Hybrid Attitude Control of a Two-CubeSat Virtual Telescope in a Highly Elliptical Orbit

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Outline

- Mission
- Orbit design
- System and mission design
- Controller design
- Conclusion

small SATELLITE
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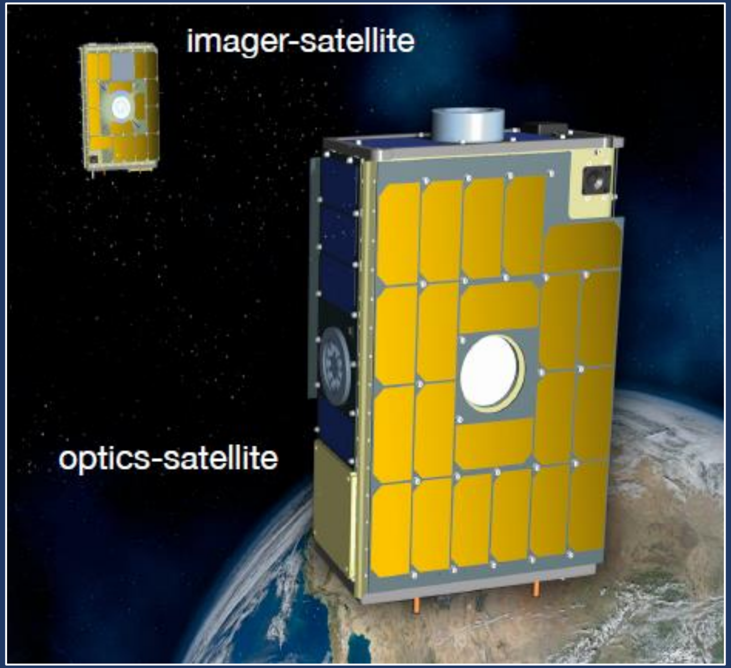
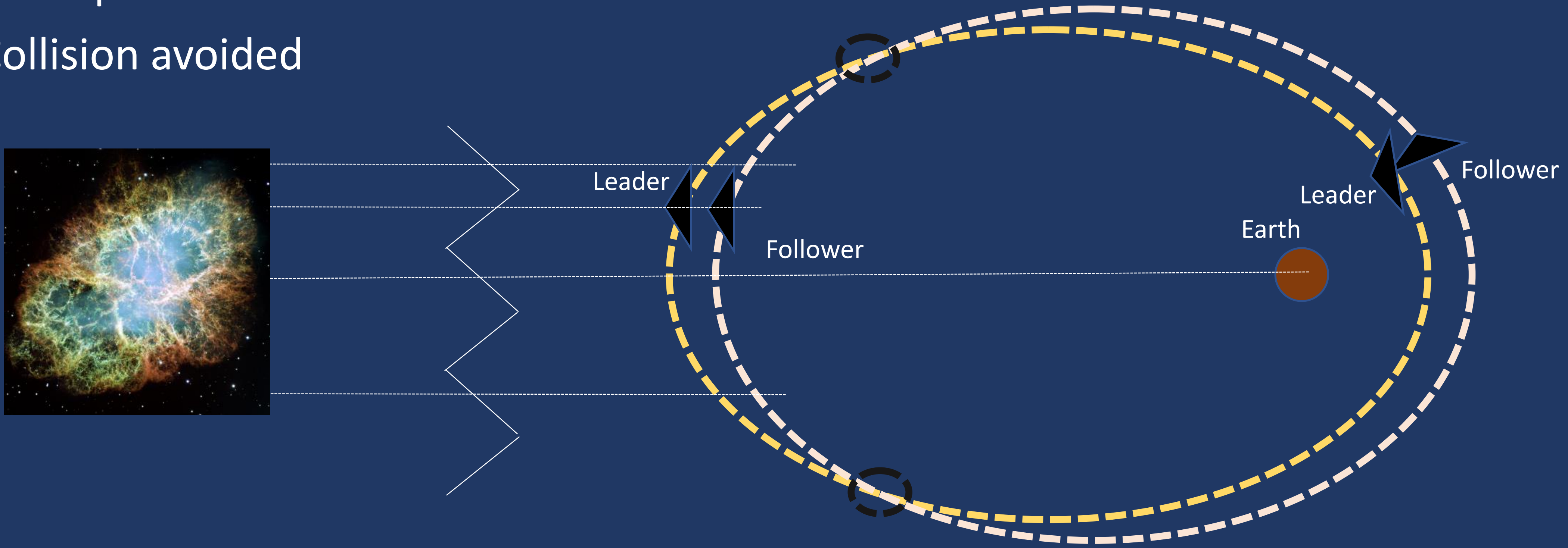
Mission

- Virtual Telescope for X-ray Observations
- Attitude formation control
- High attitude formation accuracy
- Highly eccentric geostationary orbit
- Approximately 1 hour observing the Crab Nebula



Orbit Design

- The orbits have the same parameters except the eccentricity
- Same period
- Collision avoided



Mission Design

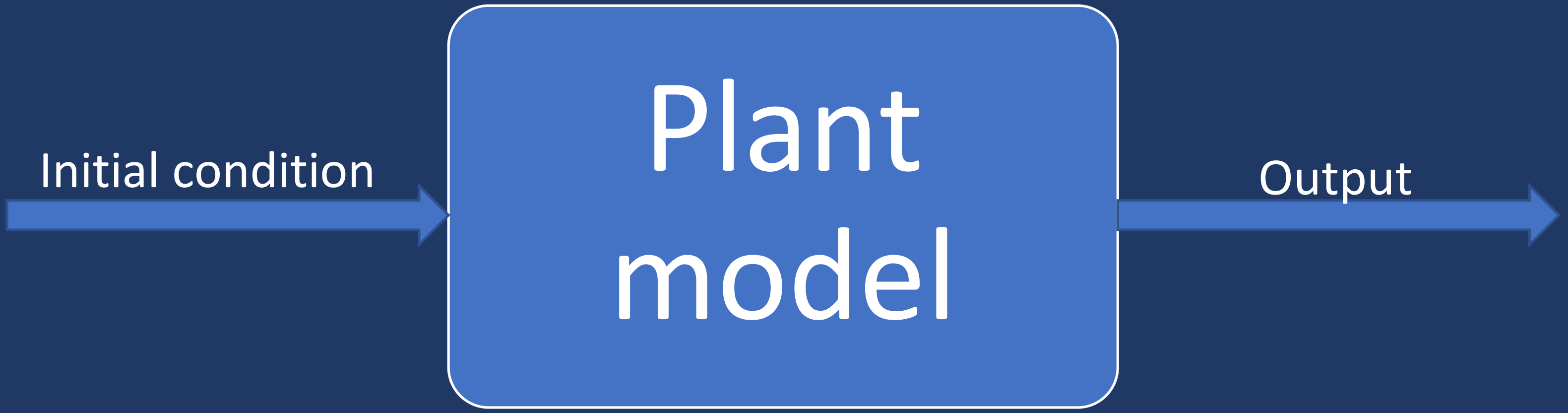
- Phase 1:
- open-loop formation phase
- Phase 2:
- the development phase
- Phase 3:
- scientific phase
- Phase4:
- semi-open-loop formation phase

mission phases specifications

	controller	**Sensors and filter**	**Camera**
Phase 1	off	off	off
Phase2	Sliding mode	On	Off
Phase 3	Sliding mode	On	On
Phase 4	Anti gravity gradient	Off	off

Phase 1: Open-Loop Formation Phase

- Sensors are off, No filtering, zero input torque



Plant Model Equations

$$\dot{q}^{bI} = \frac{1}{2} E(q^{bI}) \omega_b{}^{bI}$$

$$\dot{\omega}_b{}^{bI} = J^{-1}(-[\omega_b{}^{bI} \times] J \omega_b{}^{bI} + \bar{L} + L_g) + w_g$$

$$\dot{h} = -[\omega_b{}^{bI} \times] h - \bar{L}$$

$$L_g = \frac{3\mu}{r^3} [\vec{o}_{3b} \times] I \vec{o}_{3b}$$

$$\vec{o}_{3b} = The\ third\ column\ of\ R^{bo}$$

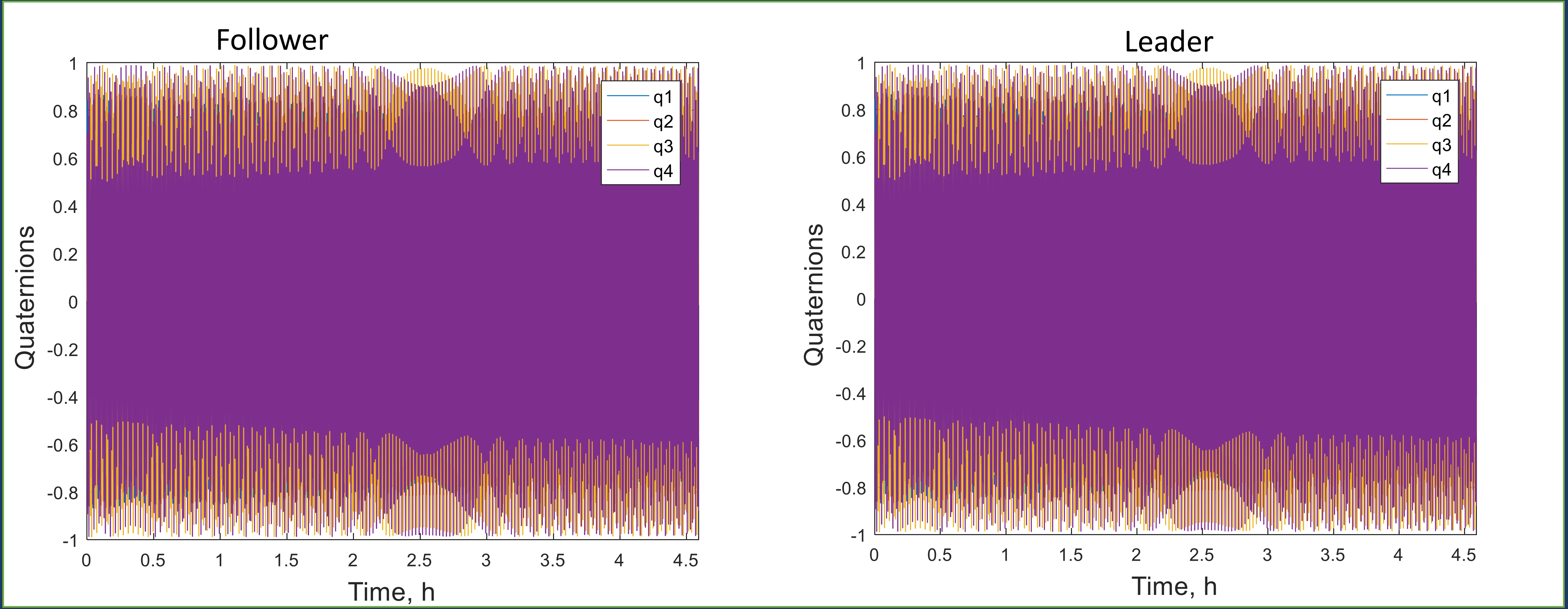
$$o : Orbital\ \ frame$$

$$\bar{L} = Input$$

$$L_g = Gravity\ gradient\ torque$$

$$w_g = Disturbances\ \ from\ drag,\ \ solar - radiation\ \ pressure,$$
$$other\ celestical\ bodies,\ \ etc.$$

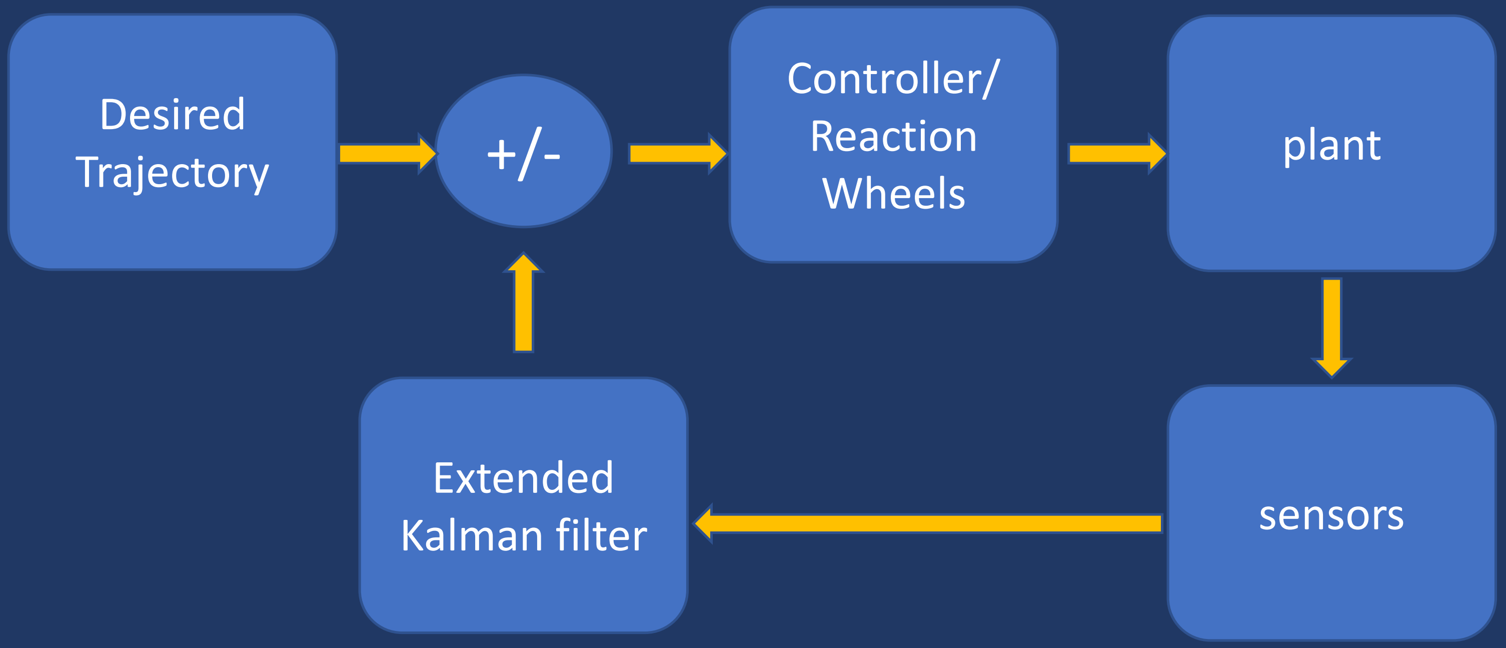
Phase 1



Follower
Leader
Quaternions
Time, h
q1
q2
q3
q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

Phase 2: Development Phase

Sensors : gyroscope and star tracker; Camera is off



Desired Trajectory

- Desired quaternion based on observing the Crab Nebula

$$q = \begin{bmatrix} -0.5591 \\ 0.0158 \\ -0.0106 \\ 0.8289 \end{bmatrix}$$

- Desired Euler angles based on observing the Crab Nebula and 3-2-1 sequence

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} -2.0235 \\ 0.8173 \\ -68.0144 \end{bmatrix} \textit{degrees}$$

Controller/ Reaction Wheels

- Sliding mode controller

$$\delta q = \begin{bmatrix} \delta q_{1:3} \\ \delta q_4 \end{bmatrix} = q \otimes q_c^{-1}$$

$$s = (\omega - \omega_c) + ksign(\delta q_4)\delta q_{1:3}$$

$$L = J\left\{\frac{k}{2}\left[|\delta q_4|(\omega - \omega_c) - sign(\delta q_4)\delta q_{1:3} \times (\omega + \omega_c)\right] + \right\}\dot{\omega}_c - G\bar{s}$$

$$\bar{s}_i = sat(s_i, \varepsilon_i) \quad i = 1, 2, 3$$

$$J = J + Disturbance, \quad Disturbance = 0.2\begin{bmatrix} \cos(t)J_1^{\,2} \\ \sin(t)J_2^{\,2} \\ 0.5J_3^{\,2} \end{bmatrix}$$

$$\bar{L} = \delta T(\varepsilon_L)\left[\left\{J_{3*3} + diag(f_L)\right\}L + b_L + w_L\right]$$

$\varepsilon_L = Misalignment$

$f_L = Scale\ \ factor\ biases$

$b_L = Bias$

$w_L = Actuator\ noise$

Sensors and Extended Kalman Filter

- Sensors: Star camera and gyroscope

$$Gyro = \delta T(\varepsilon_\omega)\left[\left\{J_{3*3} + diag(f_\omega)\right\}\omega + b_\omega + w_\omega\right]$$

$$\varepsilon_L = Misalignment$$

$$f_L = Scale\ \ factor\ biases$$

$$b_L = Bias$$

$$w_L = noise$$

$$Star\ camera = T^{sb}\theta + b_s + w_s$$

$$b_L = Bias$$

$$w_L = noise$$

$$States = \begin{bmatrix} \theta \\ b_s \\ b_w \end{bmatrix}_{9\times 1} = x$$

$$q^{bI+} = \delta q(\theta) \otimes q^{bI-}$$

Kalman filter

Model

$$\dot{x} = f(x,u,w,t),\ \ w \sim N(0,S)$$

$$y_k = h(x) + \upsilon_k,\ \ \upsilon_k \sim N(0,R_k)$$

$$Initialize: x_0, P_0$$

Propagation

$$\dot{\hat{x}} = f(\hat{x},u,t)$$

$$\hat{P} = \hat{\phi}\hat{P}_0\hat{\phi}^T + \hat{Q}$$

$$F = \frac{\delta f}{\delta x}|_{\hat{x}}$$

$$\hat{\phi} = e^{Fdt}$$

$$\hat{Q} = \int_{t_0}^{t} \hat{\phi} S \hat{\phi}^T dt$$

Gain

$$K_k = P_k^- H_k^T [H_k P_k^- H_k^T + R_k]^{-1}$$

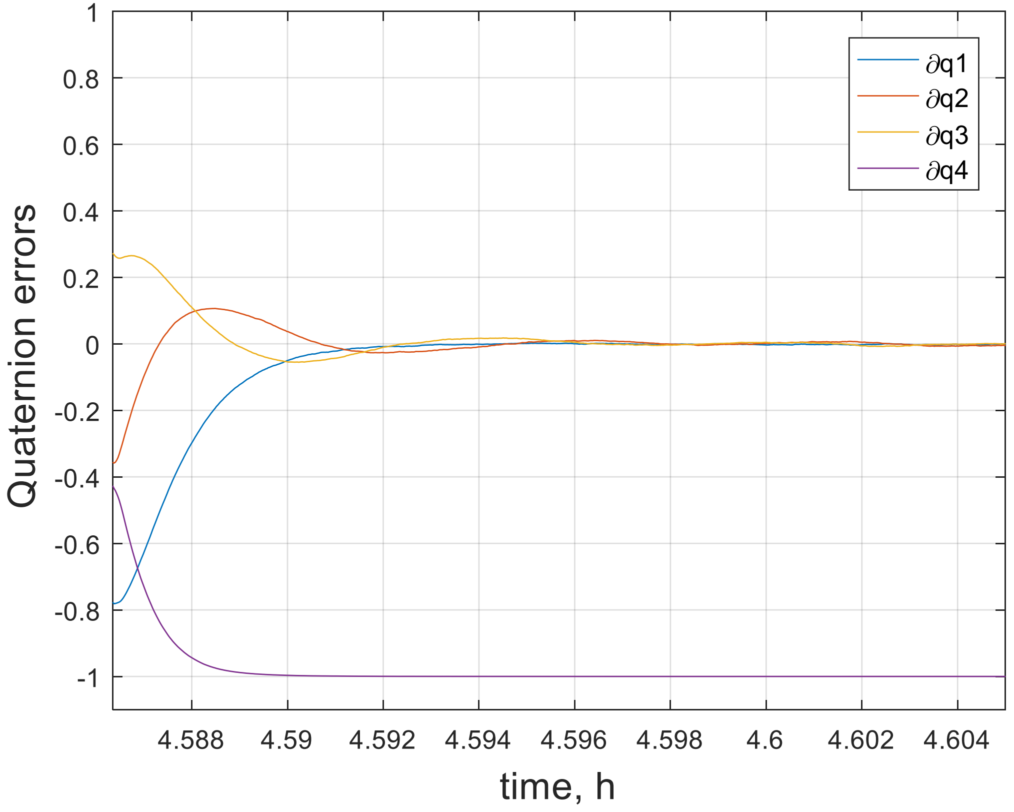
$$H_k = \frac{\delta h}{\delta x}|_{\hat{x}_k^-}$$

Update

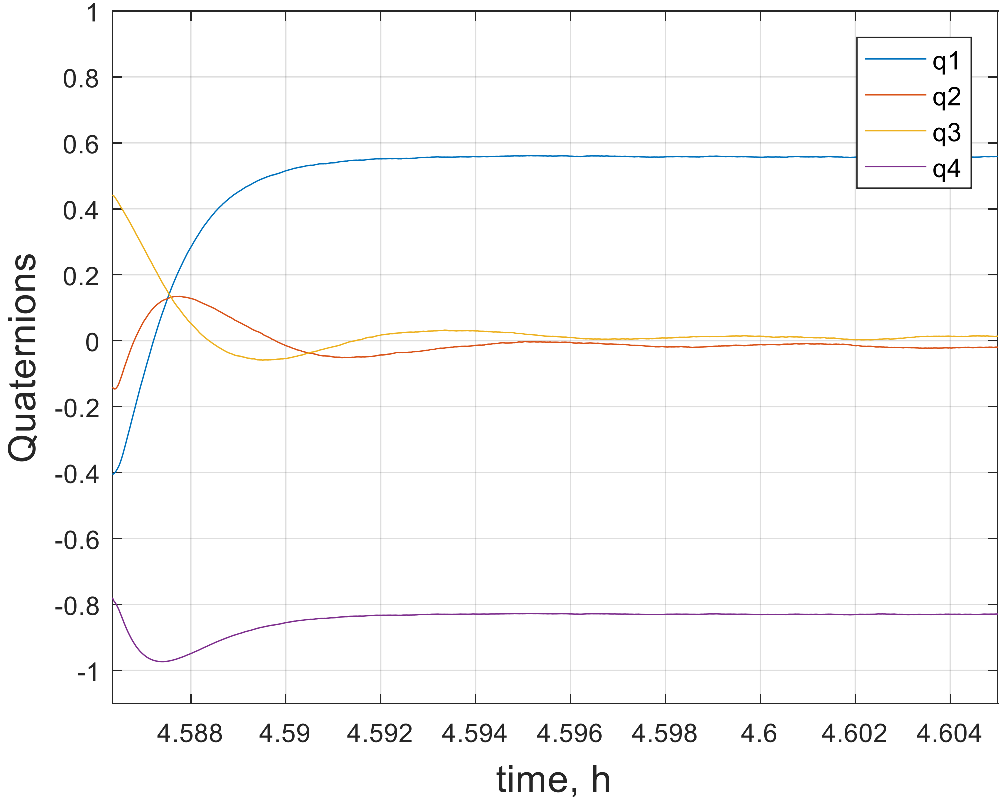
$$\hat{x}_k^+ = \hat{x}_k^- + K_k[y_k - h(\hat{x}_k^-)]$$

$$P_k^+ = [I - K_k H_k]P_k^-$$

Follower

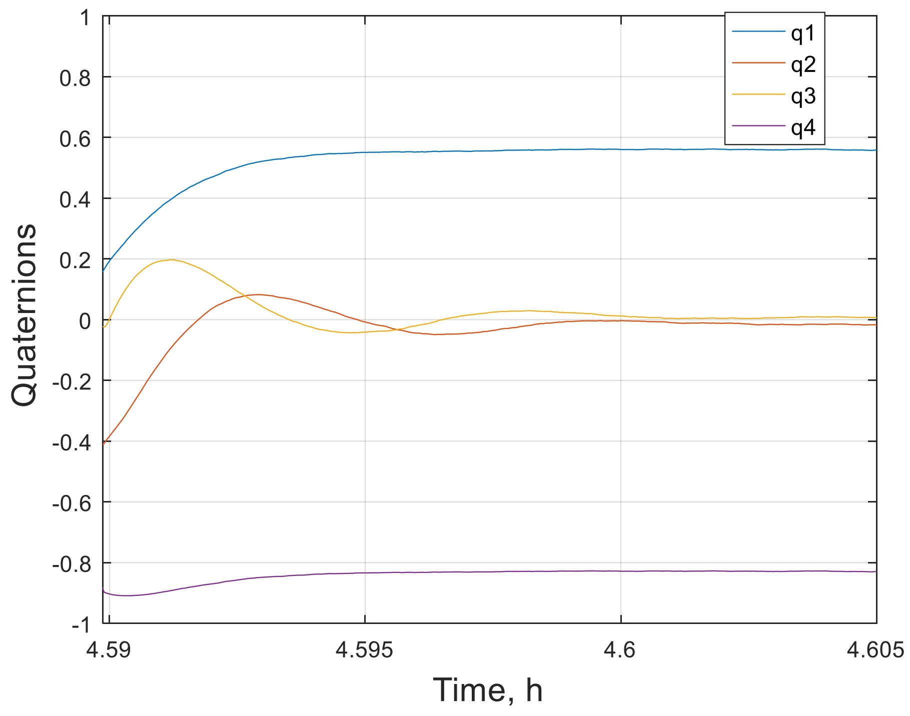


Quaternion errors
time, h
∂q1
∂q2
∂q3
∂q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
4.588
4.59
4.592
4.594
4.596
4.598
4.6
4.602
4.604

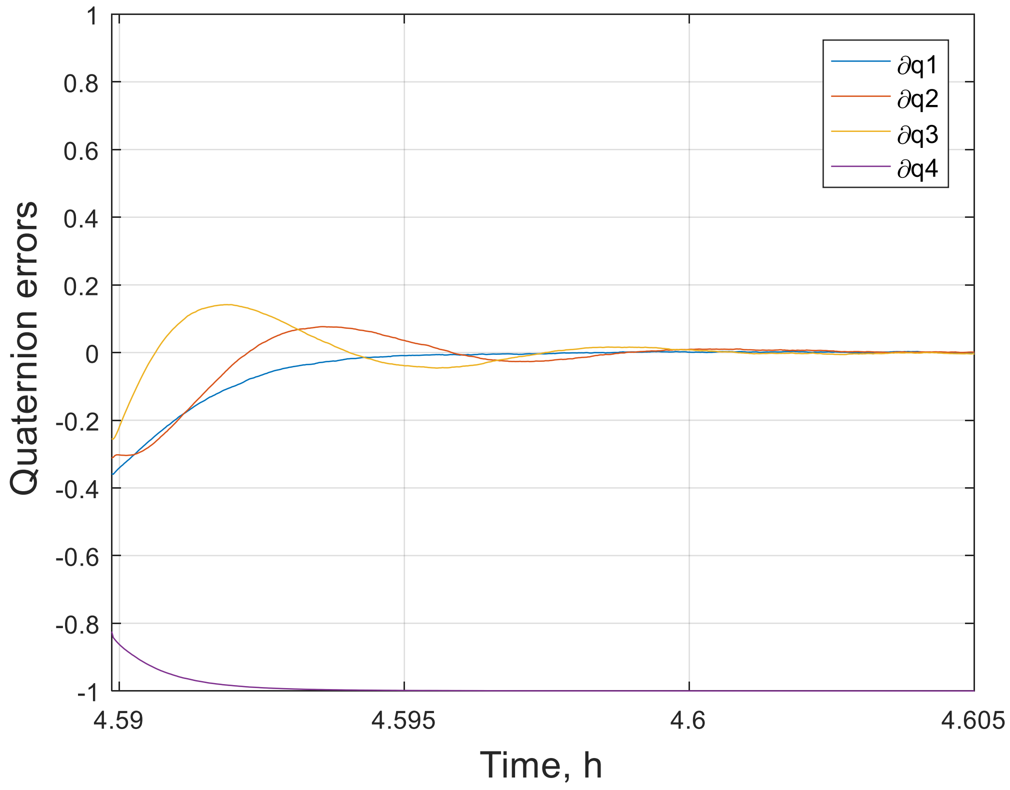


Quaternions
time, h
q1
q2
q3
q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
4.588
4.59
4.592
4.594
4.596
4.598
4.6
4.602
4.604

Leader



Quaternions
Time, h
q1
q2
q3
q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
4.59
4.595
4.6
4.605



Quaternion errors
Time, h
∂q1
∂q2
∂q3
∂q4
1
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0.6
0.4
0.2
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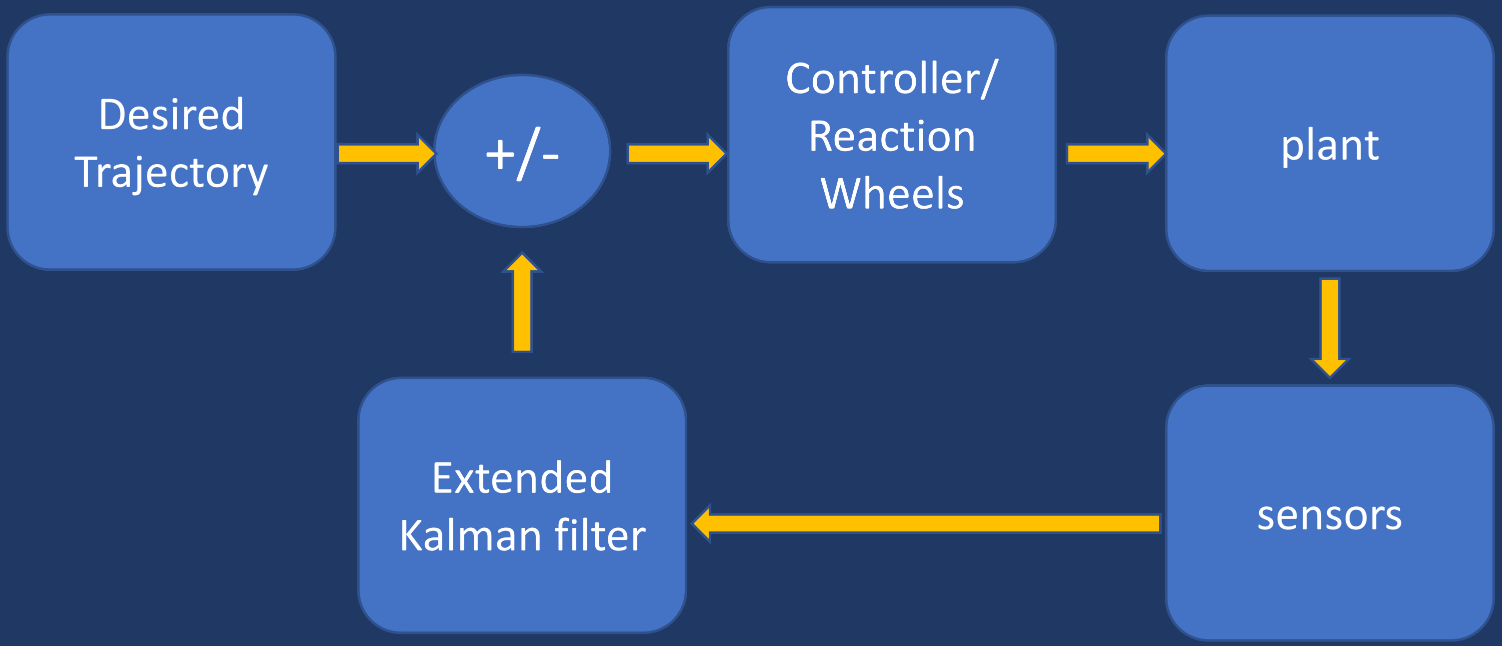
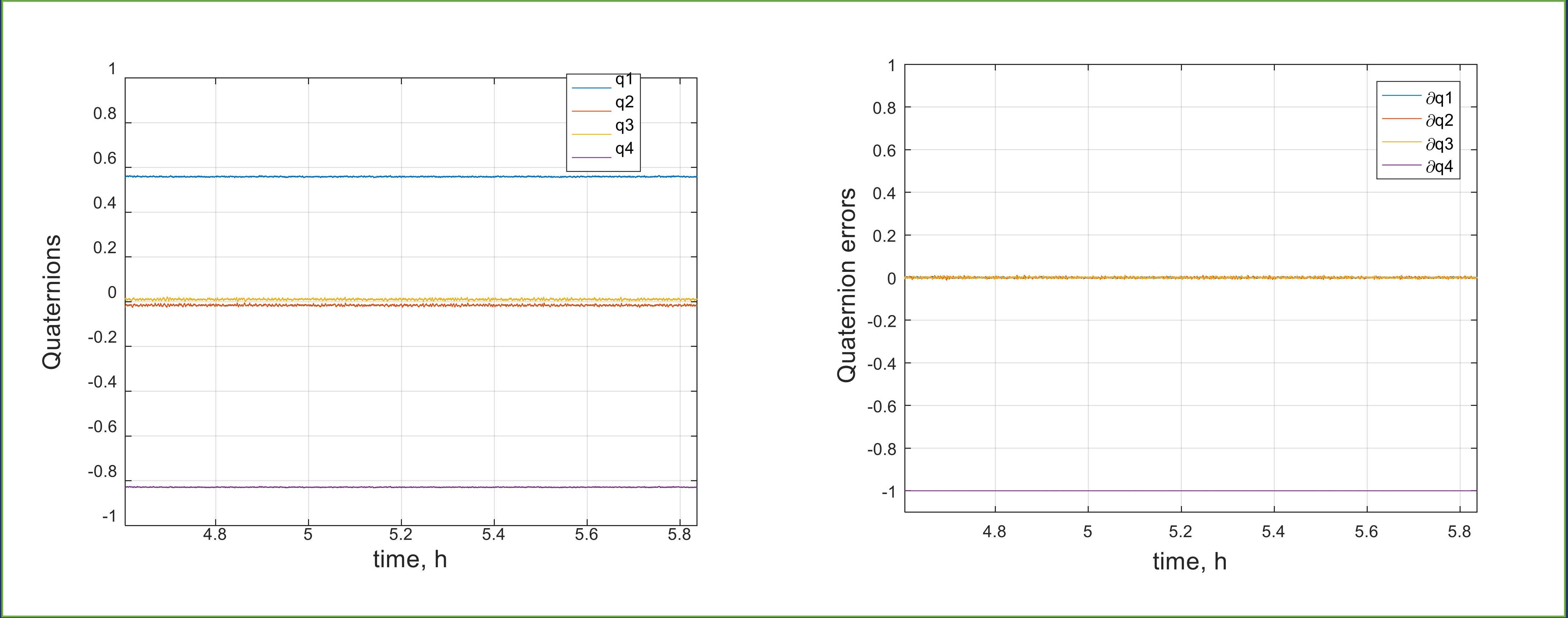
-0.2
-0.4
-0.6
-0.8
-1
4.59
4.595
4.6
4.605

Phase 3: Scientific Phase

Sensors : gyroscope and star tracker; Camera is on

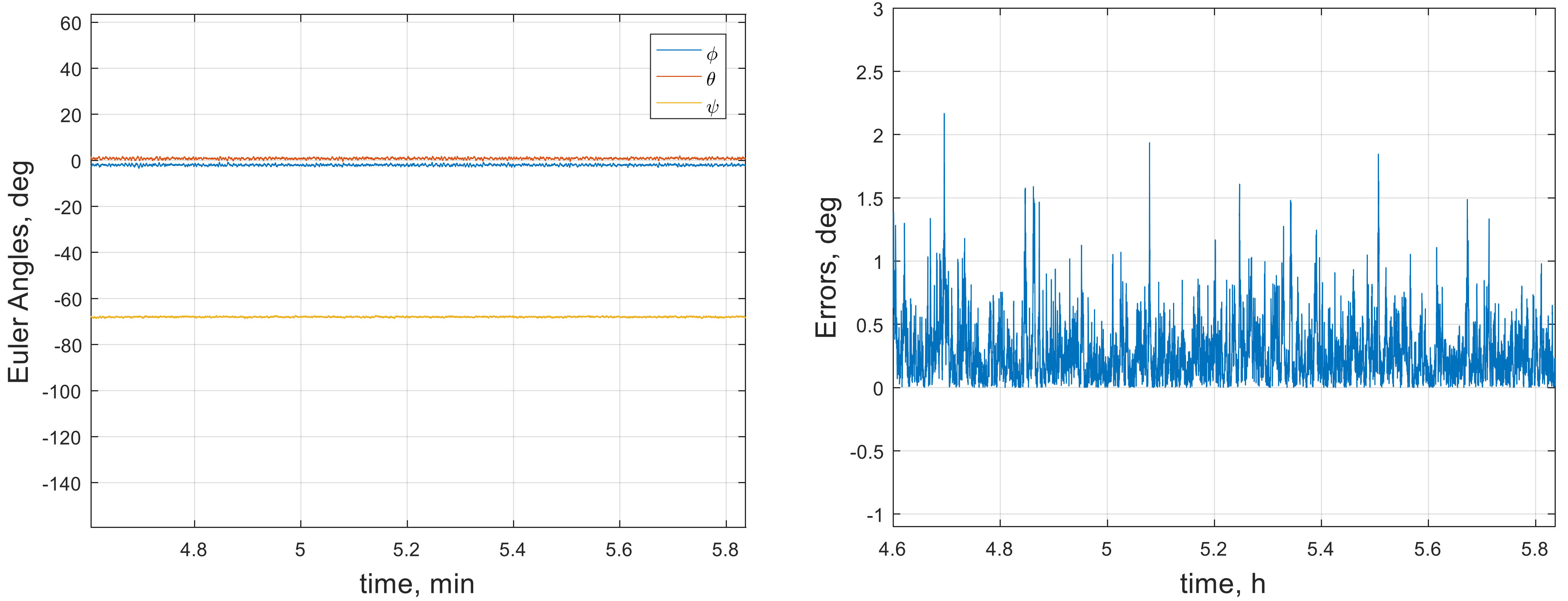


Follower



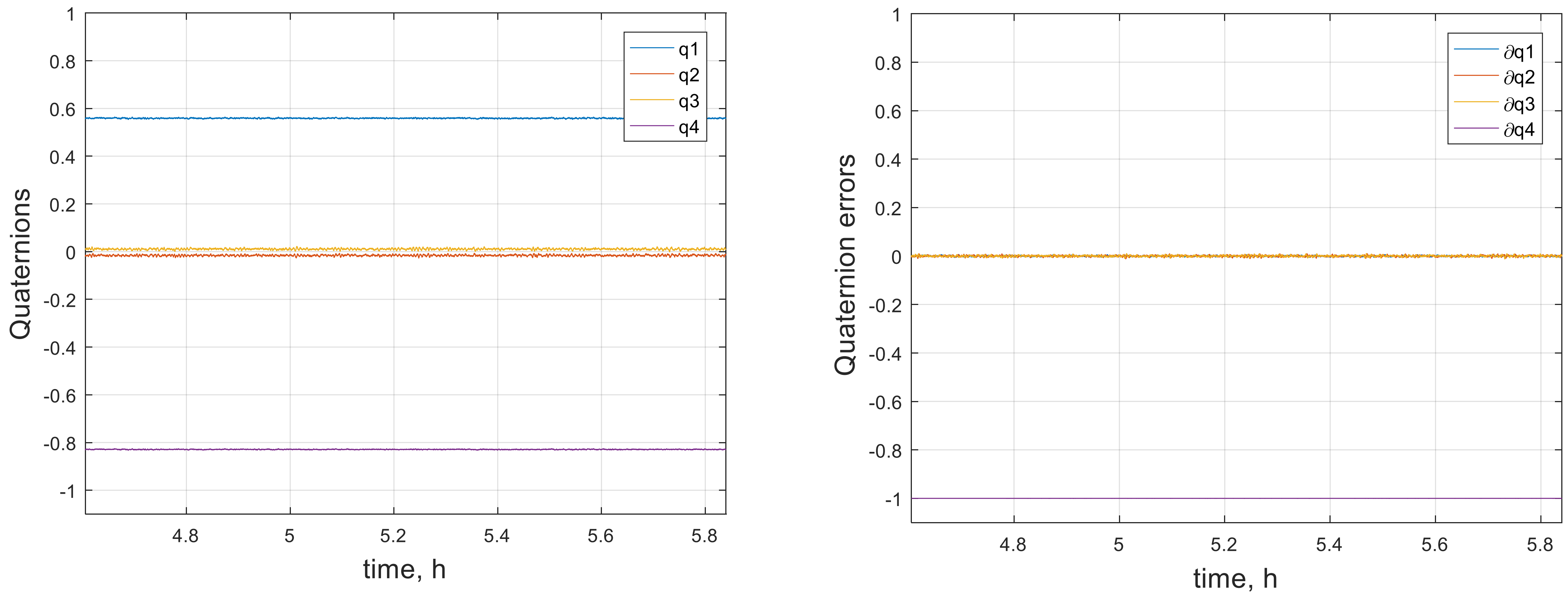
Quaternions
q1
q2
q3
q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
4.8
5
5.2
5.4
5.6
5.8
time, h
Quaternion errors
∂q1
∂q2
∂q3
∂q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
4.8
5
5.2
5.4
5.6
5.8
time, h

Follower



60
40
20
0
-20
-40
-60
-80
-100
-120
-140
Euler Angles, deg
ϕ
θ
ψ
4.8
5
5.2
5.4
5.6
5.8
time, min
3
2.5
2
1.5
1
0.5
0
-0.5
-1
Errors, deg
4.6
4.8
5
5.2
5.4
5.6
5.8
time, h

Leader


Quaternions
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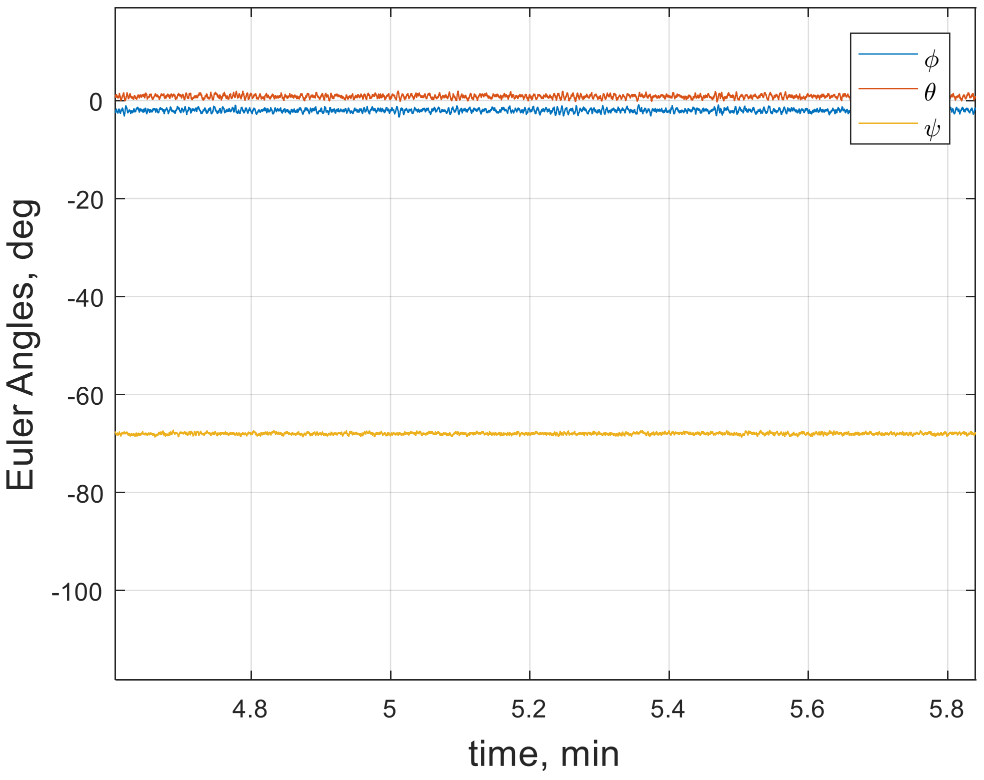
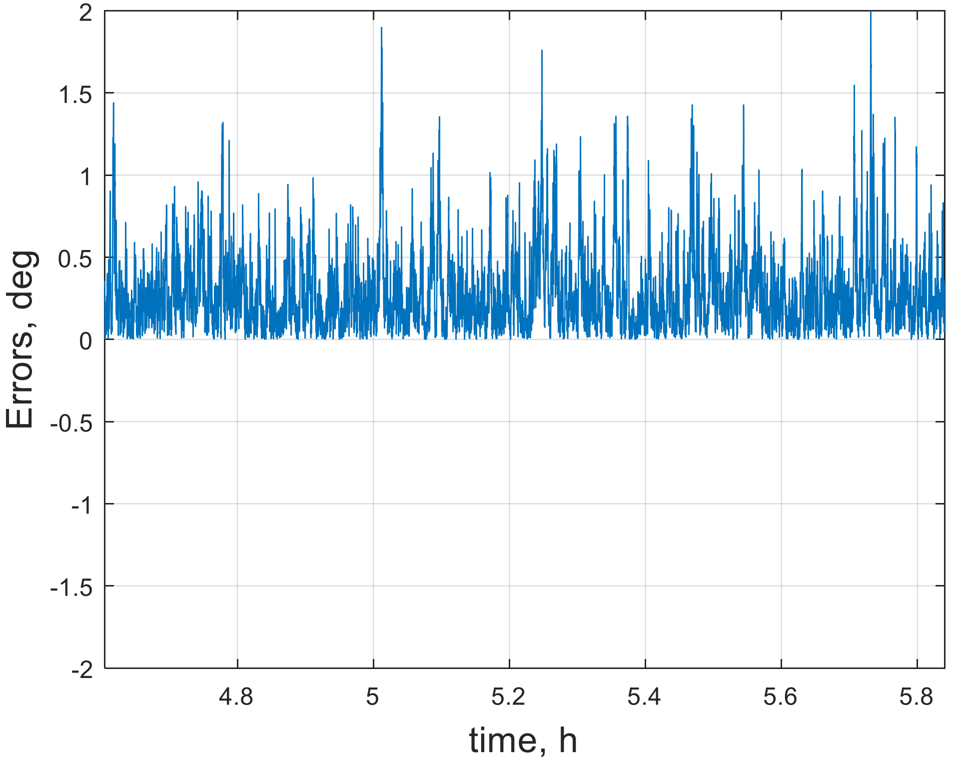
q2
q3
q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
4.8
5
5.2
5.4
5.6
5.8
Quaternion errors
time, h
∂q1
∂q2
∂q3
∂q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
4.8
5
5.2
5.4
5.6
5.8

Leader



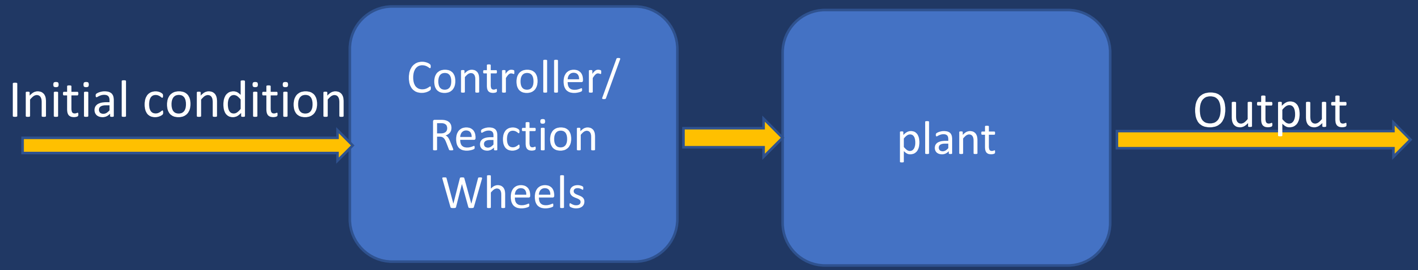
Euler Angles, deg
0
-20
-40
-60
-80
-100
4.8
5
5.2
5.4
5.6
5.8
time, min
ϕ
θ
ψ



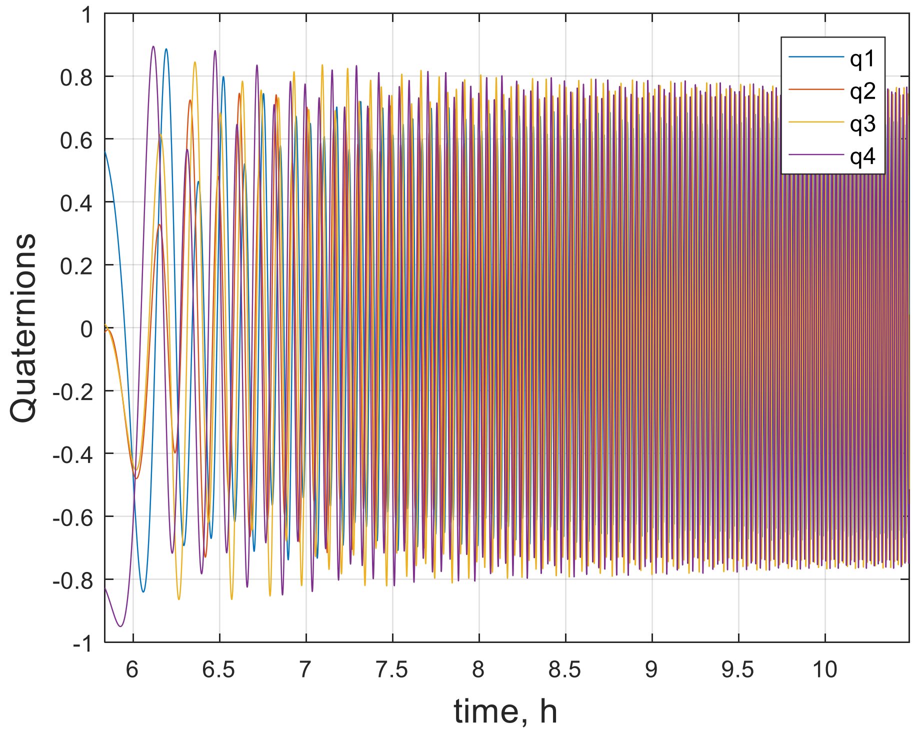
Errors, deg
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
4.8
5
5.2
5.4
5.6
5.8
time, h

Phase 4: Semi-Open Loop Formation Phase

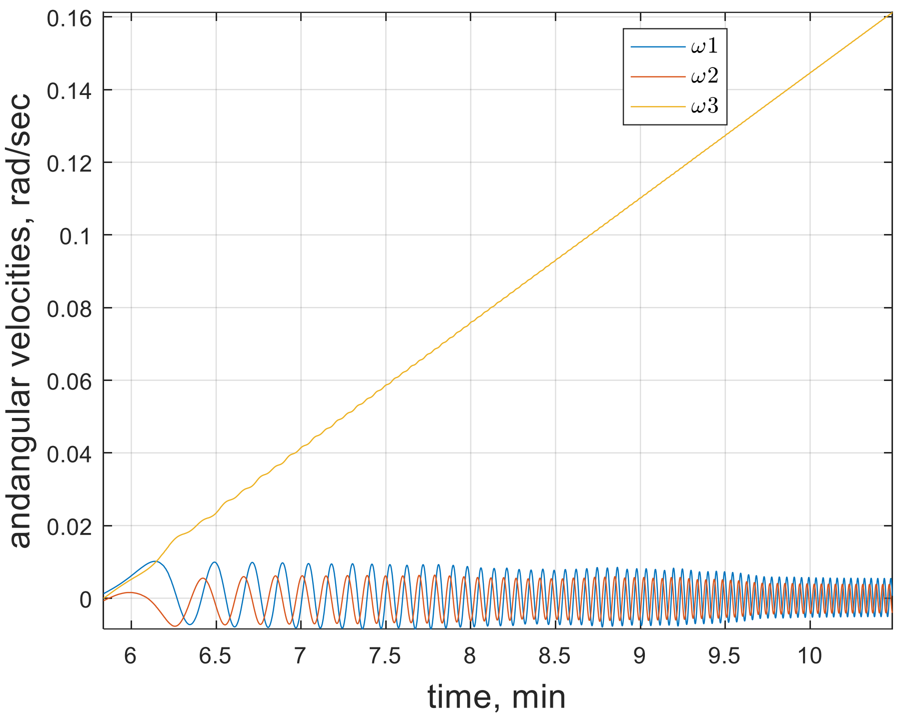
No sensor, Camera is off, Anti gravity gradient torque



Follower

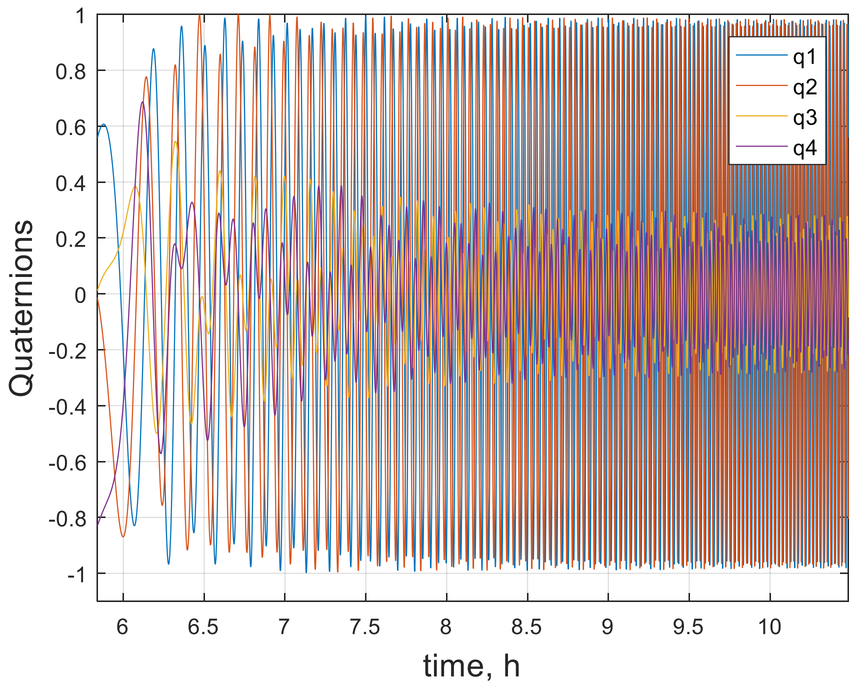


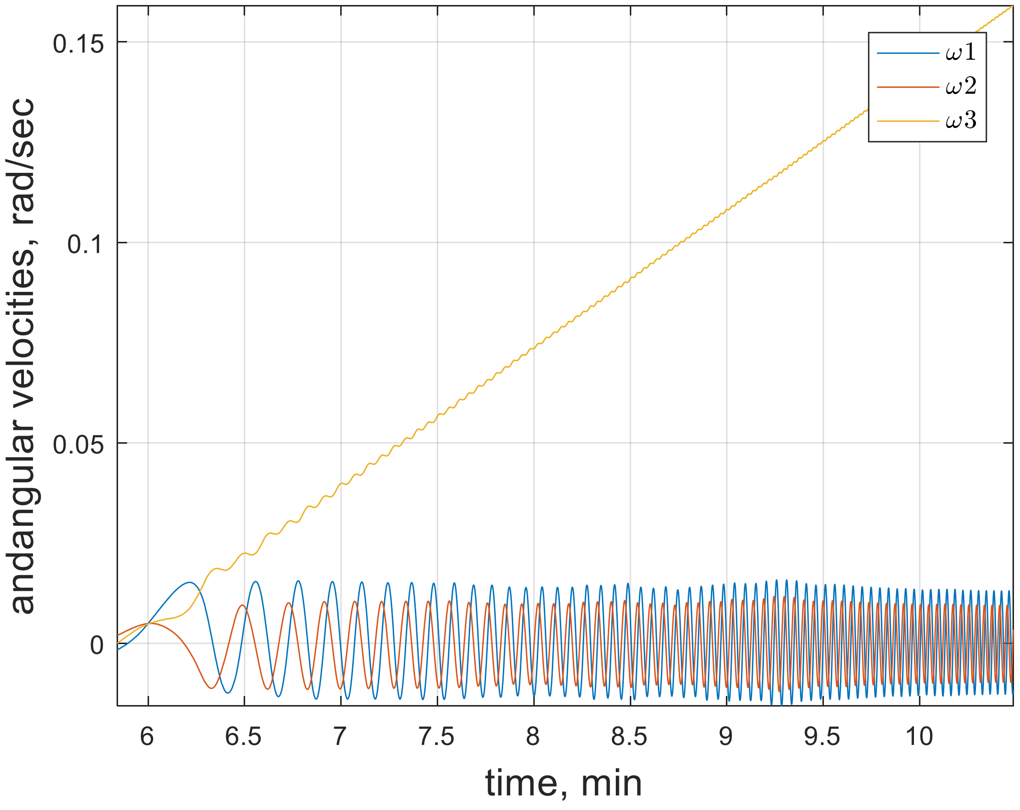
Quaternions
time, h
q1
q2
q3
q4



andangular velocities, rad/sec
time, min
ω1
ω2
ω3

Leader


Quaternions
time, h
q1
q2
q3
q4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
6
6.5
7
7.5
8
8.5
9
9.5
10


andangular velocities, rad/sec
time, min
ω1
ω2
ω3
0.15
0.1
0.05
0
6
6.5
7
7.5
8
8.5
9
9.5
10

Conclusion - Future Work

- The designed orbits worked well.
- The sliding mode controller is robust against system uncertainty.
- The EKF and the sliding mode controller, in the presence of noise, give us 0.5 deg accuracy.
- To reach the desired sub-arcsecond accuracy, we need to introduce additional constraints, such as relative position, and filtering techniques.
- In the future work, the third angular velocity, which is the axis pointing at the Crab Nebula, will be set for better accuracy, and the energy consumption will be optimized for the whole system.

Questions/Comments?