Development of Fixed-Wing and Multi-Rotor sUAS

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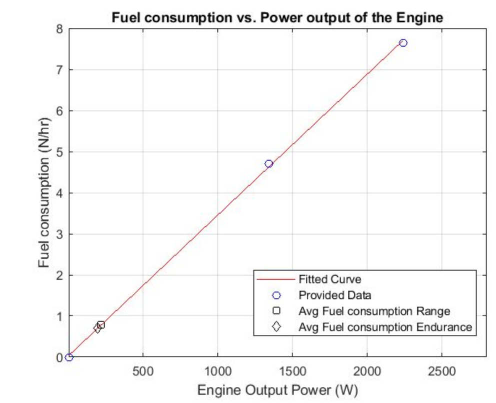
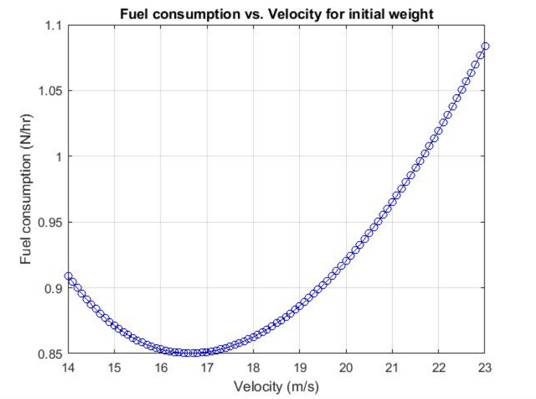
Fixed-Wing sUAS Development - Range & Endurance(I)

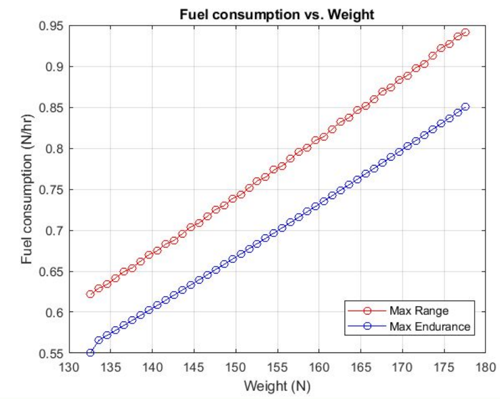
- Max range is ~4034 km and max endurance is ~65.1 hr
- Numerical integration through the changing weight
- Optimizing the velocity throughout the trip for best fuel consumption (endurance) & best fuel consumption / velocity (range)
- Due to oversized engine, fuel consumption curve breaks down estimating low values (e.g. idle = 450 W vs. power needed ~ 200W)



$$Endurance = \int_{w_{initial}}^{w_{final}} \frac{1}{fuel\ rate} dw$$

$$Range = \int_{w_{initial}}^{w_{final}} \frac{velocity}{fuel\ rate} dw$$





Fixed-Wing sUAS Development - Dynamics Model (II)

Longitudinal Dynamics Model
for Altitude Hold

$$\dot{\underline{\boldsymbol{x}}} = \underline{\boldsymbol{A}}_{long}\underline{\boldsymbol{x}} + \underline{\boldsymbol{B}}_{long}\underline{\boldsymbol{u}}$$

$$\begin{pmatrix} \dot{\bar{u}} \\ \dot{\bar{w}} \\ \dot{\bar{q}} \\ \dot{\bar{\theta}} \\ \dot{\bar{h}} \end{pmatrix} = \begin{pmatrix} X_u & X_w & X_q & -g\cos\theta^* & 0 \\ Z_u & Z_w & Z_q & -g\sin\theta^* & 0 \\ M_u & M_w & M_q & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \sin\theta^* & -\cos\theta^* & 0 & u^*\cos\theta^* + w^*\sin\theta^* & 0 \end{pmatrix} \begin{pmatrix} \bar{u} \\ \bar{w} \\ \bar{q} \\ \bar{\theta} \\ \bar{h} \end{pmatrix}$$

$$+ \begin{pmatrix} X_{\delta_e} & X_{\delta_t} \\ Z_{\delta_e} & 0 \\ M_{\delta_e} & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \bar{\delta}_e \\ \bar{\delta}_t \end{pmatrix},$$

Lateral Dynamics Model
for Coordinated Turn

$$\dot{\underline{\boldsymbol{x}}} = \underline{\boldsymbol{A}}_{latr}\underline{\boldsymbol{x}} + \underline{\boldsymbol{B}}_{latr}\underline{\boldsymbol{u}}$$

$$\begin{pmatrix} \dot{\bar{v}} \\ \dot{\bar{p}} \\ \dot{\bar{r}} \\ \dot{\bar{\phi}} \\ \dot{\bar{\psi}} \end{pmatrix} = \begin{pmatrix} Y_v & Y_p & Y_r & g\cos\theta^*\cos\phi^* & 0 \\ L_v & L_p & L_r & 0 & 0 \\ N_v & N_p & N_r & 0 & 0 \\ 0 & 1 & \cos\phi^*\tan\theta^* & q^*\cos\phi^*\tan\theta^* - r^*\sin\phi^*\tan\theta^* & 0 \\ 0 & 0 & \cos\phi^*\sec\theta^* & p^*\cos\phi^*\sec\theta^* - r^*\sin\phi^*\sec\theta^* & 0 \end{pmatrix}$$

$$\times \begin{pmatrix} \bar{v} \\ \bar{p} \\ \bar{r} \\ \bar{\phi} \\ \bar{\psi} \end{pmatrix} + \begin{pmatrix} Y_{\delta_a} & Y_{\delta_r} \\ L_{\delta_a} & L_{\delta_r} \\ N_{\delta_a} & N_{\delta_r} \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \bar{\delta}_a \\ \bar{\delta}_r \end{pmatrix},$$

Fixed-Wing sUAS Development - LQR Control (III)

- State-space dynamics: $$\begin{cases} \dot{\underline{\boldsymbol{x}}} = \boldsymbol{A}\underline{\boldsymbol{x}} + \boldsymbol{B}\underline{\boldsymbol{u}} \\ \underline{\boldsymbol{u}} = -\boldsymbol{K}\underline{\boldsymbol{x}} \end{cases}$$

Select

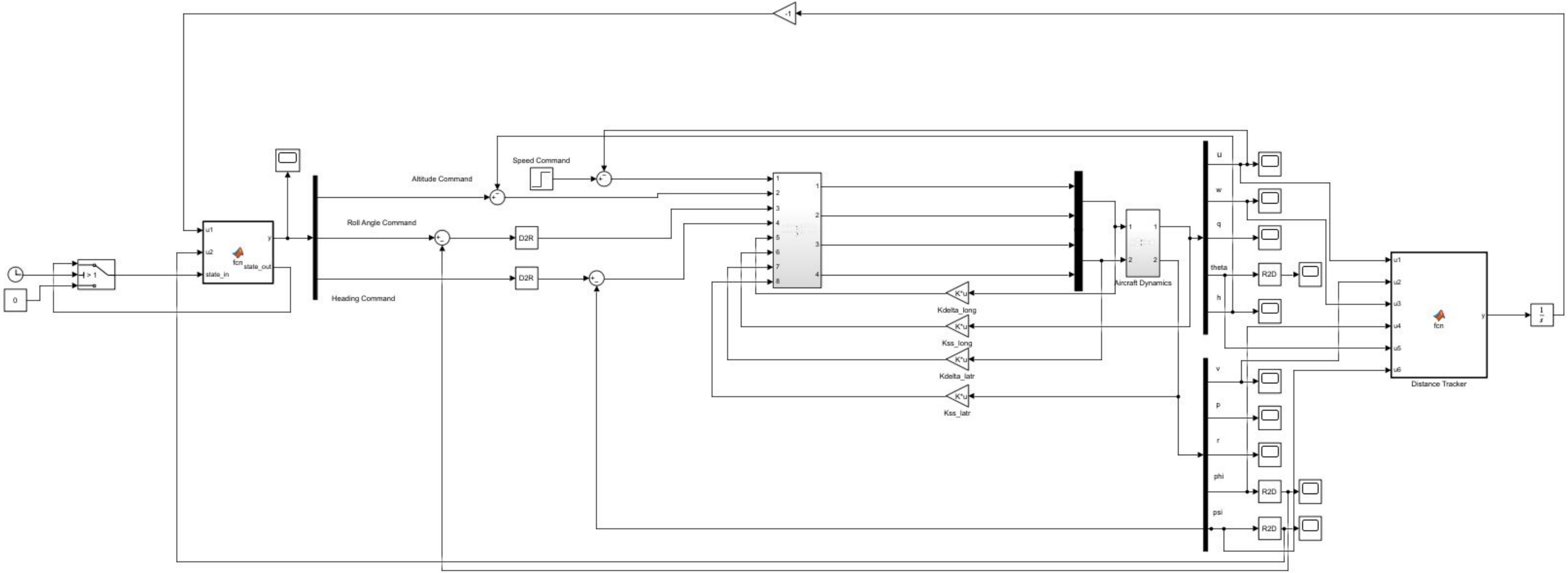
- Linear Quadratic Performance Index: $$\boxed{J = \frac{1}{2}\int_0^{\infty} \left(\underline{\boldsymbol{x}}^T \boldsymbol{Q} \underline{\boldsymbol{x}} + \underline{\boldsymbol{u}}^T \boldsymbol{R} \underline{\boldsymbol{u}} \right) dt}$$

- Closed-loop system: $$\boxed{\boldsymbol{A_c} = \boldsymbol{A} - \boldsymbol{B}\boldsymbol{K}}$$

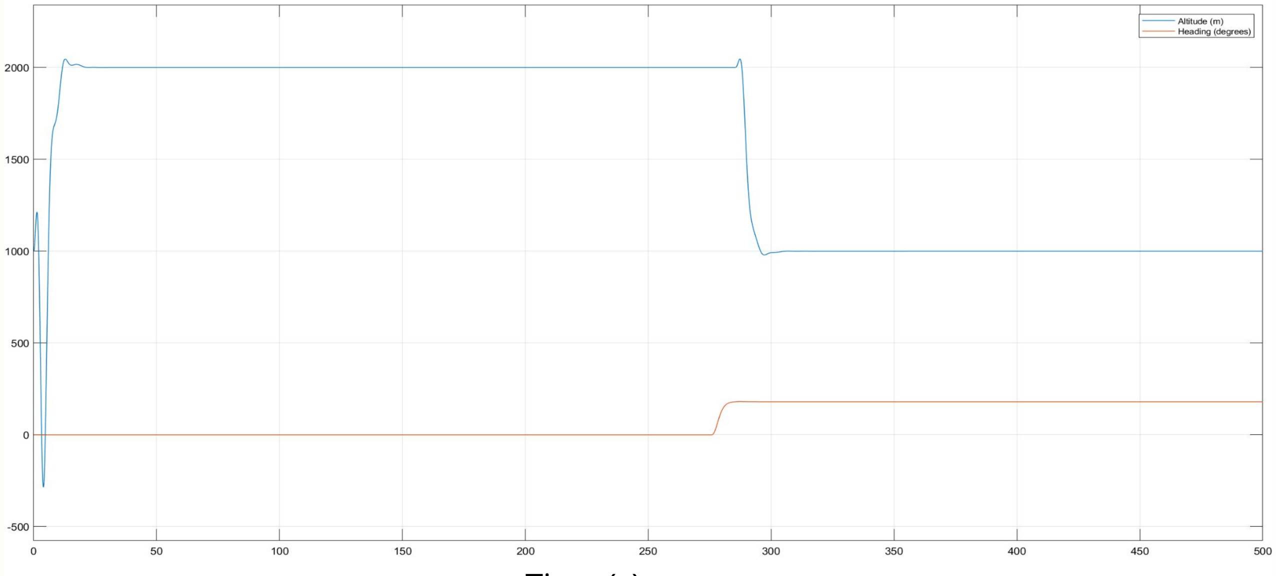
- Advantages of LQR:
  - Known to provide robust stability and optimal control
  - Computationally efficient
  - Easy to implement → `[K,S,CLP]=lqr(SYS,Q,R,N)`

Fixed-Wing sUAS Development - Control Structure (IV)

Goal: Perform an ascent to 2000m, a 180° turn, and a descent to 1000m



Fixed-Wing sUAS Development - Results (V)

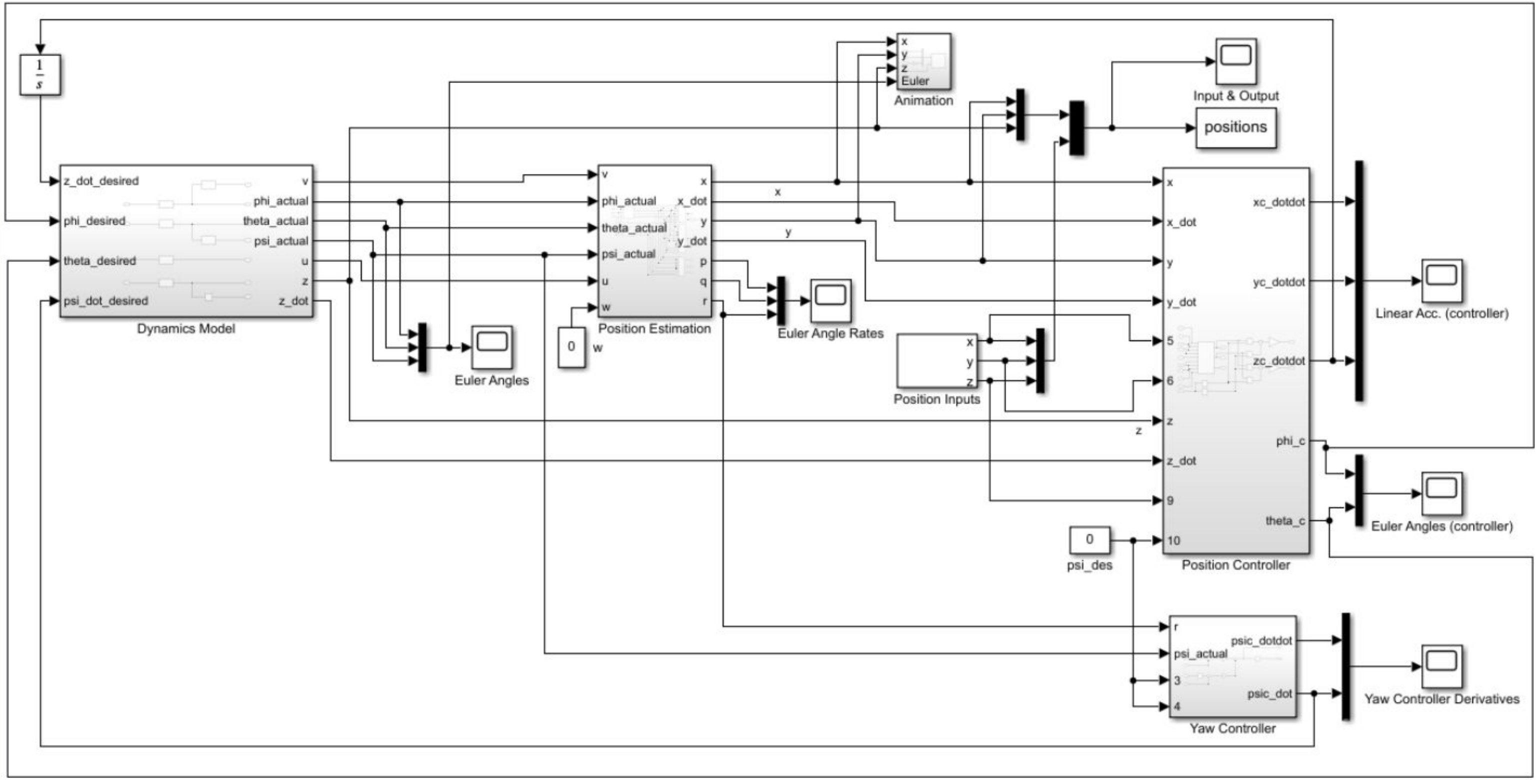


Time (s)

- Commands are performed, but the turn is not performed with the desired radius
- Instability at beginning of simulation for altitude, possibly due to tuning issues with Q and R parameters

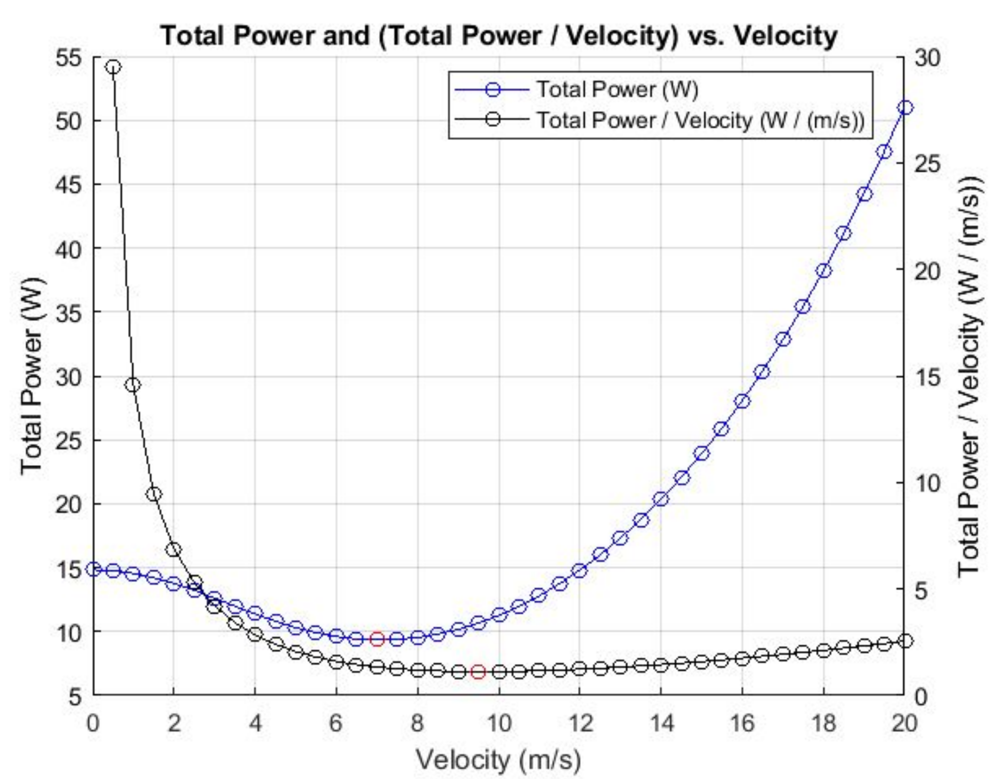
Multi-Rotor sUAS Development - Overview (I)

Goal:
Simulate a quadcopter travelling between
(0, 0, 0),
(0, 0, 2),
(5, 6, 4),
(-5, -6, 4),
(0, 0, 2),
(0, 0, 0)



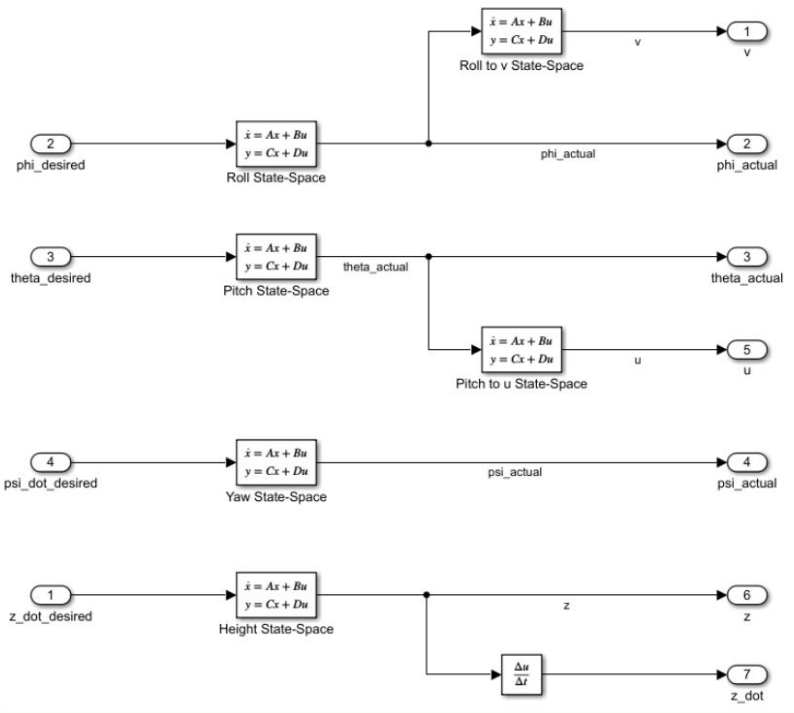
Multi-Rotor sUAS Development - Range & Endurance (II)

- Max endurance is ~68.1 min at a speed of 7 m/s
- Max range is ~34.061 km at a speed of 9.5 m/s
- Forward flight momentum theory used for total power calculation in velocity increments of 0.5 between 0-20 m/s
- Max endurance is at minimum power max range is at minimum (power/velocity)
- 0th order battery model used (assume constant efficiencies)



Multi-Rotor sUAS Development - Dynamics and Position Estimation (III)

Dynamics Model



Position Estimation

$$\begin{pmatrix} \dot{p}_n \\ \dot{p}_e \\ \dot{p}_d \end{pmatrix} = \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix}, \qquad (3.1)$$

Inertial Frame

Body Frame

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} c\theta & 0 & -c\phi s\theta \\ 0 & 1 & s\phi \\ s\theta & 0 & c\phi c\theta \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}$$

Body Frame

Inertial Frame

Multi-Rotor sUAS Development - Control (IV)

- Use equations from Lecture 9 - Part III
- Tuning procedure:
  - Increase Kp until no undershoot
  - Increase Kd to speeden response time
  - Iterate
- Added integral control for y to reduce steady-state error
- Tradeoff between faster response time with oscillations or slower response time without oscillations (damping)

Tuned PID Gains

	P	I	D
x	20	-	35
y	25	3.5	20
z	30	-	8
ψ	10	-	0.01

$$\ddot{x}_c = \cancel{\ddot{x}_{des}} + k_{p,x}(x_{des} - x) + k_{d,x}(\cancel{\dot{x}_{des}} - \dot{x})$$

$$\ddot{y}_c = \cancel{\ddot{y}_{des}} + k_{p,y}(y_{des} - y) + k_{d,y}(\cancel{\dot{y}_{des}} - \dot{y}) + k_{i,y}\int_0^t (y_{des} - y)\, dt$$

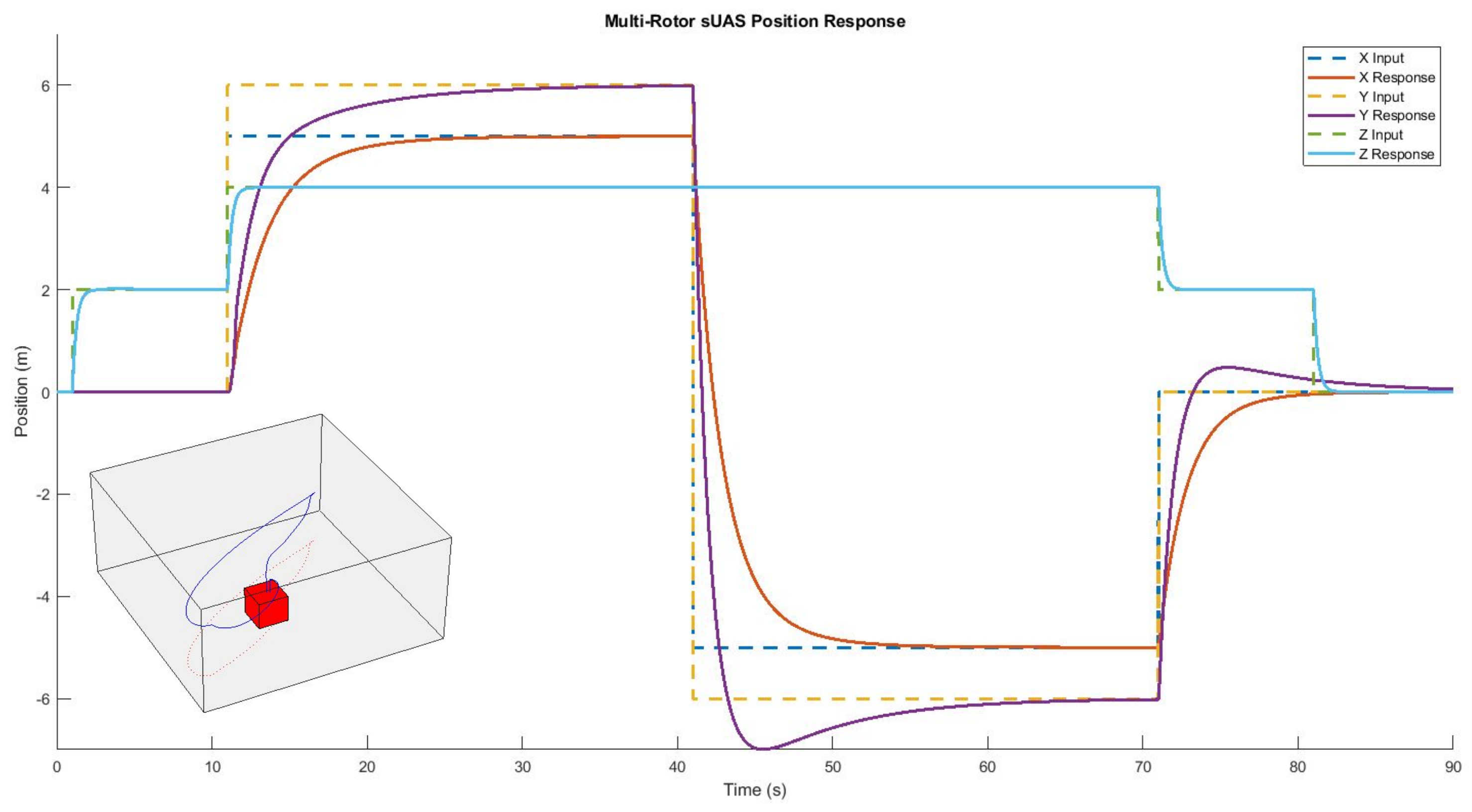
$$\ddot{z}_c = \cancel{\ddot{z}_{des}} + k_{p,z}(z_{des} - z) + k_{d,z}(\cancel{\dot{z}_{des}} - \dot{z})$$

$$\phi_c = (\ddot{x}_c \sin\psi_{des} - \ddot{y}_c \cos\psi_{des})/g$$

$$\theta_c = (\ddot{x}_c \cos\psi_{des} - \ddot{y}_c \sin\psi_{des})/g$$

$$\psi_c = \psi^{des}$$

Multi-Rotor sUAS Development - Results (V)



Conclusion

- Simulations were conducted on a fixed-wing Aerosonde UAV and a quadcopter
- Range and endurance estimates were developed for both. Fixed wing estimates were beyond expected values
- A linear dynamics model was developed for both UASs using Simulink
- A LQR controller was used to control the fixed-wing UAS
- A PID controller was used to control the quadrotor
- Fixed wing model still needs further optimization to reduce oscillations, while the quadcopter model generally performs as expected.
- Learned that trying to decrease settling time usually results in increased overshoot (balance is required)