# Trajectory Control of A Fixed-wing Crop Monitoring Drone: A Case Study

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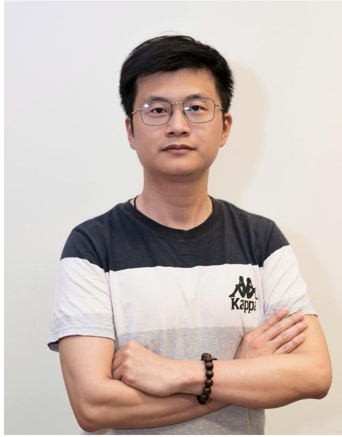

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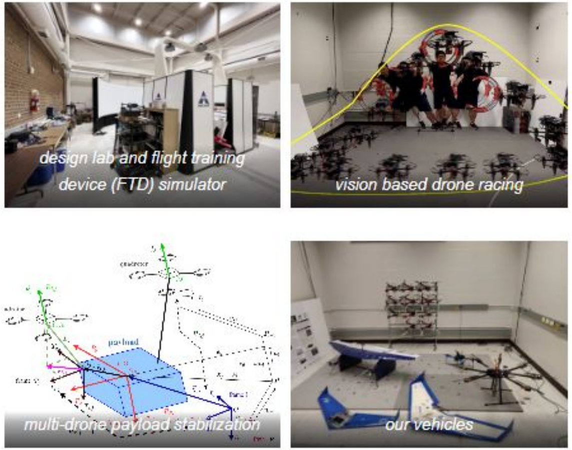

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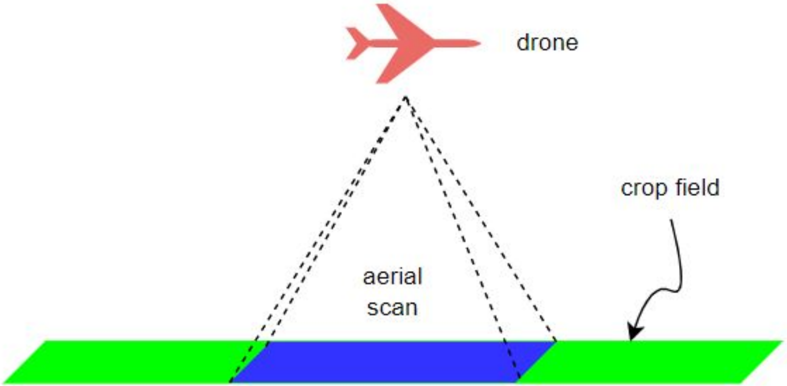
- **Aircraft nonlinear model**
- **Longitudinal and lateral controller design**
- **Simulations and discussions**
- **Conclusion and future work**

# Project Background

- Using UAVs to perform automated crop monitoring is essential in the agricultural industry.
- Key challenge: planning and control.
- This talk presents a control scheme to control a fixed-wing drone to follow the desired path.



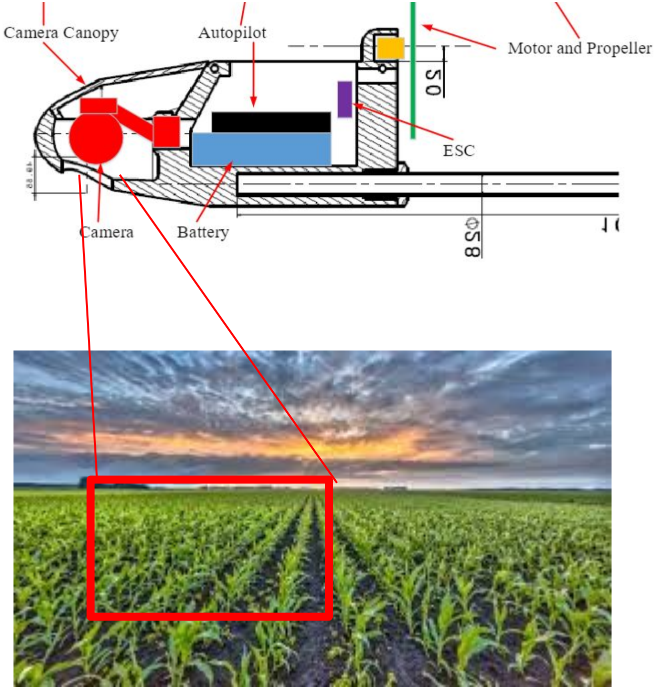


Fig. 1 Automated Crop Monitoring

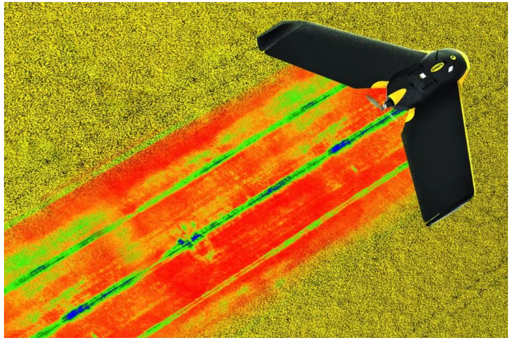
# Project Background

Why fixed-wing drone?

- Range and endurance
- Payload capacity

Fixed-wing vs quadrotor

Parrot



Source: https://newatlas.com/parrot-sequoia-crop-sensor/41727/

DJI

Source: https://enterprise-insights.dji.com/blog/drones-for-farms

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Fig. 2 Fixed-wing vs Quadrotor

# Problem formulation

- Two primary challenge: planning and control.

- The goal of this work: a flight control framework so that the drone can fly according to typical scanning patterns.

- Maintain stable flight for sensor scanning.

- Back-and-forth and spiral scanning patterns consisting straight-line segments and circular arcs.

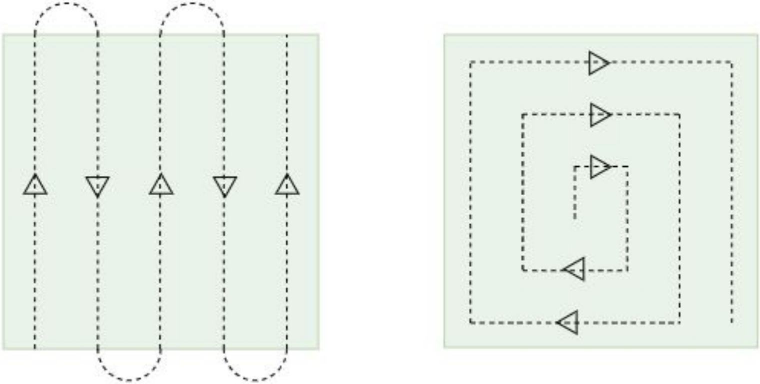


Fig. 3 Back-and-forth and spiral scanning patterns

# Related works

- Classic linearized control: pole placement, LQG [1]
- LQR [2]
- Nonlinear and MPC [3]

- Contribution:

**On-going research**

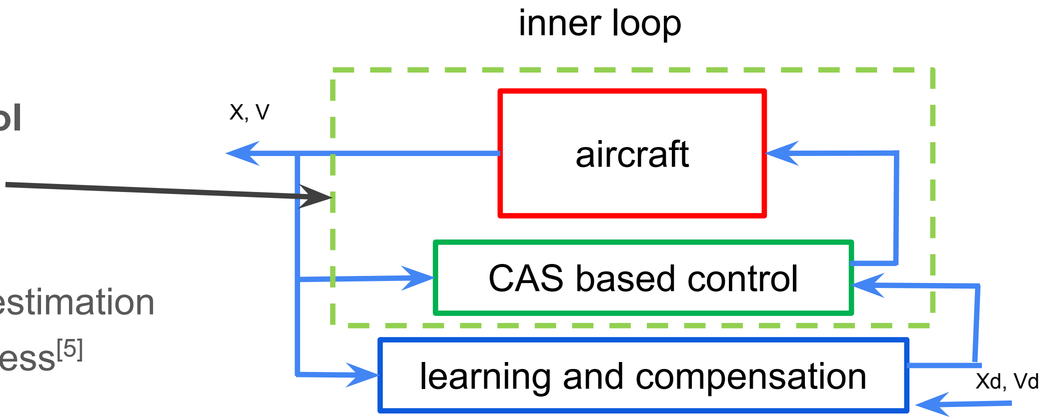
- Path control based on the Control augmented system (CAS).
- C* control algorithm.[4]
- Machine Learning for disturbance estimation and compensation: gausssian process[5]

[1] Stevens, Brian L., Frank L. Lewis, and Eric N. Johnson. Aircraft control and simulation: dynamics, controls design, and autonomous systems. John Wiley & Sons, 2015.
[2] Ashari, Ahmad, et al. "Flight Trajectory Control System on Fixed Wing UAV using Linear Quadratic Regulator." International Journal of Engineering Research and (2019).
[3] Kang, Yeonsik, and J. Karl Hedrick. "Linear tracking for a fixed-wing UAV using nonlinear model predictive control." IEEE Transactions on Control Systems Technology 17.5 (2009): 1202-1210.

# Contribution

## On-going research

- **Path control based on the Control augmented system (CAS).**
- **C* control algorithm.[4]**
- Machine Learning for disturbance estimation and compensation: gausssian process[5]



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[4] Niedermeie, Dominik, and Anthony A. Lambregts. "Fly-by-wire augmented manual control-basic design considerations." International Congress of the Aeronautical Sciences. Vol. 100. 2012.

[5] Cao, Gang, Edmund M-K. Lai, and Fakhrul Alam. "Gaussian process model predictive control of an unmanned quadrotor." Journal of Intelligent & Robotic Systems 88 (2017): 147-162.

# The Aircraft Model

- Standard fixed-wing aircraft dynamics[1]

$$\Sigma_T : \begin{cases} m\dot{\boldsymbol{v}}_I = \boldsymbol{L}_I + \boldsymbol{Y}_I + \boldsymbol{D}_I + \boldsymbol{T}_I + m\boldsymbol{g}_I \\ \dot{\boldsymbol{x}}_I = \boldsymbol{v}_I \end{cases} ;$$

$$\Sigma_R : \begin{cases} \boldsymbol{J}\dot{\boldsymbol{\omega}}_B + \boldsymbol{\omega}_B^{\times}\boldsymbol{J}\boldsymbol{\omega}_B = \boldsymbol{\tau}_B \\ \dot{\boldsymbol{R}}_{IB} = \boldsymbol{R}_{IB}\boldsymbol{\omega}_B^{\times} \end{cases}$$

$$\boldsymbol{L} = \boldsymbol{L}(q_\infty, \bar{q}, \alpha, \delta_e)$$

$$\boldsymbol{Y} = \boldsymbol{Y}(q_\infty, \bar{q}, \bar{r}, \alpha, \beta, \delta_a, \delta_r)$$

$$\boldsymbol{D} = \boldsymbol{L}(q_\infty, \bar{q}, \alpha, \beta, \delta_e)$$

$$\begin{bmatrix} \boldsymbol{D}_I \\ \boldsymbol{Y}_I \\ \boldsymbol{L}_I \end{bmatrix} = \boldsymbol{R}_{IB}\boldsymbol{R}_{BW} \begin{bmatrix} \boldsymbol{D} \\ \boldsymbol{Y} \\ \boldsymbol{L} \end{bmatrix}$$

$$\boldsymbol{\tau}_B = \boldsymbol{f}_\tau(q_\infty, \bar{p}, \bar{q}, \bar{r}, \alpha, \beta, \delta_e, \delta_a, \delta_r)$$

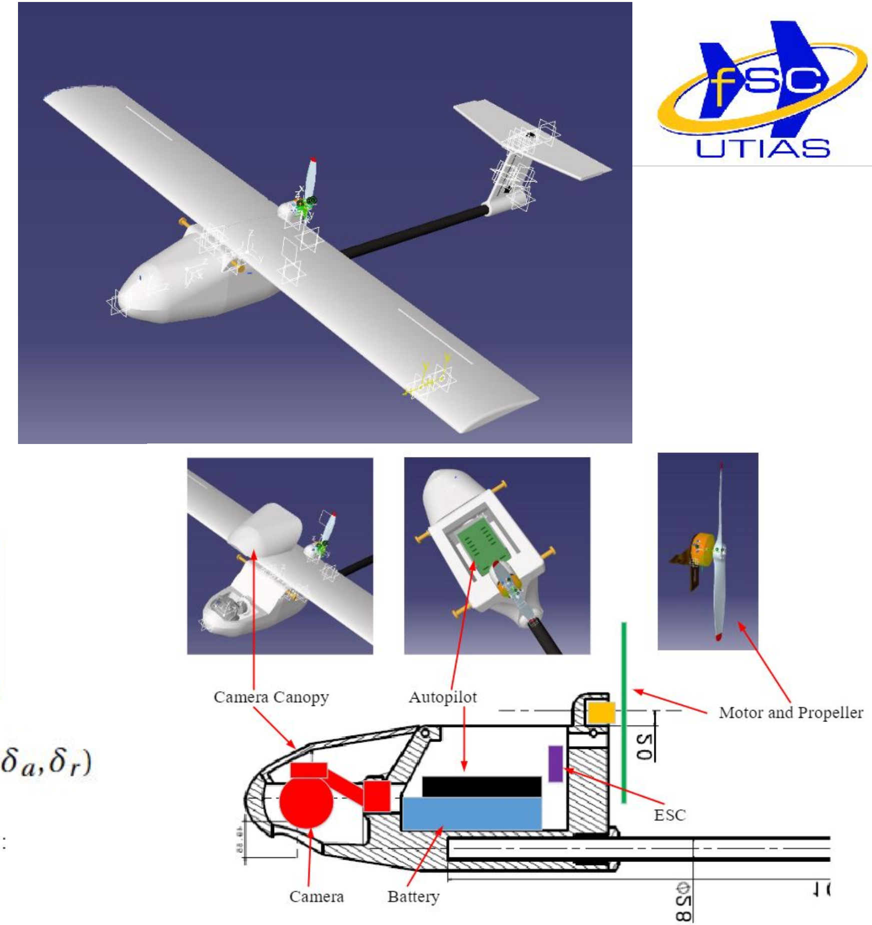


Fig. 4 Aircraft Model

[1] Stevens, Brian L., Frank L. Lewis, and Eric N. Johnson. Aircraft control and simulation: dynamics, controls design, and autonomous systems. John Wiley & Sons, 2015.

# Motor and Propeller Model

- The motor is modeled as a DC motor:

$$\underbrace{dt_{cmd}U}_{\text{Voltage input}} = \underbrace{R_a i_a}_{\text{Resistance}} + \underbrace{L_a \frac{di_a}{dt}}_{\text{Inductance}} + \underbrace{e_b}_{\text{Back EMF:}}$$

Input:Throttle

Motor torque: $\tau = \eta K_T i_a$

Back EMF: $e_b = K_e \omega$

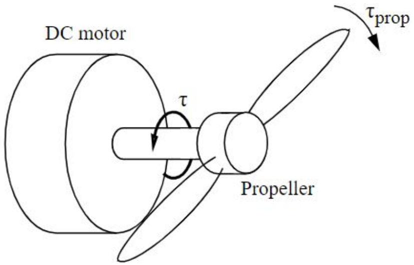


Fig. 5 Motor-propeller connection

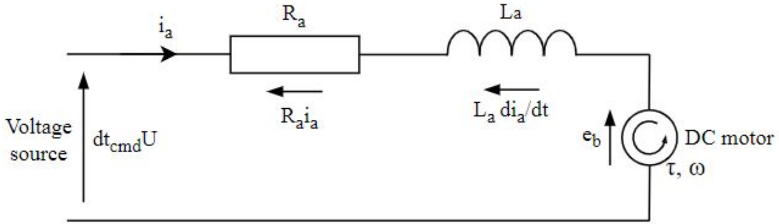
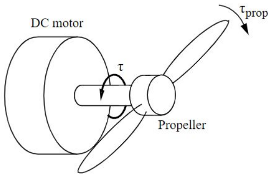


Fig. 6 DC motor model

# Propeller Thrust Model

- The propeller is modeled as a shaft under torque.
- Gyroscopic effects are ignored for small drone.



The shaft dynamics:

$$I\dot{\omega} = \underbrace{\tau}_{\text{Motor torque}} - \underbrace{\tau_{prop}}_{\text{Resistance torque by the propeller}}$$

The advanced ratio: $J = \dfrac{V}{\nu d}$

Thrust and power coefficients: $C_T = f(J), \quad C_P = f(J)$

The thrust:

$$T_{prop} = C_T \rho \nu^2 d^4 = 4\pi^2 C_T \rho \omega^2 d^4$$

The required power and torque:

$$P_{prop} = \tau_{prop}\omega = C_P \rho \nu^3 d^5$$
$$\tau_{prop} = 4\pi^2 C_P \rho \omega^2 d^5$$

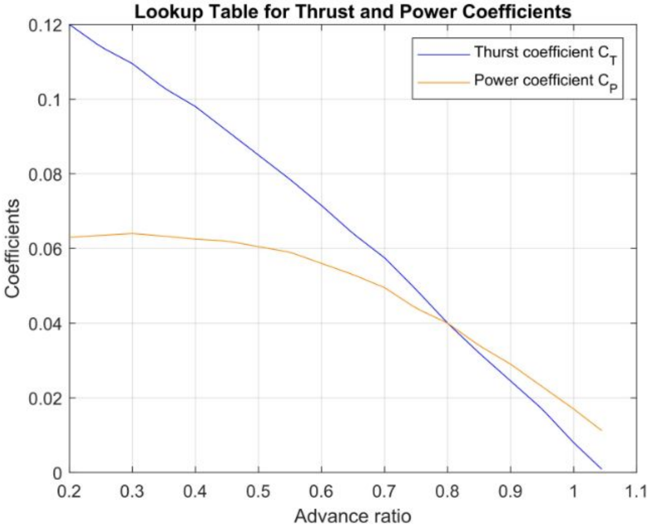


Fig. 7 Propeller Thrust and Power

# Longitudinal Inner Loop

$$C^{\star} = (\Delta n_z)_{pilot} + \frac{V_{co}}{g} q$$

- Control Augmented System (CAS)[1] is widely used in fly-by-wire systems of commercial aircraft.

Normal load

Stick command

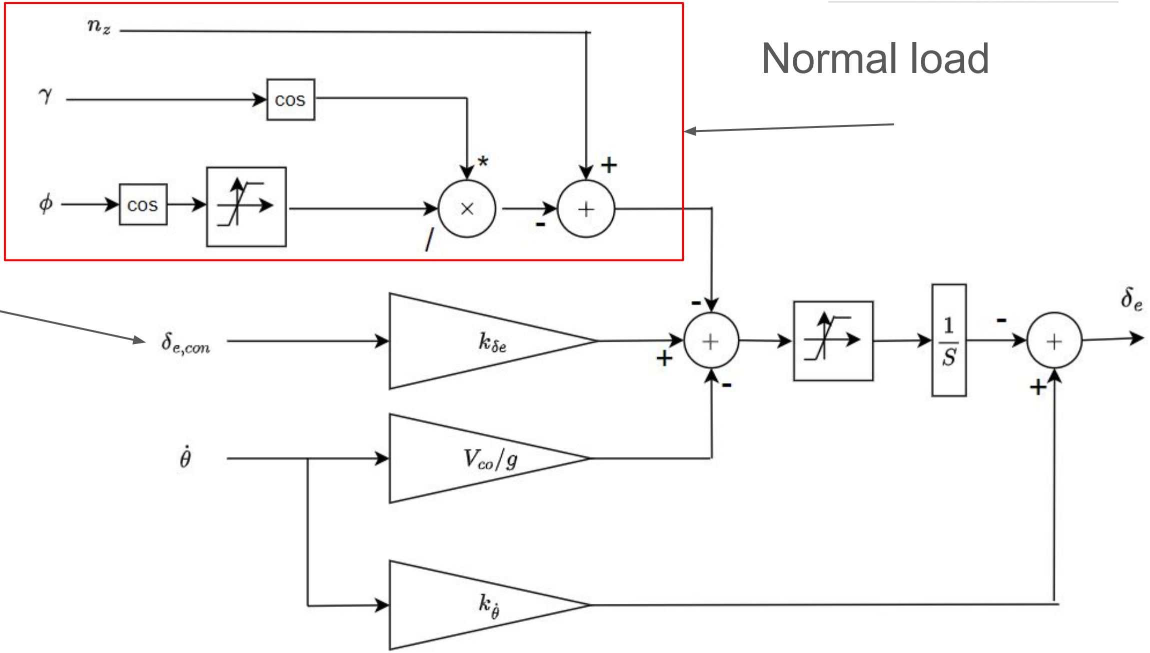
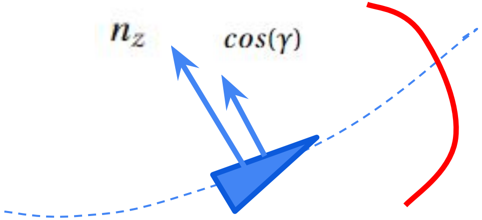


Fig. 8 Longitudinal CAS diagram

- For drones, stick command can be used to control the longitudinal motion.



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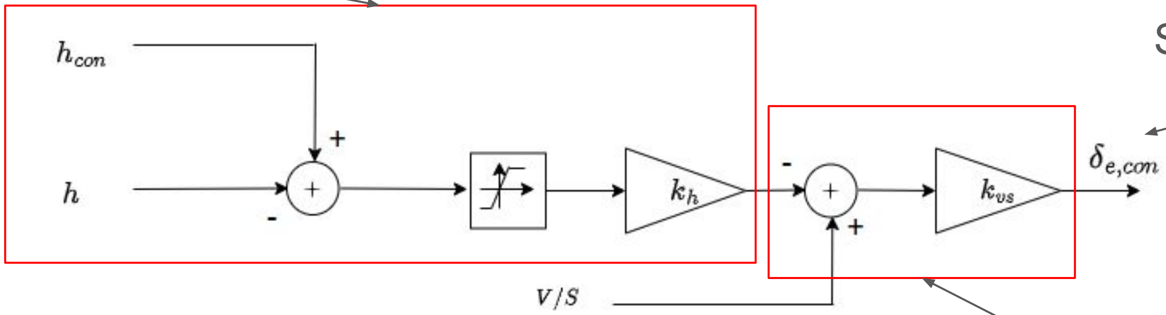
[1] Niedermeie, Dominik, and Anthony A. Lambregts. "Fly-by-wire augmented manual control-basic design considerations." International Congress of the Aeronautical Sciences. Vol. 100. 2012.

# The Altitude Hold Control

Convert the altitude difference to altitude rate

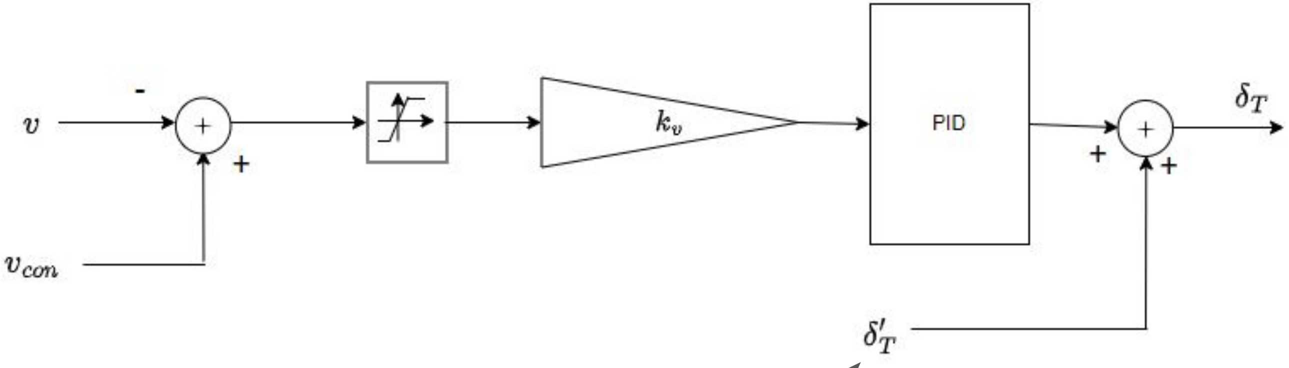


Stick command

Fig. 9 Altitude Hold Control

Climb rate different to ‘virtual stick input’

# The Auto Throttle/ Airspeed Control



Trim throttle

Fig. 10 Airspeed Control

# The Bank angle/ Yaw rate control

Cascade Control

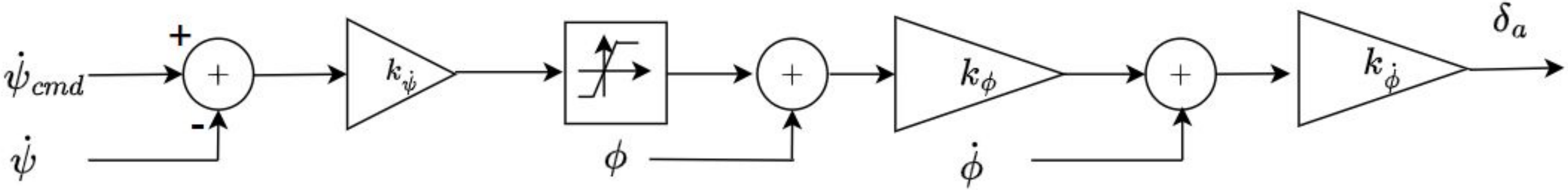


Fig. 11 Bank angle control

# The Bank angle/ Yaw rate control (Con’d)

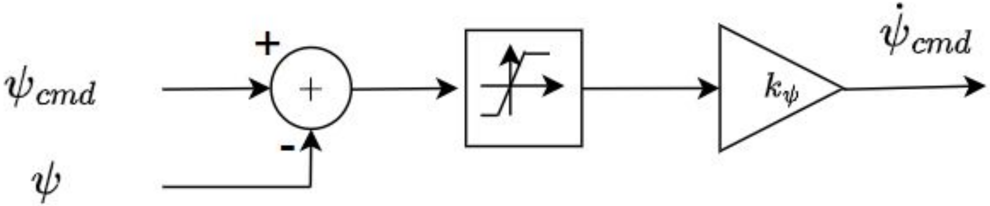


Fig. 12 Yaw angle control

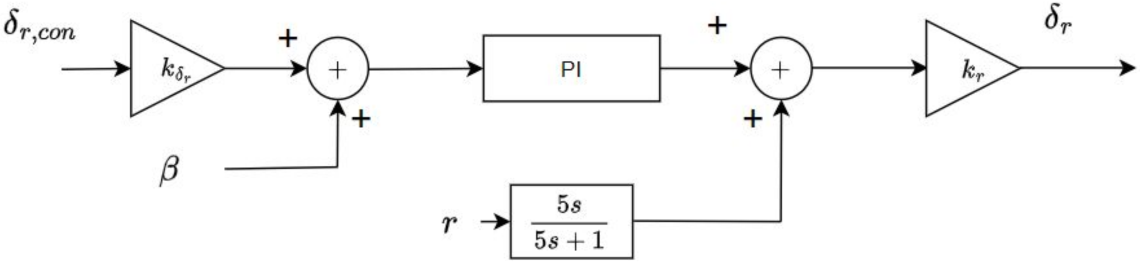
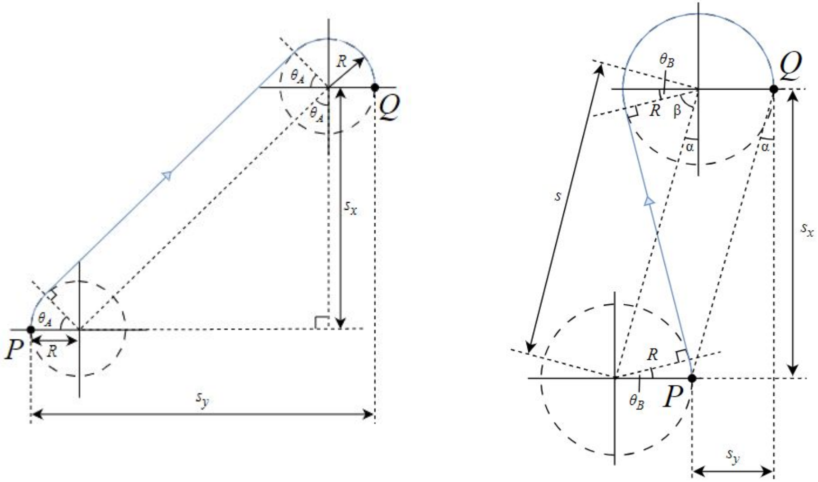


Fig. 13 Yaw channel damping

# Planned Trajectory

- All the path segments are on the same height for the crop monitoring mission.
- The speed may vary when the drone flies on different path segments



Path switched by upper-level logic

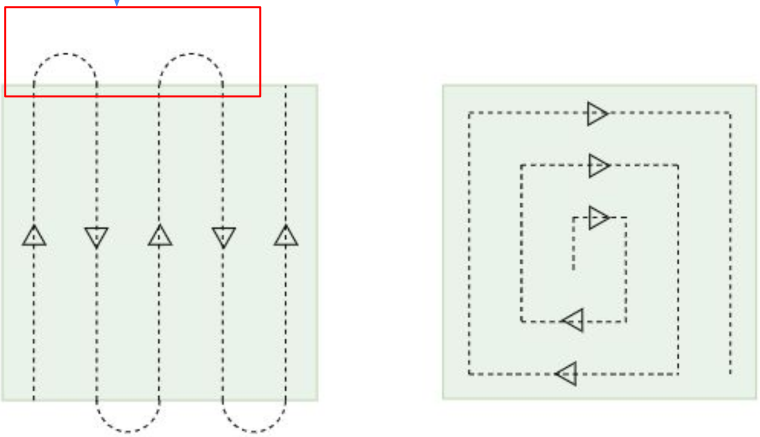


Fig. 14 Typical flight patterns for a crop monitoring mission

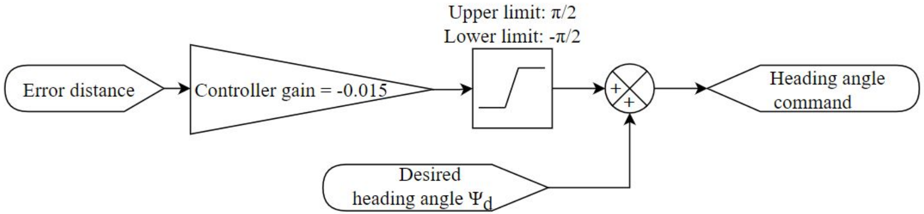
# Horizontal Straight-Line Path Following Control

- Treat the auto throttle control and the heading angle control as the inner loop.
- Convert the horizontal error distance into the heading angle command

1. Calculate the horizontal error distance from the desired path.

$$error\ distance = y'_{plane} - y'_{path}$$

2. Convert the error distance to the heading angle command



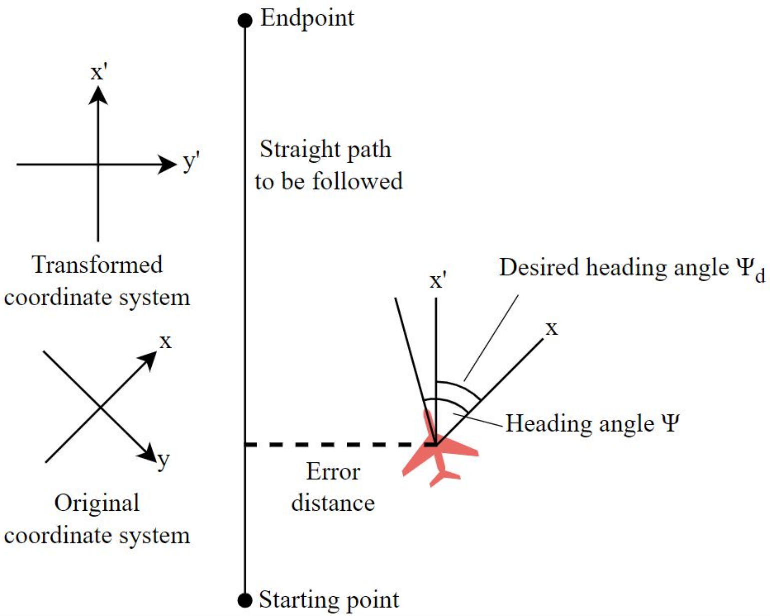


Fig. 15 Straight-line path following control

# Horizontal Circular Path Following

- Convert the radius error and the rate change of radius to yaw rate command.
- Use yaw rate to adjust the cruising radius and angular velocity.

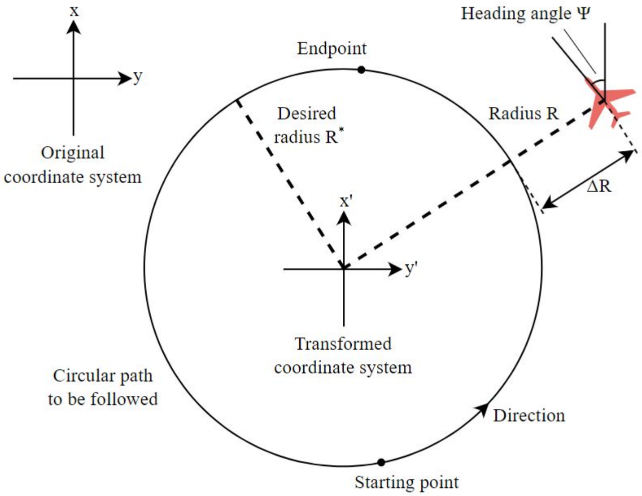


Fig.16 Circular path coordinate system

1. Transforming the position of the aircraft to the path coordinate system and calculate the actual cruise radius.

$$R = \sqrt{x'^2 + y'^2} = \sqrt{(x-H)^2 + (y-K)^2}$$

2. Calculate the rate of change of the radius:

$$\Delta\dot{R} = \frac{2(x-H)\dot{x} + 2(y-H)\dot{y}}{2\sqrt{(x-H)^2 + (y-K)^2}} = \frac{x'\dot{x} + y'\dot{y}}{\sqrt{x'^2 + y'^2}}$$

3. Set the desired angular speed (steady-state yaw rate):

$$\dot{\psi}_d = \frac{V^*_{turn}}{R^*}$$

# Horizontal Circular Path Following (Cont’d)

4. Calculate the desired rate of change of ΔRd:

$$\Delta \dot{R}_d = k_r \Delta R$$

Approach the

5. Calculate yaw rate command:

$$\dot{\psi}_c = \dot{\psi}_d + k_s(\Delta \dot{R} - \Delta \dot{R}_d)$$

where $\Delta \dot{R} = \dfrac{x'\dot{x} + y'\dot{y}}{\sqrt{x'^2 + y'^2}}$ $\dot{\psi}_d = \dfrac{V^*_{turn}}{R^*}$

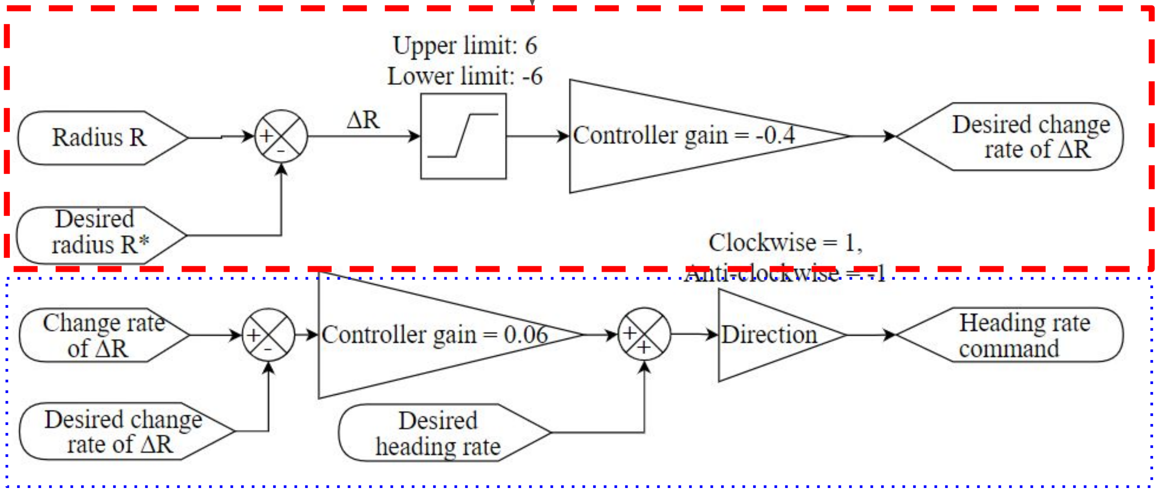


Fig. 17 Circular arc path following control

# Overall Diagram of Control Design

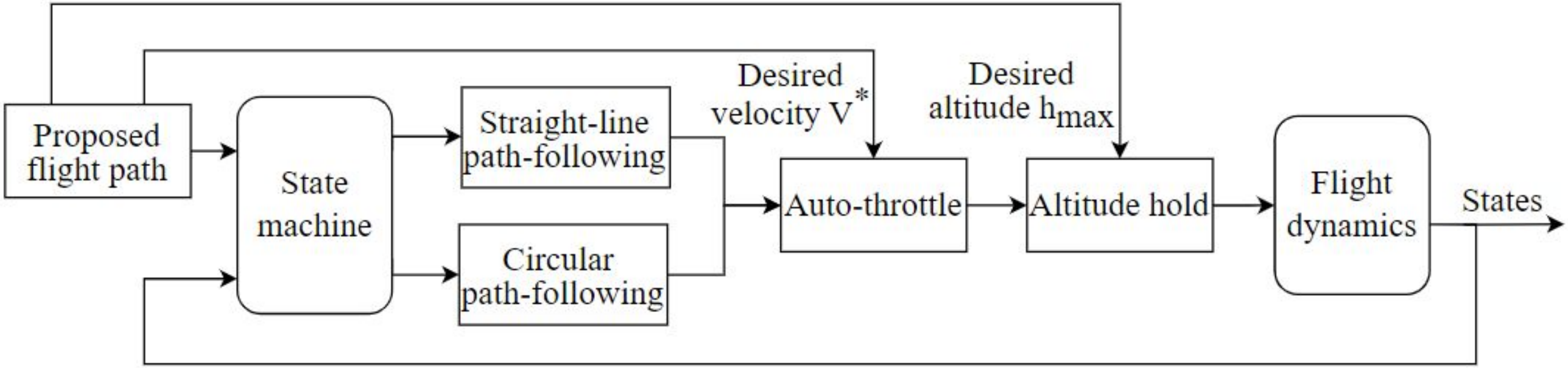


Fig. 18 The overall Controller Diagram

# Simulation in Simulink

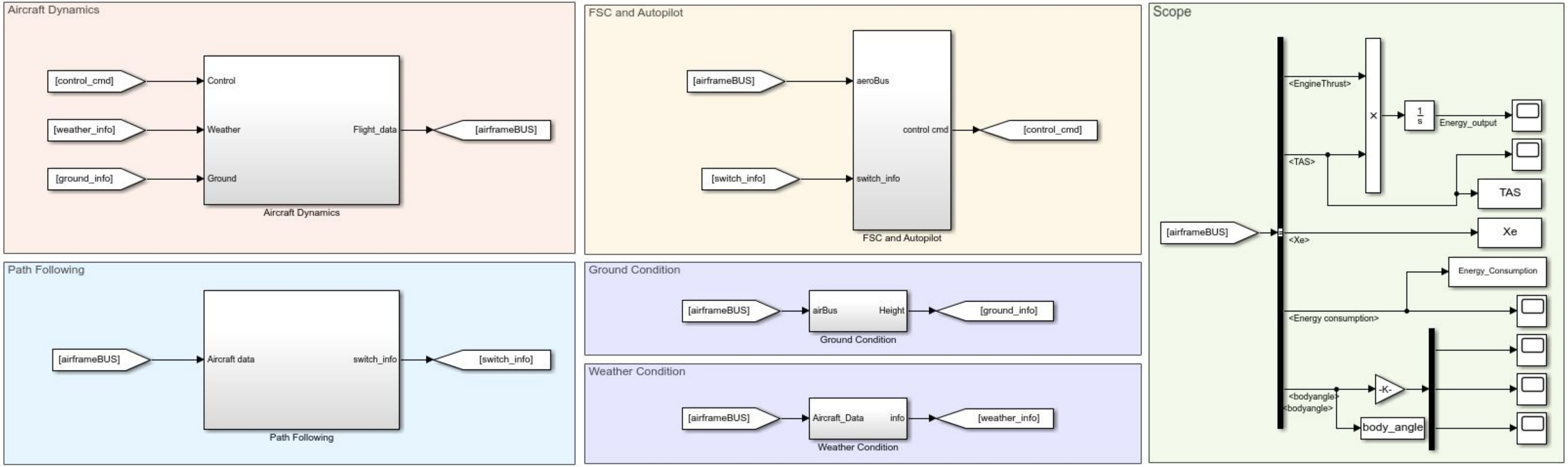
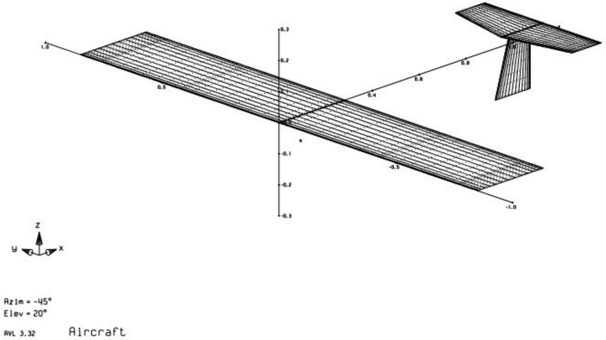
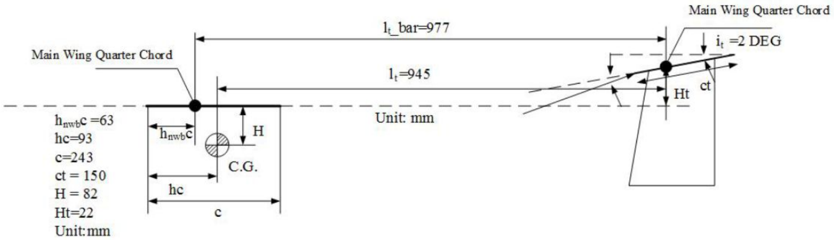


Fig. 19 Simulink diagram

# Parameters

- emperical formula + xfoil





| Symbol | $RE = 2.1 \times 10^5$ | $RE = 3.2 \times 10^5$ |
|---|---|---|
| $C_{D0}$ | 0.038 | 0.035 |
| $k_{CL}$ | 0.073 | 0.073 |
| $C_{L\alpha}$ (1/deg) | 0.08 | 0.08 |
| $V_{op}$ (km/h) | 45 | 45 |
| $V_{stall}$ (km/h) | $28^\star$ | $28^\star$ |
| $L/D_{max}$ | 9.5 | 9.5 |

| Stability derivatives | Symbol | Value |
|---|---|---|
| Total Lift Slope (/rad) | $C_{L\alpha}$ | 5.22 |
| Static Margin | $K_n$ | 0.18 |
| Static Longitudinal Stability | $C_{m\alpha}$ | -0.96 |
| Dynamic Longitudinal Stability | $C_{mq}$ | -19.73 |
| Neutral Point | $h_n$ | 0.56 |
| Zero AOA Pitching Moment | $C_{m0}$ | 0.19 |

# Simulation result: Straight-line path following

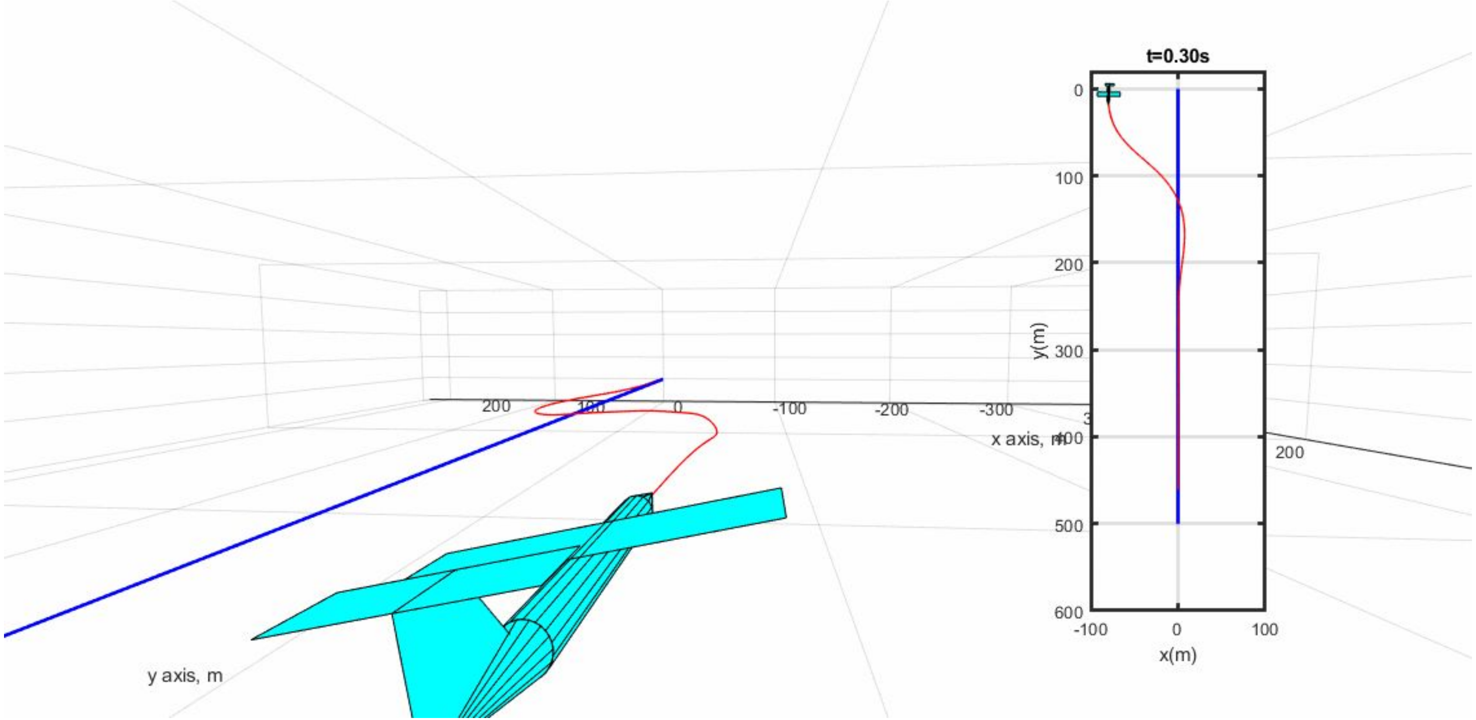


Fig. 20 Straight-line path following

# Simulation result: Circular path following

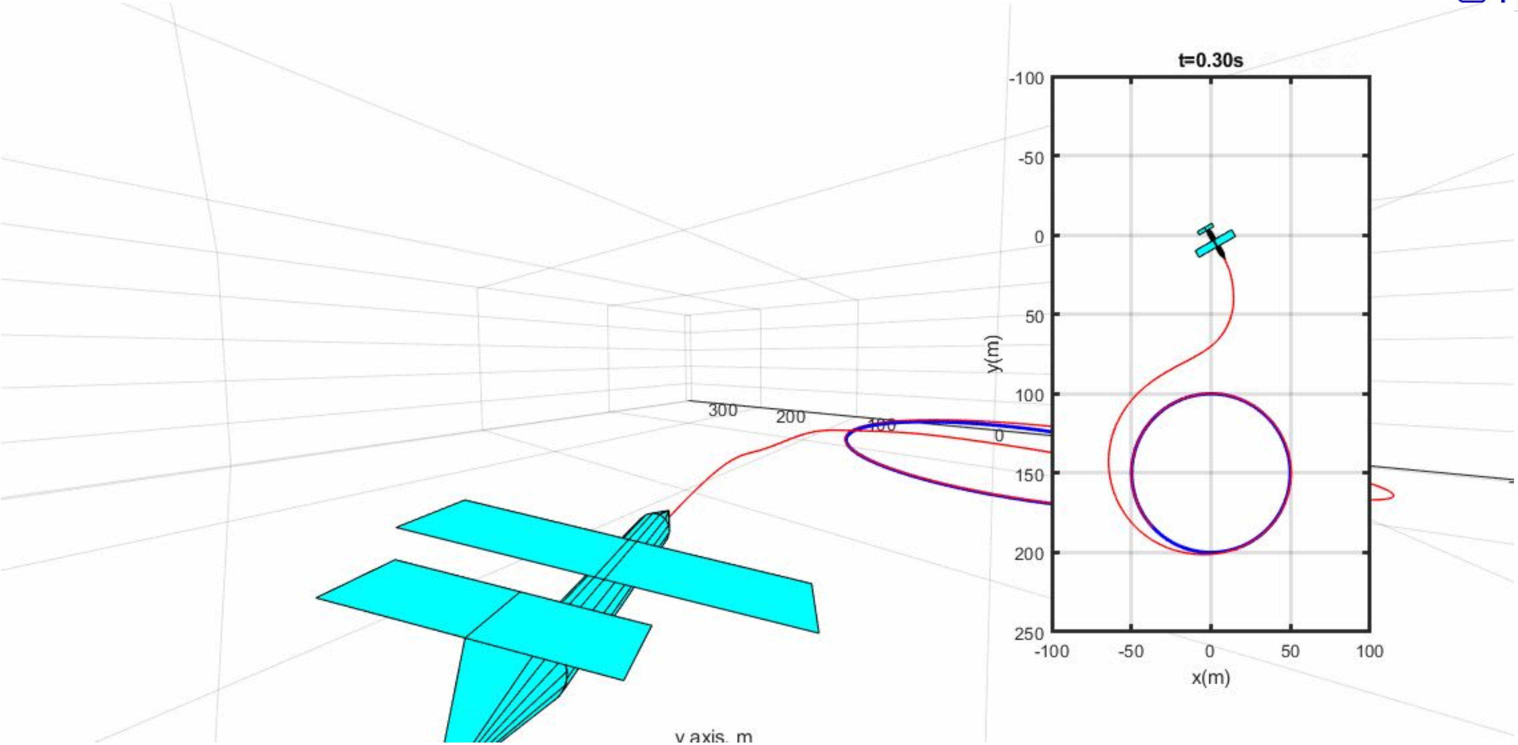
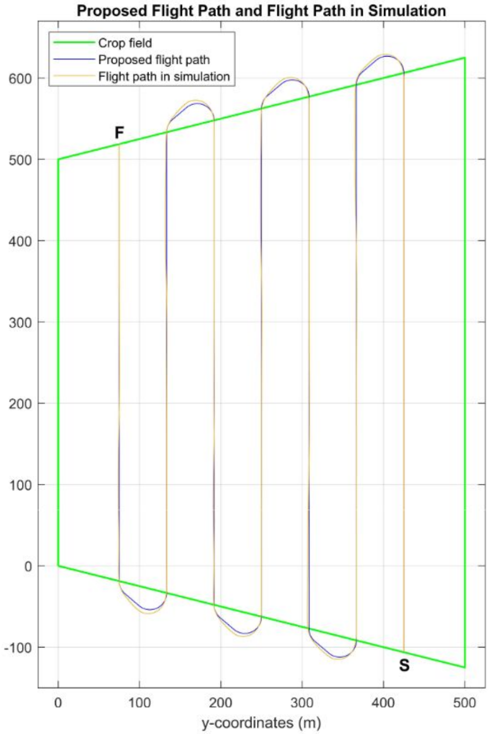


Fig. 21Circular path following

# Simulation Complete Crop Field Monitoring



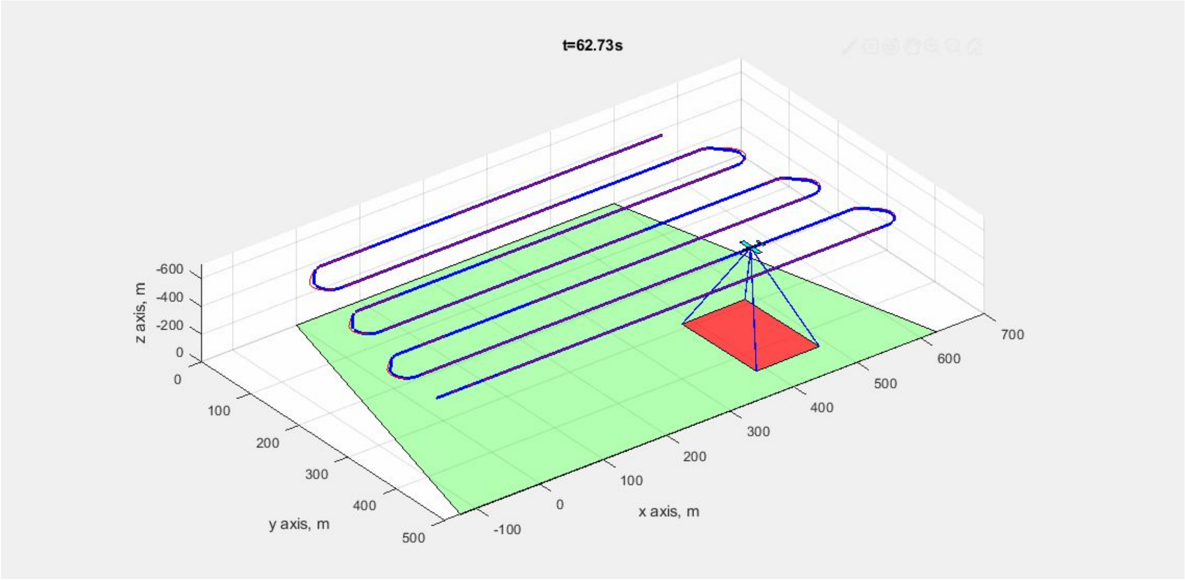


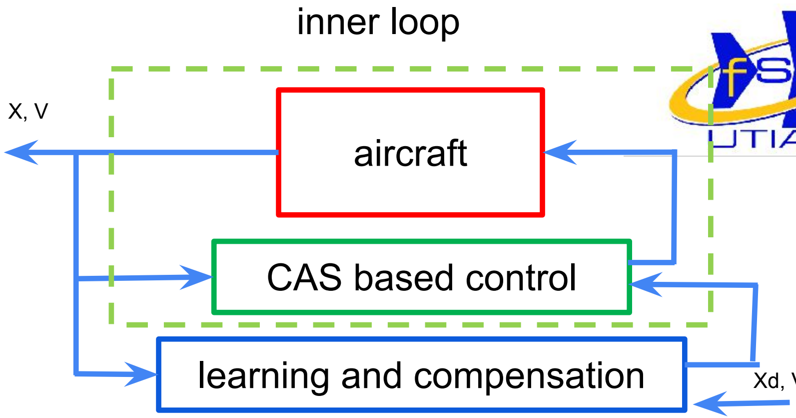
Fig. 22 The path for crop scanning

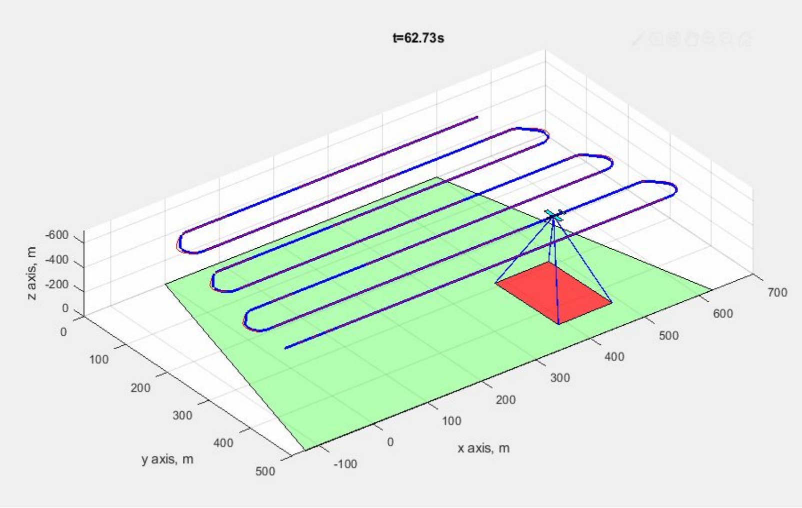
# Conclusion and Future work

- A flight control scheme for a fixed-wing drone to perform crop monitoring mission is presented.

Next step:

- Current stabilization scheme is treated as the inner loop.
- Gaussian process to estimate and compensate for residual unmodelled dynamics.





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