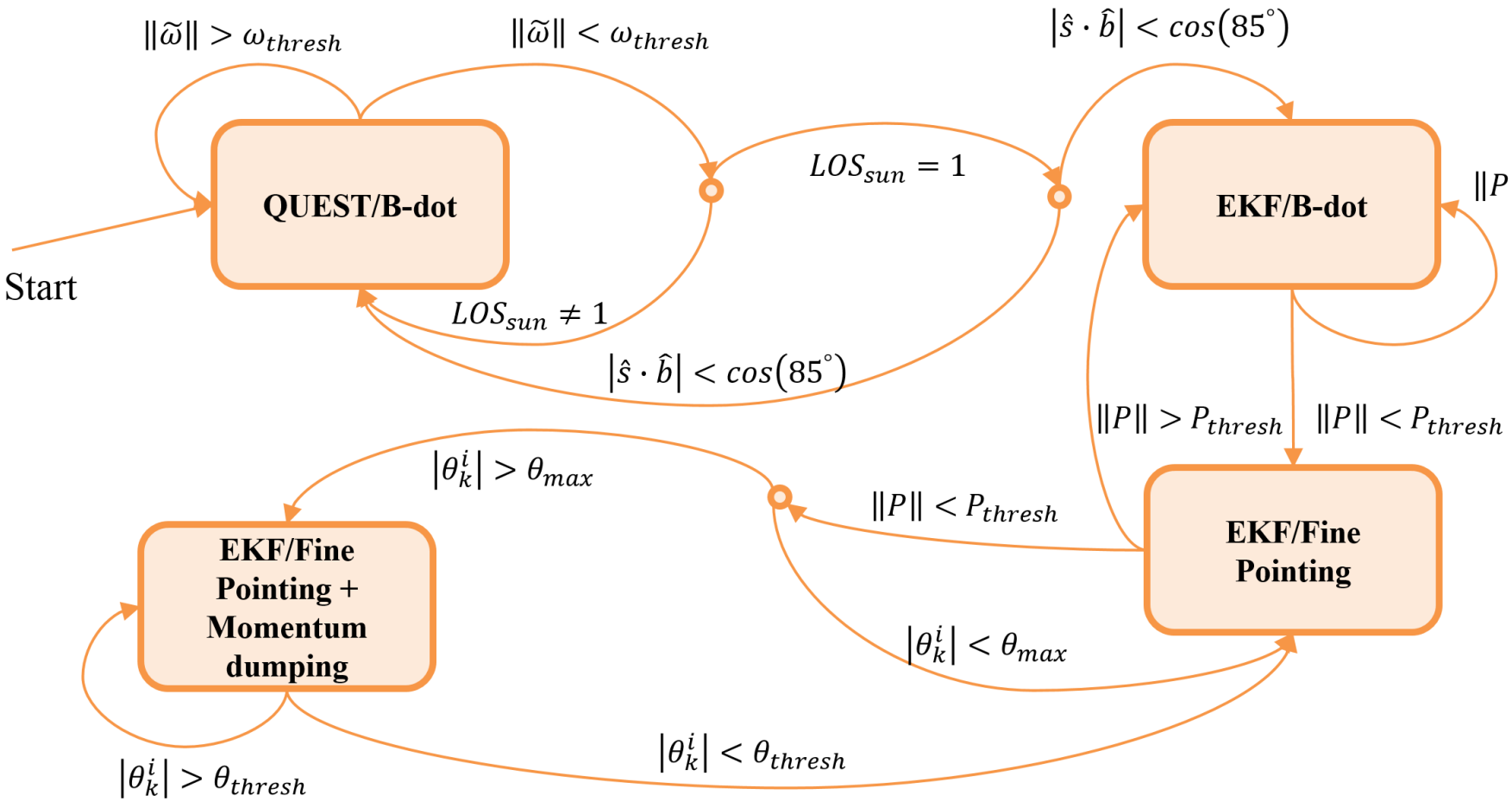
- Exact attitude and body angular velocity estimation is required

Magnetometer, Wheel momentum

$$m_k = -\frac{k_{mag}}{\|b_k\|^2}\left(b_k\right)^\times \pi_k.$$

Hybrid ADCS development

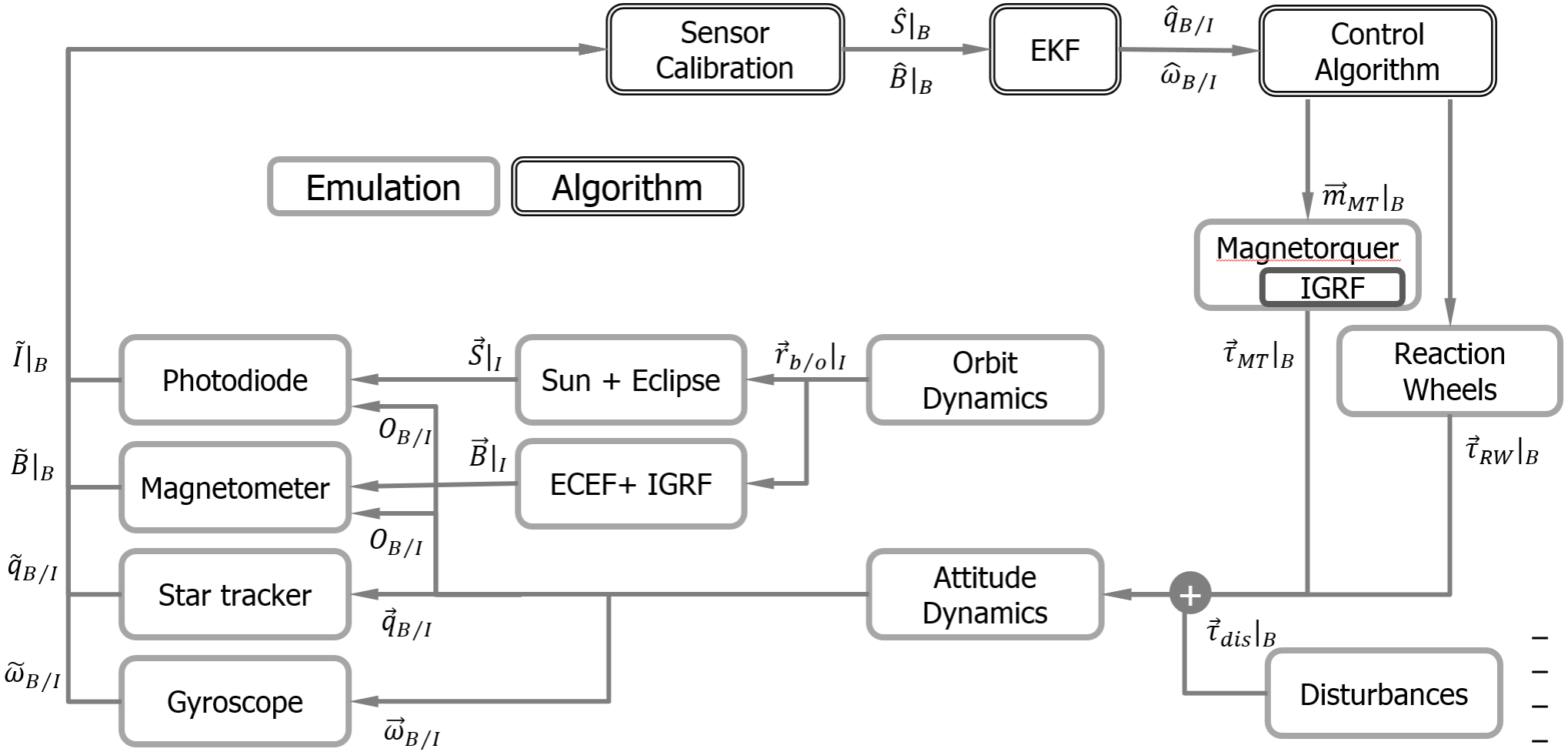
- **Muti-algorithmic hybrid system is implemented for a active ADCS of CubeSat**



$\|\cdot\|$	: vector, matrix norm
$\tilde{\omega}$	: gyroscope measurement
ω_{thresh}	: gyroscope threshold (minimum)
LOS_{sun}	: line of sight to Sun, 0 means eclipse
$\hat{b}$	: normalized magnetic vector
$\hat{s}$	: normalized Sun vector
P	: covariance matrix of EKF
P_{thresh}	: covariance matrix maximum threshold
θ_k^i	: i-th reaction wheel rotating speed
θ_{max}	: reaction wheel rotating speed maximum
θ_{thresh}	: reaction wheel rotating speed threshold

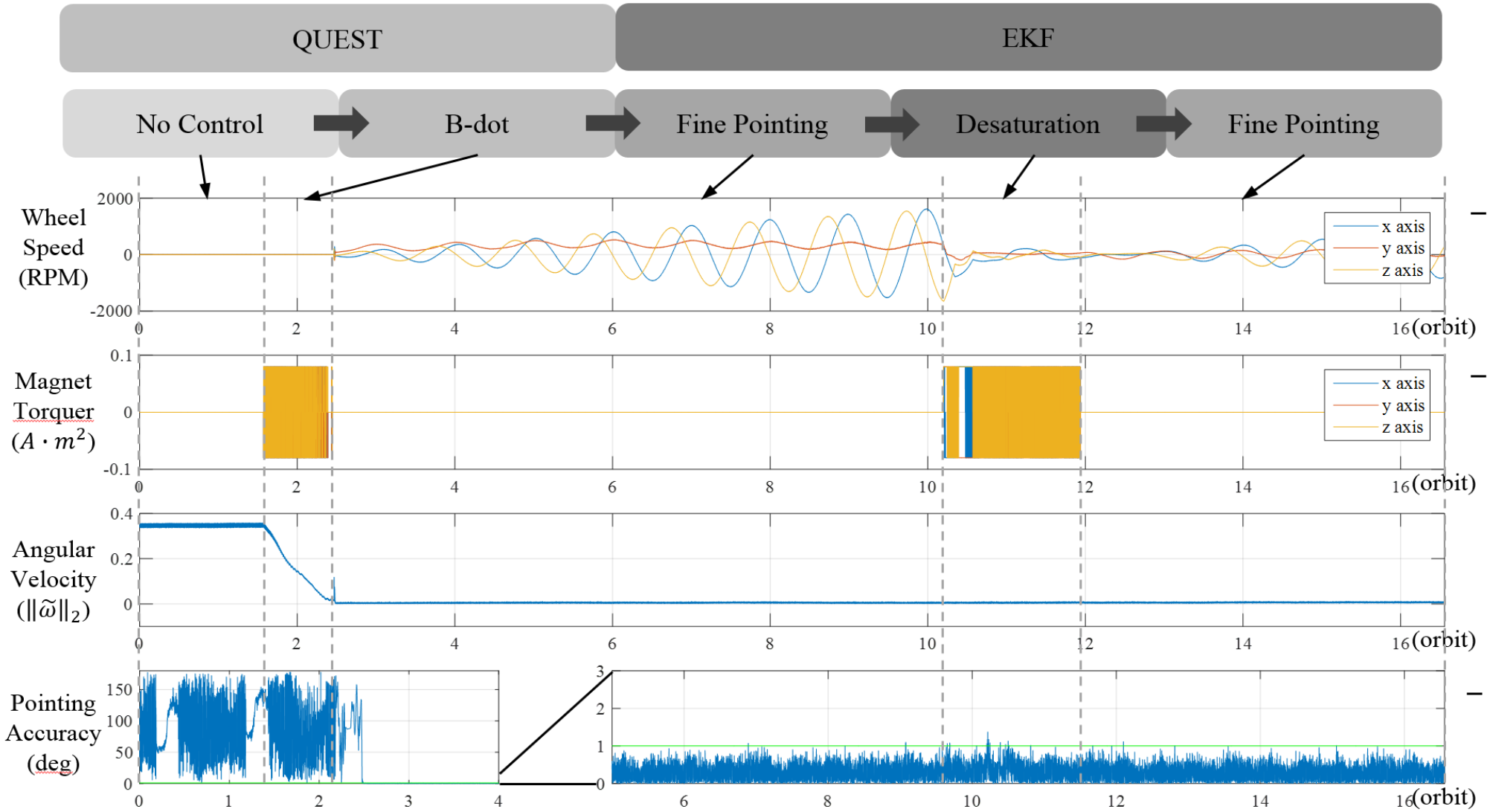
Simulation : Structure

SO(3) **Lie group variational integrator of Spacecraft with reaction wheel assembly**



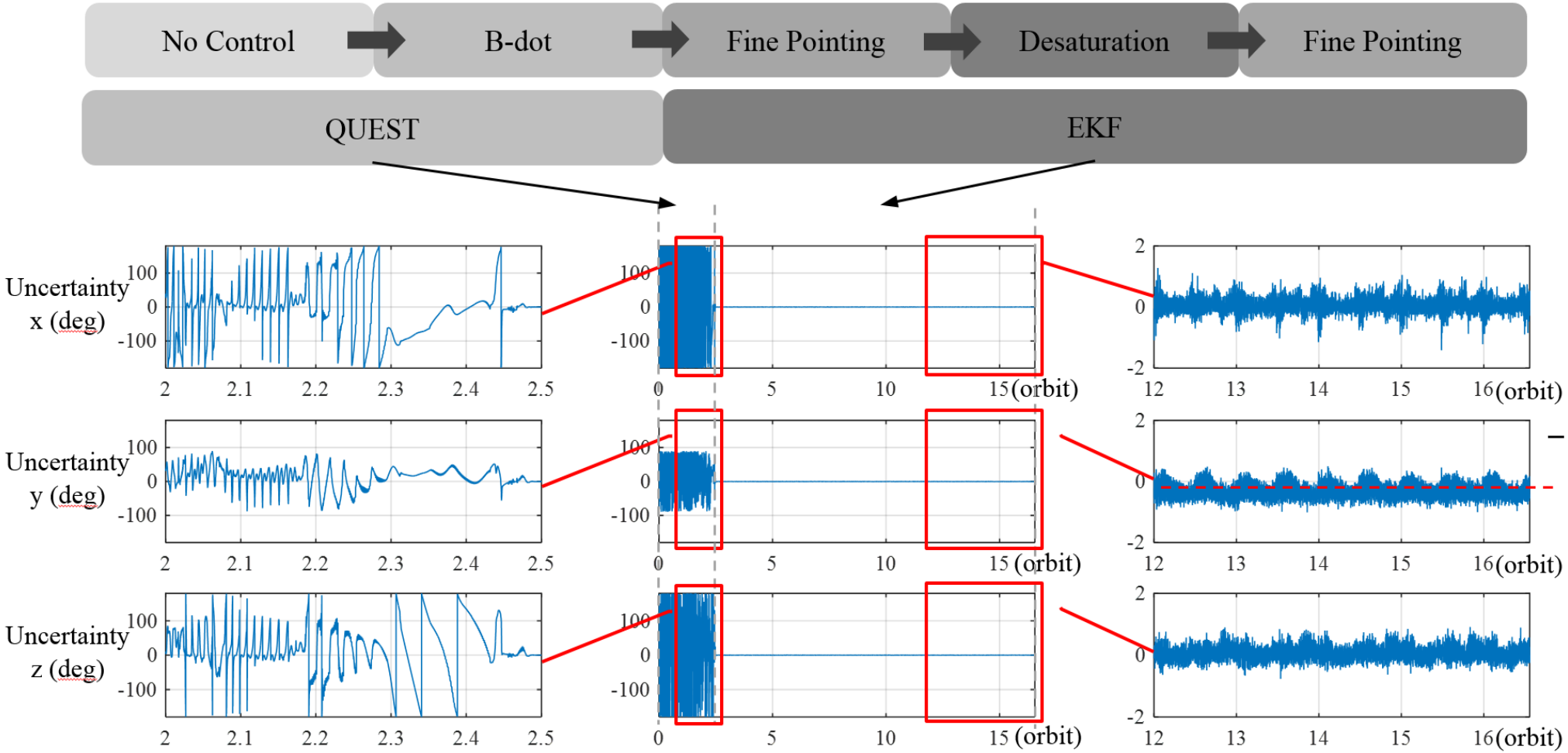
- **Gravity gradient**
- **Solar pressure**
- **Aerodynamic drag**
- **Residual dipole**

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

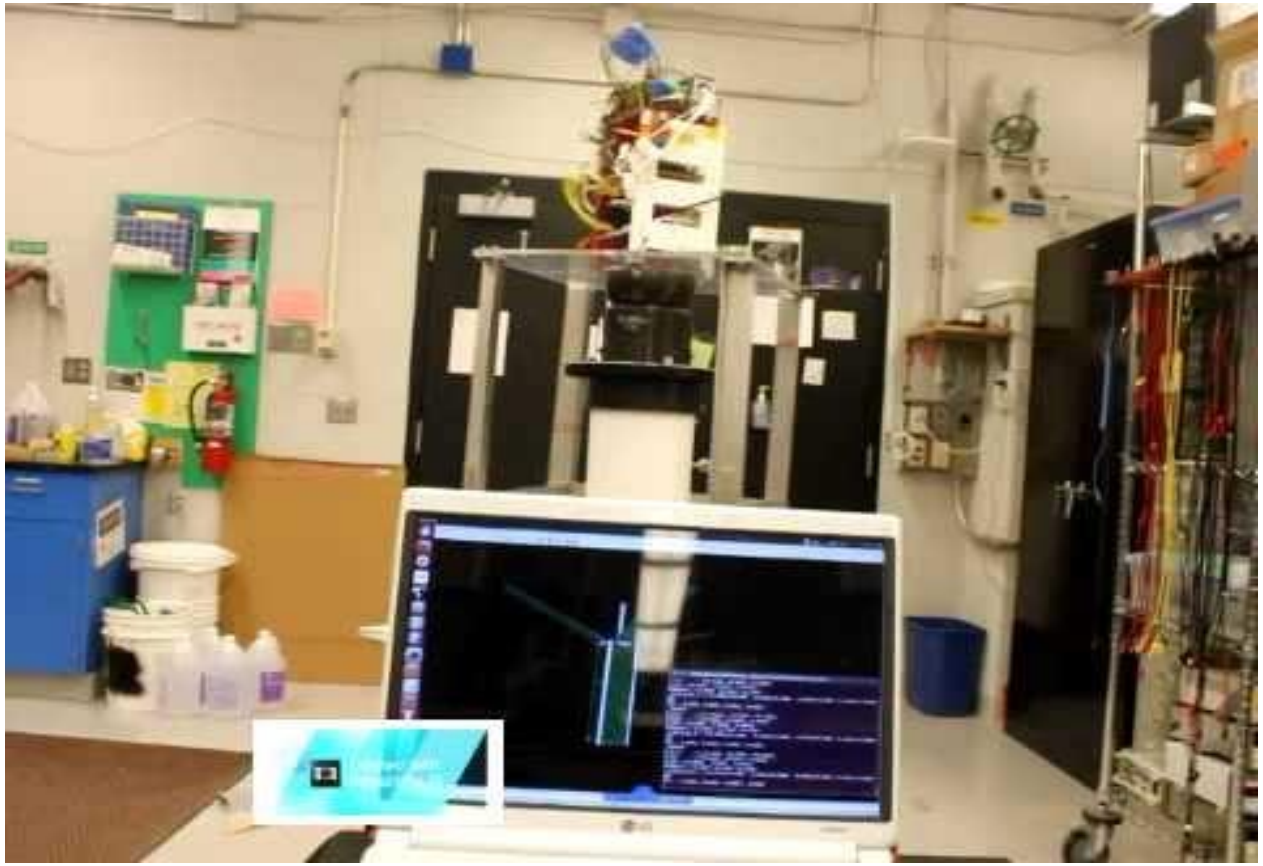


- **Y axis uncertainty has lower average because of the star tracker delay**

- **Uncertainties are smaller when spacecraft has low angular velocity**

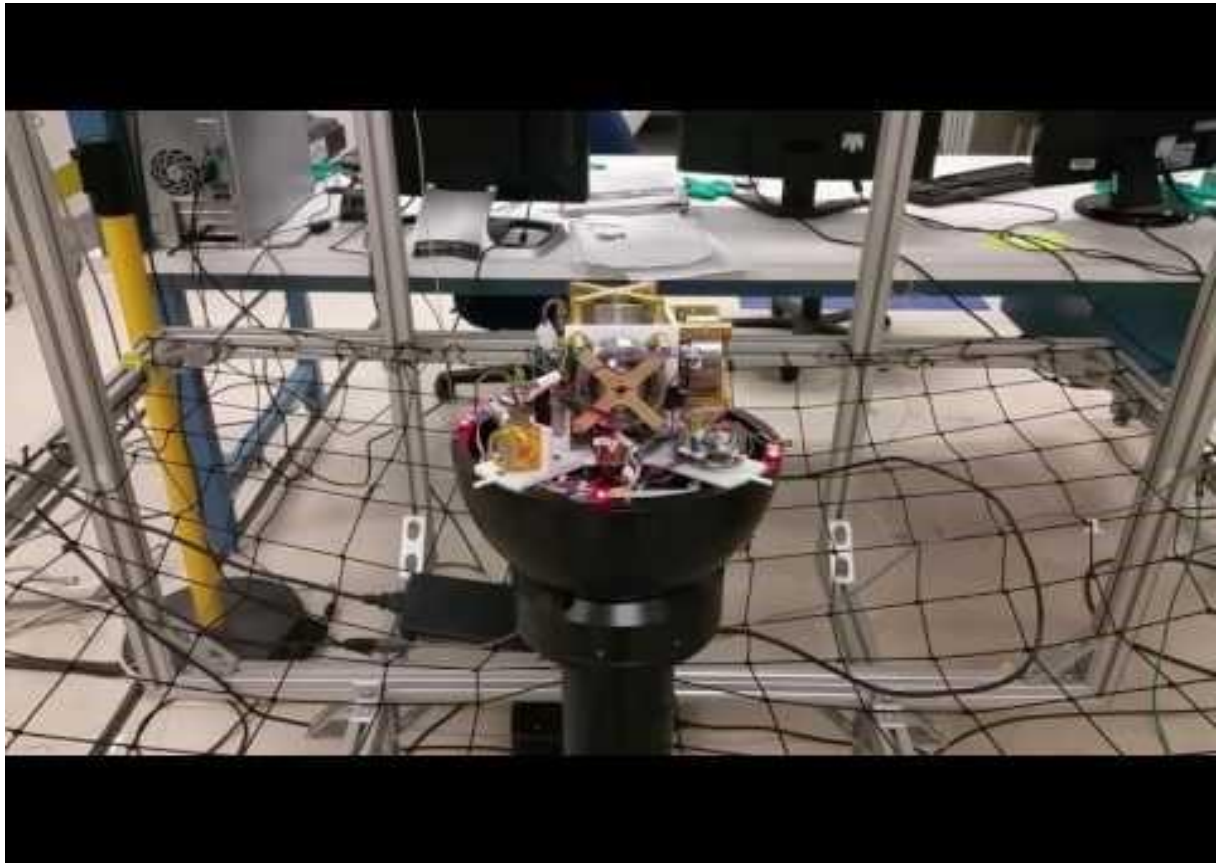
Hardware-in-the-loop simulation

- **The test in MXL**



https://youtu.be/lm_yzOqYAJc

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



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.**