Introduction to Multicopter Design and Control

Lesson 13 Mission Decision-Making

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Preface

What are the mission decision-making mechanisms under the Flight Control System and Semi-Autonomous Control manners, respectively?

Outline

1. Fully-Autonomous Control (FAC)
2. Semi-Autonomous Control (SAC)
3. Conclusion

1. Fully-Autonomous Control

□ Brief Introduction

（1） Mission planning

Missions are often planned by remote pilots off-line. A mission planning process consists of the mission stages-division and task-definition at each waypoint.

（2） Path planning

Path planning aims to produce a flyable path between two waypoints. Flyable path is either a continuous-time trajectory or a series of discrete-time goal waypoints.

（3） Low level control

Control motors to realize the tracking

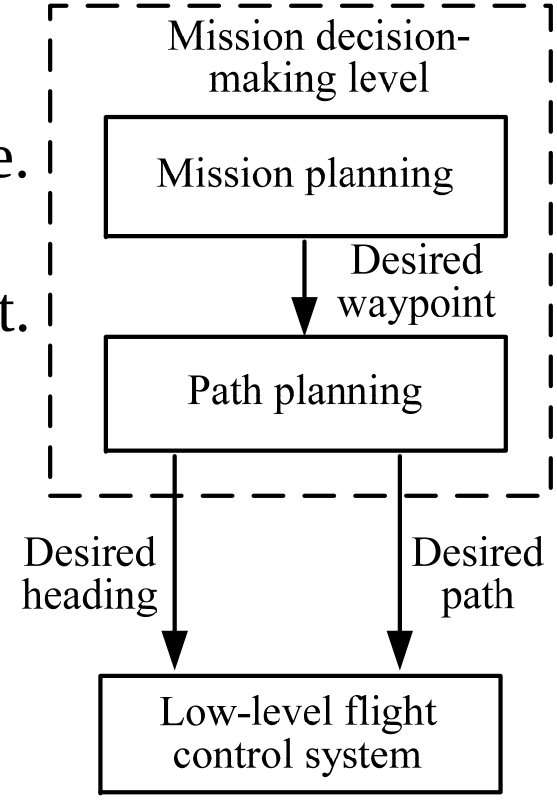


Figure 13.1 The hierarchical structure diagram of FAC manner

1. Fully-Autonomous Control

☐ Brief Introduction

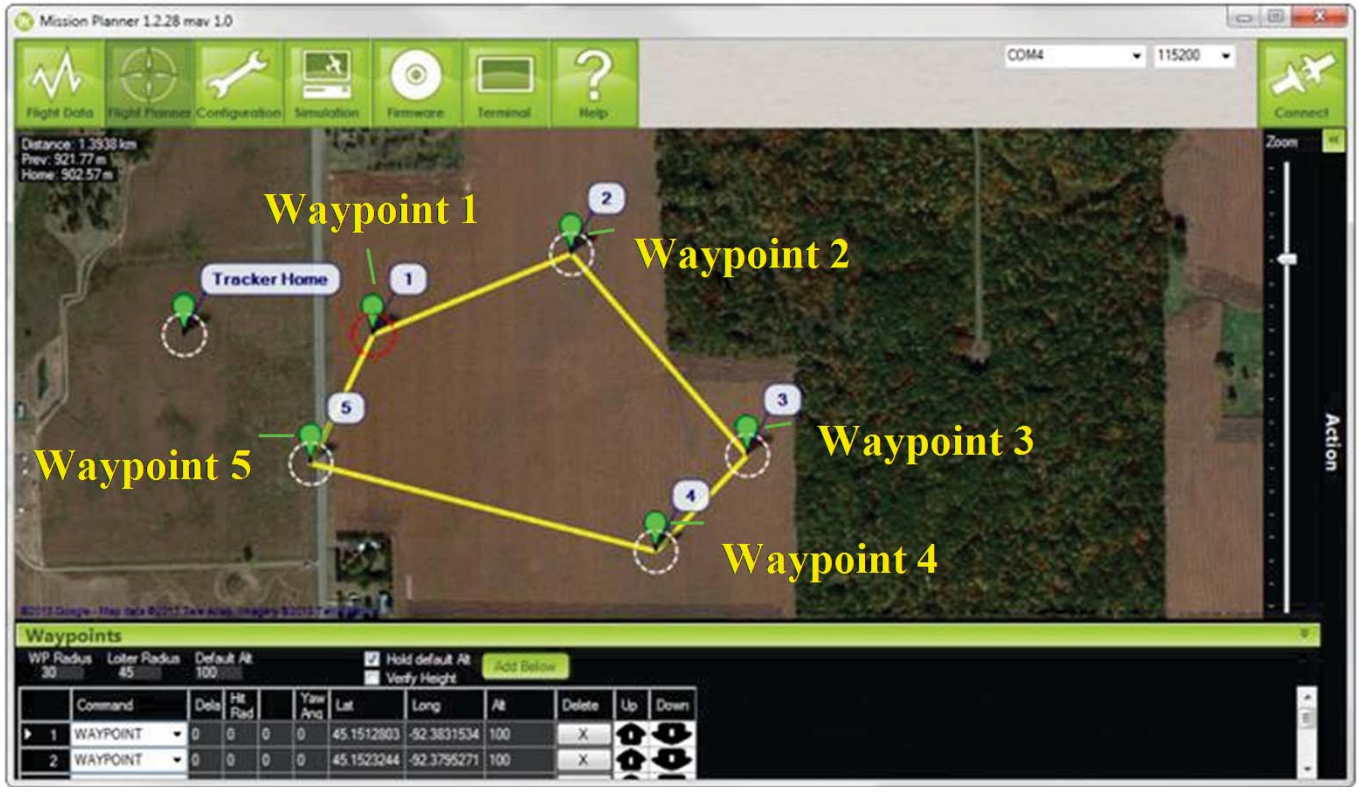
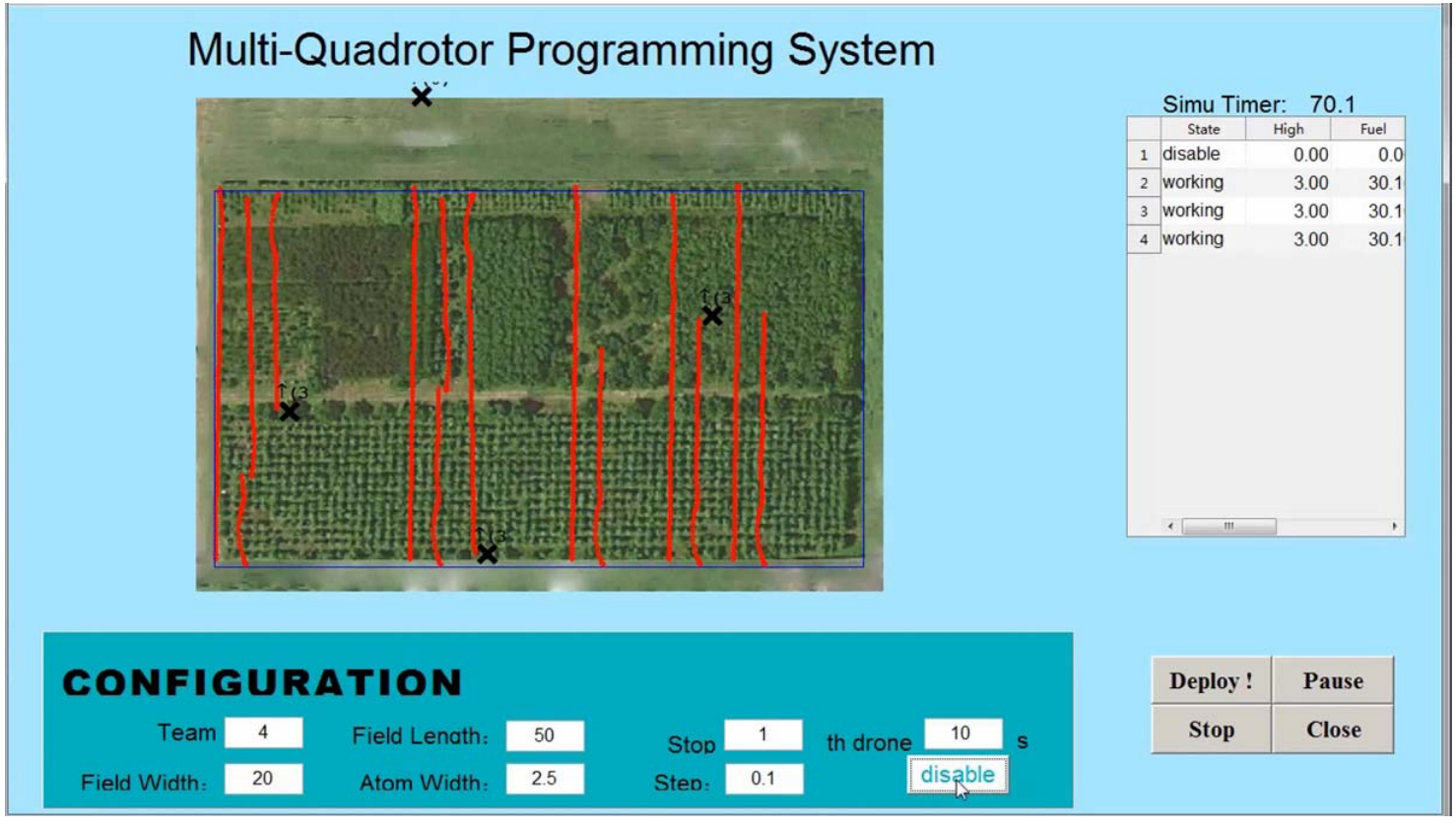


Figure 13.1 Path planning interface in Mission Planner

1. Fully-Autonomous Control

☐ Brief Introduction



Video: A Pesticide Spray Mission Performed by Multi-quadrotors: Simulation Phase,https://youtu.be/fkp043jE5fQ

1. Fully-Autonomous Control

□ Mission Planning

（1） Mission requirements

1） Given conditions

① The desired waypoints

$$\mathbf{p}_{\mathrm{wp},0}, \mathbf{p}_{\mathrm{wp},1}, \cdots, \mathbf{p}_{\mathrm{wp},k}, \cdots, \mathbf{p}_{\mathrm{wp},n_{\mathrm{wp}}}$$

$$\in \mathbb{R}^3, k = 0, \cdots, n_{\mathrm{wp}}$$

② Real-time position $\mathbf{p}$

and battery capacity b .

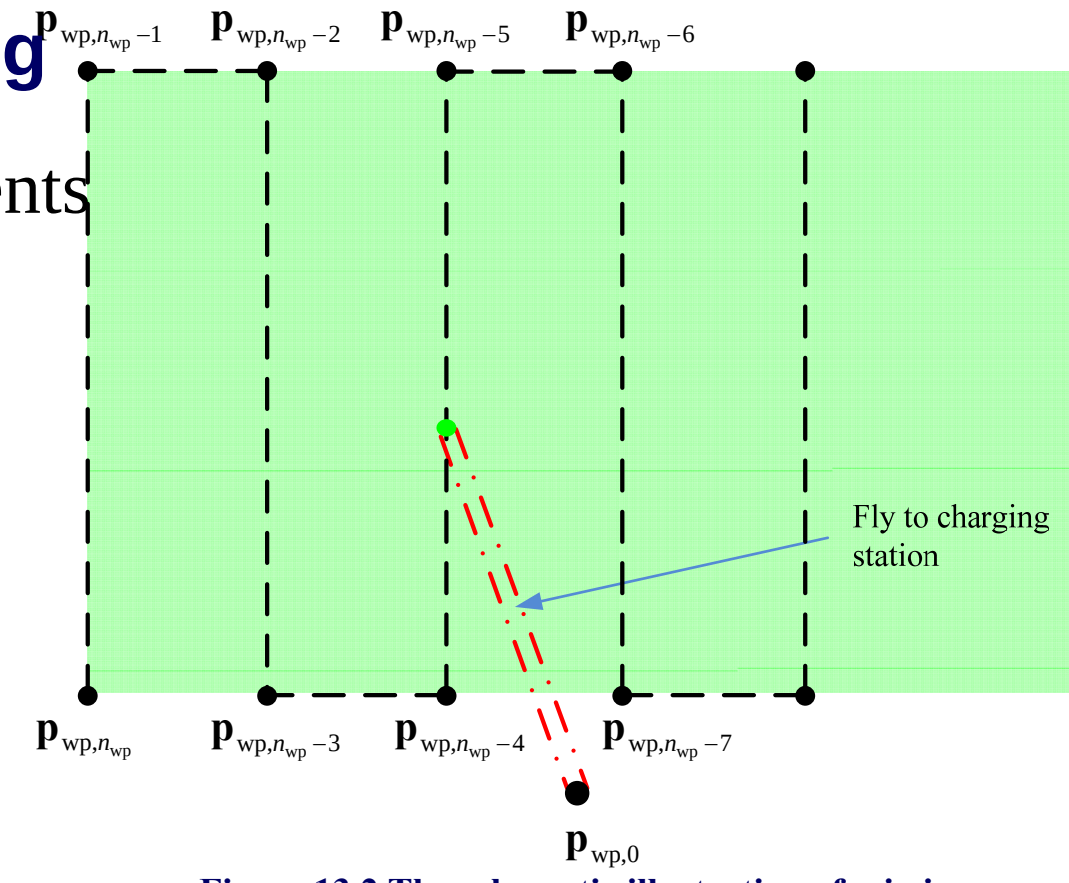


Figure 13.2 The schematic illustration of mission planning about farmland traversal

1. Fully-Autonomous Control

□ Mission Planning

2） Mission requirements

① Starting from $\mathbf{p}_{\mathrm{wp},0}$, the multicopter is required to traverse all the waypoints and follow an S-shaped path;

②The desired yaw always points to the next waypoint;

③When battery capacity falls below threshold, the multicopter will fly to the base to charge, and then continue to traverse the remaining waypoints.

④After completing all waypoints, the multicopter will fly back to the base.

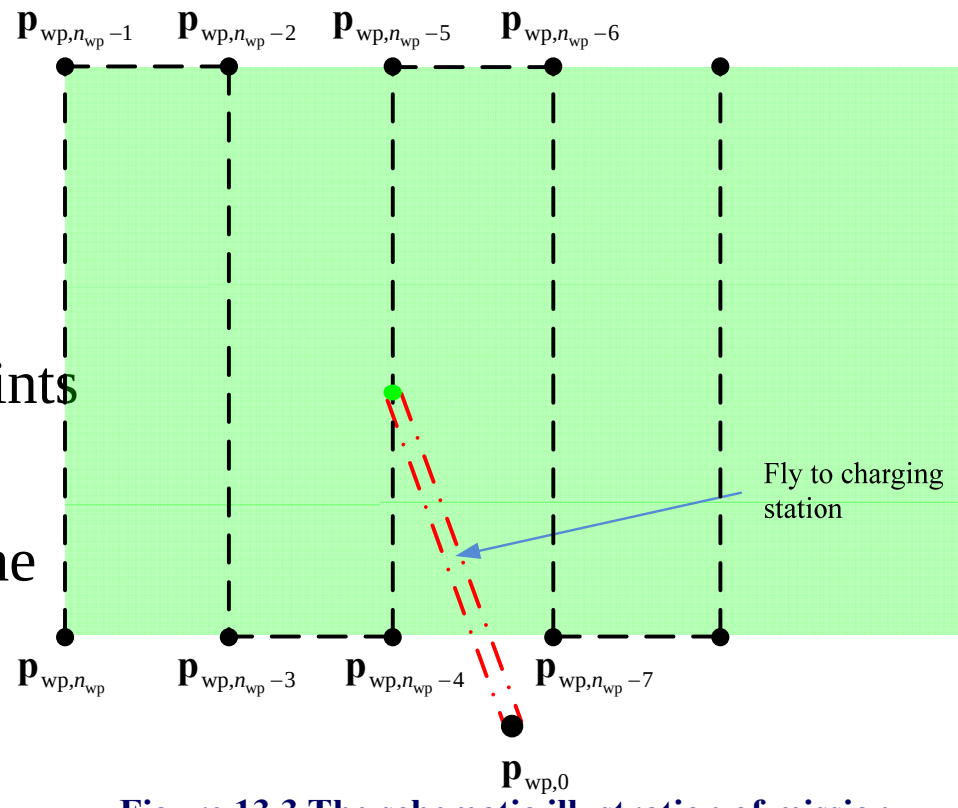


Figure 13.3 The schematic illustration of mission planning about farmland traversal

1. Fully-Autonomous Control

☐ Mission Planning

（2） A simple protocol design

Input: Real-time position $\mathbf{p}$ and battery capacity b.

Output: Real-time desired position $\mathbf{p}_{\mathrm{d}}$.

1） Determine the coordinate system of the farmland.

2） Generate the waypoints $\mathbf{p}_{\mathrm{wp},1},\cdots,\mathbf{p}_{\mathrm{wp,k}},\cdots,\mathbf{p}_{\mathrm{wp},n_{\mathrm{wp}}}$ and base position $\mathbf{p}_{\mathrm{wp},0}$, then push them into a stack successively.

3） Let $k=n_{\mathrm{wp}}$, and the current desired position $\mathbf{p}_{\mathrm{d}}=\mathbf{p}_{\mathrm{wp,k}}$, and let $\varepsilon>0, \mathrm{b}_{th}>0$, where ε is allowable position error and b_{th} stands for the allowable minimum battery capacity.

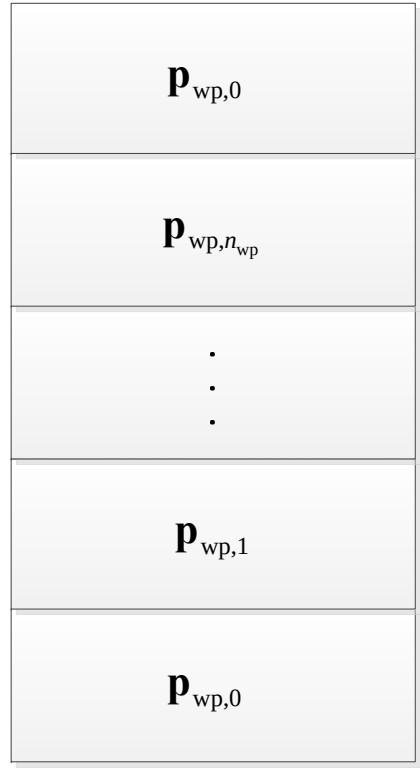


Figure 13.4 Push all waypoints and base position onto the stack

1. Fully-Autonomous Control

□ Mission Planning

（2） A simple protocol design

4） Go to Step 5） if $\|\mathbf{p}_d - \mathbf{p}\| \le \varepsilon$ and skip to Step 6) otherwise.

5） End the mission if $\boxed{\mathbf{p}_d = \mathbf{p}_{wp,0} \ \& \ k = 0}$, and charge the battery if $\boxed{\mathbf{p}_d = \mathbf{p}_{wp,0} \ \& \ k \ne 0}$ When the multicopter receives the take-off command, the mission planning protocol executes $k = k - 1$, $\mathbf{p}_d = \mathbf{p}_{wp,k}$ and goes back to Step 4). If $\boxed{\mathbf{p}_d \ne \mathbf{p}_{wp,0}}$, then the mission planning protocol will execute $k = k - 1$, $\mathbf{p}_d = \mathbf{p}_{wp,k}$. Then go to Step 7).

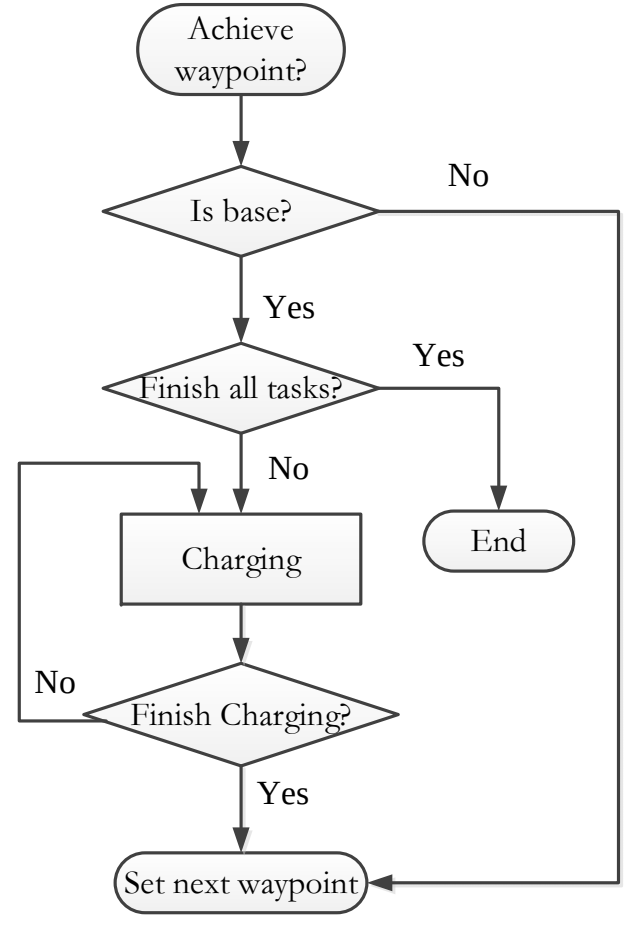


Figure 13.5 Algorithm flow chart of mission planning protocol

1. Fully-Autonomous Control

□ Mission Planning

（2） A simple protocol design

6） If $b < b_{th}$ & $\mathbf{p}_d \neq \mathbf{p}_{wp,0}$, then mission planning protocol execute the following instructions

$$k = k+1, \mathbf{p}_{wp,k} = \mathbf{p}$$

$$k = k+1, \mathbf{p}_{wp,k} = \mathbf{p}_{wp,0}$$

$$\mathbf{p}_d = \mathbf{p}_{wp,k}.$$

Otherwise go back to Step 4).

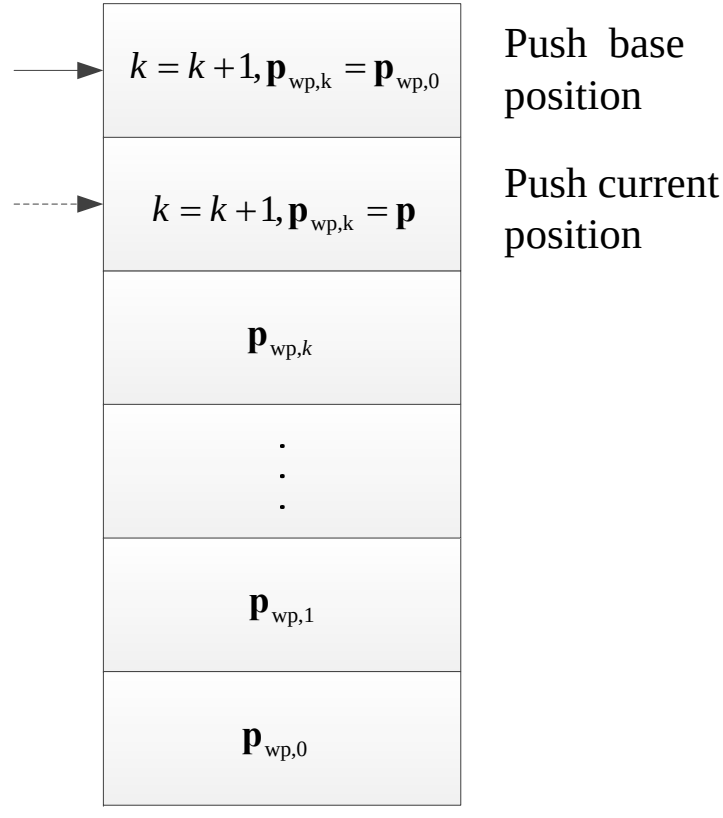


Figure 13.6 Push current position and base position onto the stack

1. Fully-Autonomous Control

☐ Path Planning

（1）Basic concepts

1）Path planning: The primary aim of path planning is to provide flyable paths, i.e., to facilitate flying a multicopter from one position to another.

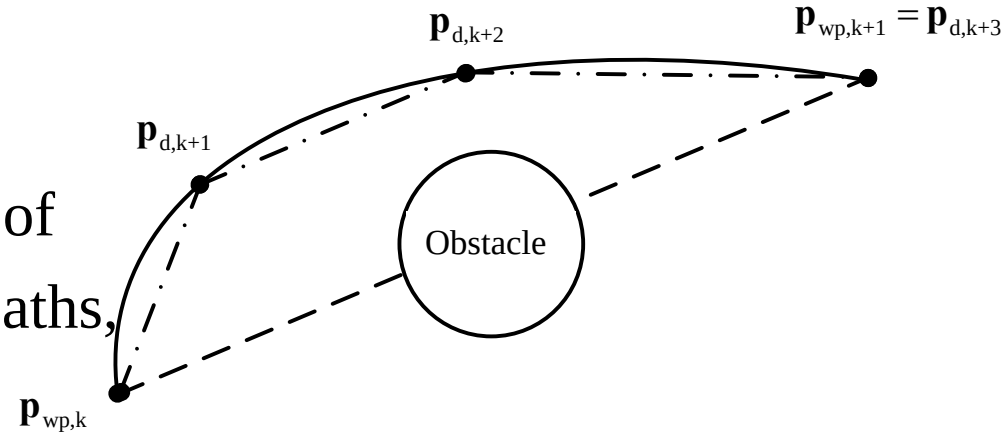


Figure 13.7 Global path planning and local path planning

2）Global path planning and local path planning[1]： The primary aim of global path planning is to produce a series of waypoints that are connected by straight lines, while the local path planning is to refine the path to be flyable according to local environmental conditions and kinematic or motion constraints of the multicopter.

[1] Tsourdos A, White B, Shanmugavel M. Cooperative path planning of unmanned aerial vehicles[M]. John Wiley & Sons, 2010. 2-12.

1. Fully-Autonomous Control

□ Path Planning

（1）Basic concepts

3 ） Artificial Potential Field (APF) method:

The airspace is formulated as an APF. The destination point and desired path are assigned attractive potentials, while the obstacles are assigned repulsive potentials.

A multicopter in the field will be attracted towards the path then fly to the destination, while being repelled by the obstacles[2].

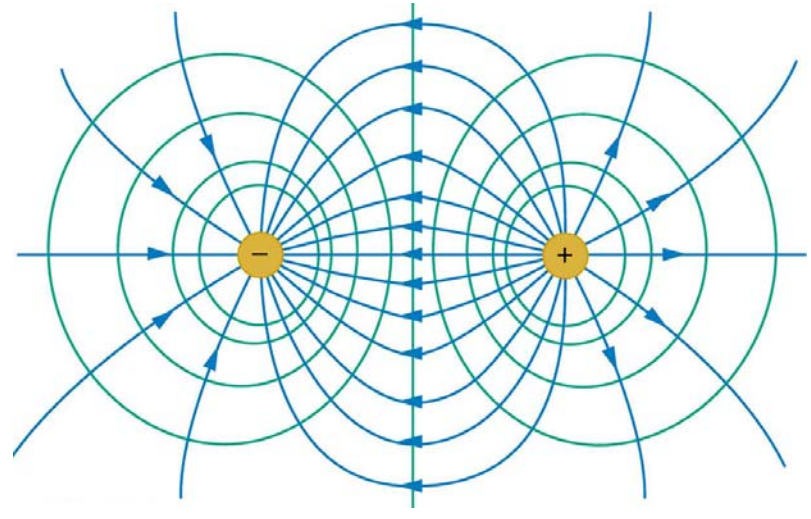


Figure 13.8 Schematic illustration of potential field

[2] Khatib O. Real-time obstacle avoidance for manipulators and mobile robots. The international journal of robotics research, 1986, 5(1): 90-98

1. Fully-Autonomous Control

□ Path Planning

（2）Straight-line path following

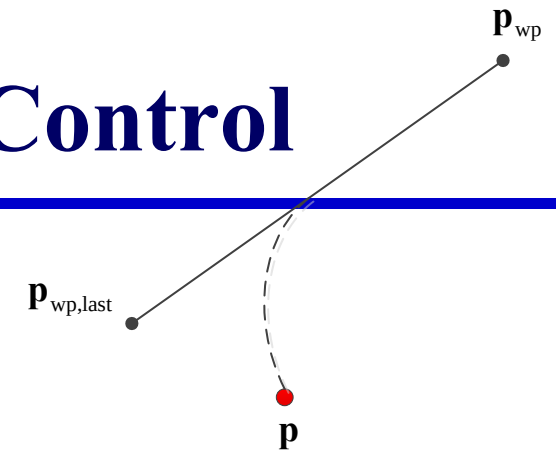


Figure 13.9 Schematic illustration of Straight-line path following

1） Problem formulation

Let $\mathbf{p} \in \mathbb{R}^3$ be the current position of a multicopter, $\mathbf{p}_{wp} \in \mathbb{R}^3$ be the goal waypoint, and $\mathbf{p}_{wp,last} \in \mathbb{R}^3$ be the previous waypoint. Design $\mathbf{u}$ to guide the multicopter to follow the straight-line through $\mathbf{p}_{wp,last} \in \mathbb{R}^3$ and $\mathbf{p}_{wp} \in \mathbb{R}^3$ until it arrives at the goal waypoint $\mathbf{p}_{wp}$.

2）Algorithm design

For simplicity, the multicopter is considered as a mass point, so that it satisfies the Newton's Second Law that

$$\dot{\mathbf{p}} = \mathbf{v}$$

$$\dot{\mathbf{v}} = \mathbf{u}$$

1. Fully-Autonomous Control

☐ Path Planning

（2） Straight-line path following

2） Algorithm design

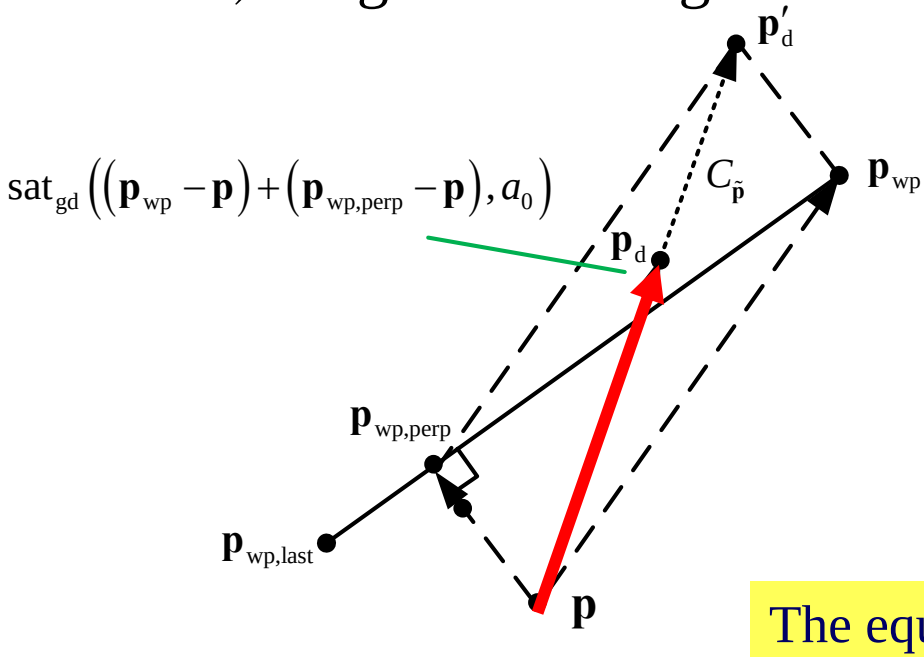


Figure 13.10 Desired position generated for straight-line path following

The foot point is expressed as

$$\mathbf{p}_{\mathrm{wp,perp}}=\mathbf{p}_{\mathrm{wp}}+\left(\mathbf{p}_{\mathrm{wp,last}}-\mathbf{p}_{\mathrm{wp}}\right)\frac{\left(\mathbf{p}-\mathbf{p}_{\mathrm{wp}}\right)^{\mathrm{T}}\left(\mathbf{p}_{\mathrm{wp,last}}-\mathbf{p}_{\mathrm{wp}}\right)}{\left\|\mathbf{p}_{\mathrm{wp}}-\mathbf{p}_{\mathrm{wp,last}}\right\|^2}$$

Then

$$\mathbf{p}-\mathbf{p}_{\mathrm{wp,perp}}=\mathbf{A}\left(\mathbf{p}-\mathbf{p}_{\mathrm{wp}}\right)$$

where

$$\mathbf{A}=\mathbf{I}_3-\frac{\left(\mathbf{p}_{\mathrm{wp,last}}-\mathbf{p}_{\mathrm{wp}}\right)\left(\mathbf{p}_{\mathrm{wp,last}}-\mathbf{p}_{\mathrm{wp}}\right)^{\mathrm{T}}}{\left\|\mathbf{p}_{\mathrm{wp}}-\mathbf{p}_{\mathrm{wp,last}}\right\|^2}$$

The equation $\mathbf{A}\left(\mathbf{p}-\mathbf{p}_{\mathrm{wp}}\right)=0$ implies that $\mathbf{p}\in\mathbb{R}^3$ is in the straight-line through $\mathbf{p}_{\mathrm{wp,last}}\in\mathbb{R}^3$ and $\mathbf{p}_{\mathrm{wp}}\in\mathbb{R}^3$.

1. Fully-Autonomous Control

☐ Path Planning

（2）Straight-line path following

2）Algorithm design

Define $\tilde{\mathbf{p}}_{\mathrm{wp}} = \mathbf{p} - \mathbf{p}_{\mathrm{wp}}$. The saturation on control needs to be considered. The Lyapunov function can be designed as

$$V_1 = \underbrace{\int_{C_{\tilde{\mathrm{p}}}} \mathrm{sat}_{\mathrm{gd}}\left(k_0\tilde{\mathbf{p}}_{\mathrm{wp}} + k_1\mathrm{A}\tilde{\mathbf{p}}_{\mathrm{wp}}, a_0\right)^{\mathrm{T}} \mathrm{d}\tilde{\mathbf{p}}_{\mathrm{wp}}}_{\text{Get close to the waypoint and the straight-line path}} + \frac{k_2}{2}\mathbf{v}^{\mathrm{T}}\mathbf{v}$$

Where $k_0, k_1, k_2 \in \{0\} \cup \mathbb{R}_+, a_0 \in \mathbb{R}_+$.The derivative of V_1 is

$$\dot{V}_1 = \mathrm{sat}_{\mathrm{gd}}\left(k_0\tilde{\mathbf{p}}_{\mathrm{wp}} + k_1\mathrm{A}\tilde{\mathbf{p}}_{\mathrm{wp}}, a_0\right)^{\mathrm{T}} \mathbf{v} + k_2\mathbf{v}^{\mathrm{T}}\mathbf{u}$$

1. Fully-Autonomous Control

☐ Path Planning

（2）Straight-line path following

2）Algorithm design

If $\mathbf{u}$ satisfies $\boxed{\mathbf{u} = -\frac{1}{k_2}\mathrm{sat}_{\mathrm{gd}}\left(k_0\tilde{\mathbf{p}}_{\mathrm{wp}} + k_1\mathrm{A}\tilde{\mathbf{p}}_{\mathrm{wp}}, a_0\right) - \frac{1}{k_2}\mathrm{sat}_{\mathrm{gd}}\left(\mathbf{v}, a_1\right)}$,then $\dot{V}_1 = -\mathbf{v}^{\mathrm{T}}\mathrm{sat}_{\mathrm{gd}}\left(\mathbf{v}, a_1\right)$, furthermore, $\dot{V}_1 = 0$ if and only if $\mathbf{v} = 0_{3\times1}$. Now $\mathbf{v} = 0_{3\times1}$ implies that

$$\frac{1}{k_2}\mathrm{sat}_{\mathrm{gd}}\left(k_0\tilde{\mathbf{p}}_{\mathrm{wp}} + k_1\mathrm{A}\tilde{\mathbf{p}}_{\mathrm{wp}}, a_0\right) = 0_{3\times1} \qquad (1)$$

Thus, the invariant set theorem indicates that the system converges globally to $(\mathbf{p}, \mathbf{v})$, where $\mathbf{p}$ is the solution to equation (1) and $\mathbf{v} = 0_{3\times1}$. The parameters k_0, k_1, k_2 will achieve a trade-off convergence between to the path and to the goal waypoint.

1. Fully-Autonomous Control

☐ Path Planning

（2） Straight-line path following

2） Algorithm design

The pseudo control input can be written as a PD controller as

$$\mathbf{u} = -\frac{k_1'}{k_2}(\mathbf{p}-\mathbf{p}_{\mathrm{d}}) - \frac{1}{k_2}\mathrm{sat}_{\mathrm{gd}}(\mathbf{v}, a_1)$$

where

$$\boxed{\mathbf{p}_{\mathrm{d}} = \mathbf{p} + \frac{1}{k_1'}\mathrm{sat}_{\mathrm{gd}}\left(k_0(\mathbf{p}_{\mathrm{wp}}-\mathbf{p}) + k_1(\mathbf{p}_{\mathrm{wp,perp}}-\mathbf{p}), a_0\right)}$$

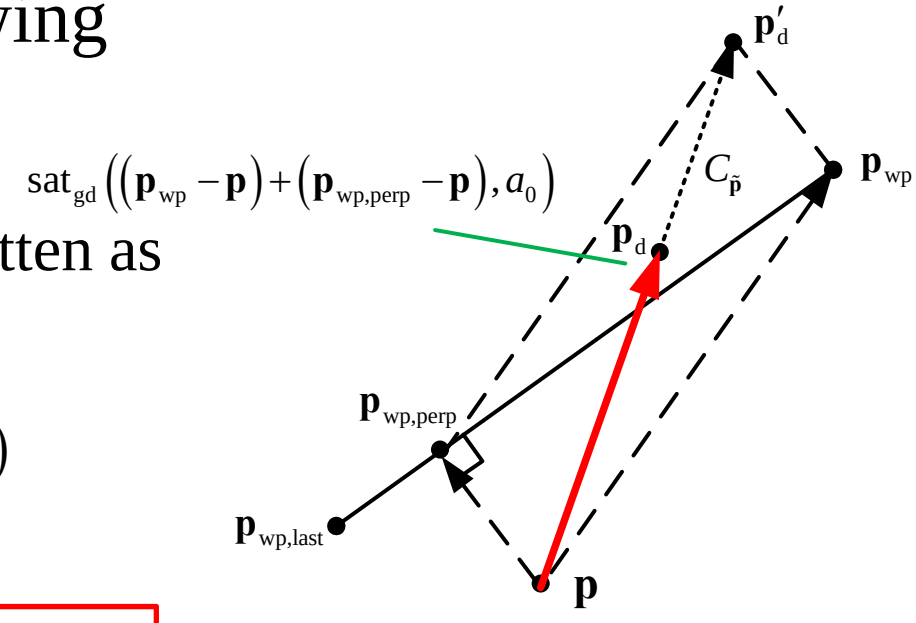


Figure 13.11 The physical meaning of $\mathbf{p}_{\mathrm{d}}$

Let $1/k_1' = k_0 = k_1 = 1$, the physical meaning of $\mathbf{p}_{\mathrm{d}}$ is shown in Figure 13.11.

1. Fully-Autonomous Control

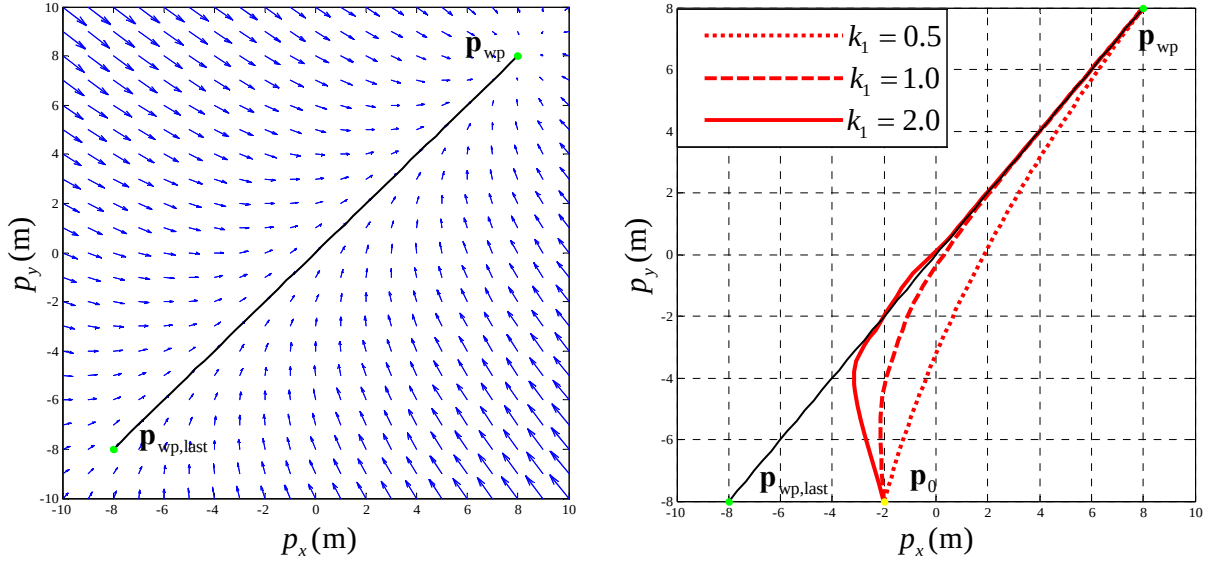
$$\mathbf{p}_{\mathrm{d}} = \mathbf{p} + \frac{1}{k_1'}\mathrm{sat}_{\mathrm{gd}}\left(k_0\left(\mathbf{p}_{\mathrm{wp}} - \mathbf{p}\right) + \boxed{k_1}\left(\mathbf{p}_{\mathrm{wp,perp}} - \mathbf{p}\right), a_0\right)$$

□ Path Planning

（2） Straight-line path following

3） Simulation

A higher k1 makes the multicopter approach the path faster.



(a) APF

(b) Three flying trajectories from $\mathbf{p}_0$ to $\mathbf{p}_{\mathrm{wp}}$

Figure 13.12 Straight-line path following by the proposed method

1. Fully-Autonomous Control

□ Path Planning

（3）Obstacle avoidance

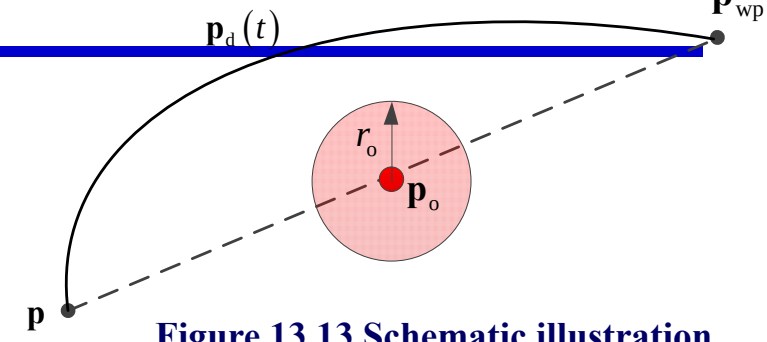


Figure 13.13 Schematic illustration of Straight-line path following

1） Problem formulation

Let $\mathbf{p} \in \mathbb{R}^3$ be the current position of a multicopter, $\mathbf{p}_{wp} \in \mathbb{R}^3$ be the goal waypoint. Design $\mathbf{u}$ to guide the multicopter to fly towards the goal waypoint $\mathbf{p}_{wp} \in \mathbb{R}^3$, meanwhile, avoid a obstacle modeled as a sphere with radius $r_o \in \mathbb{R}_+$ and center $\mathbf{p}_o \in \mathbb{R}^3$.

2） Two assumptions

1. Multicopter is not located in the obstacle
2. Goal waypoint has a certain distance from the obstacle.

Assumption 13.1. The initial position $\mathbf{p}_0 \in \mathbb{R}^3$ satisfies $(\mathbf{p}_o - \mathbf{p}_0)^T(\mathbf{p}_o - \mathbf{p}_0) - r_o^2 > 0$

Assumption 13.2. The desired waypoint $\mathbf{p}_{wp}$ satisfies $\dfrac{1}{(\mathbf{p}_o - \mathbf{p}_{wp})^T(\mathbf{p}_o - \mathbf{p}_{wp}) - r_o^2} \approx 0$

1. Fully-Autonomous Control

☐ Path Planning

（3） Obstacle avoidance

3） Algorithm design

Define $\tilde{\mathbf{p}}_{\mathrm{o}} = \mathbf{p} - \mathbf{p}_{\mathrm{o}}$. The saturation on control needs to be considered. A function is designed as

$$V_2 = \underbrace{k_0 \int_{C_{\tilde{\mathrm{p}}}} \mathrm{sat}_{\mathrm{gd}}\left(\tilde{\mathbf{p}}_{\mathrm{wp}}, a_0\right)^{\mathrm{T}} \mathrm{d}\tilde{\mathbf{p}}_{\mathrm{wp}}}_{\text{Get close to the waypoint}} + \underbrace{\frac{k_1}{2} \frac{1}{\tilde{\mathbf{p}}_{\mathrm{o}}^{\mathrm{T}} \tilde{\mathbf{p}}_{\mathrm{o}} - r_{\mathrm{o}}^2}}_{\text{Avoid the obstacle}} + \frac{k_2}{2} \mathbf{v}^{\mathrm{T}} \mathbf{v}$$

By *Assumption 13.1*, the“Avoid the obstacle”term is bounded at the initial moment of time. If the function is always bounded, then $(\mathbf{p}_{\mathrm{o}} - \mathbf{p})^{\mathrm{T}} (\mathbf{p}_{\mathrm{o}} - \mathbf{p}) > r_{\mathrm{o}}^2$, that is, the multicopter will not collide with the obstacle.

1. Fully-Autonomous Control

□ Path Planning

（3）Obstacle avoidance

3）Algorithm design

The derivative of V_2 is $\dot{V}_2 = k_0 \mathrm{sat}_{\mathrm{gd}}\left(\tilde{\mathbf{p}}_{\mathrm{wp}}, a_0\right)^{\mathrm{T}} \mathbf{v} - \dfrac{k_1}{\left(\tilde{\mathbf{p}}_{\mathrm{o}}^{\mathrm{T}}\tilde{\mathbf{p}}_{\mathrm{o}} - r_{\mathrm{o}}^2\right)^2}\tilde{\mathbf{p}}_{\mathrm{o}}^{\mathrm{T}}\mathbf{v} + k_2\mathbf{v}^{\mathrm{T}}\mathbf{u}$

If $\mathbf{u}$ satisfies

$$\mathbf{u} = -\frac{k_0}{k_2}\mathrm{sat}_{\mathrm{gd}}\left(\tilde{\mathbf{p}}_{\mathrm{wp}}, a_0\right) + \frac{k_1}{k_2\left(\tilde{\mathbf{p}}_{\mathrm{o}}^{\mathrm{T}}\tilde{\mathbf{p}}_{\mathrm{o}} - r_{\mathrm{o}}^2\right)^2}\tilde{\mathbf{p}}_{\mathrm{o}} - \frac{1}{k_2}\mathrm{sat}_{\mathrm{gd}}\left(\mathbf{v}, a_1\right)$$

then $\boxed{\dot{V}_2 = -\mathbf{v}^{\mathrm{T}}\mathrm{sat}_{\mathrm{gd}}\left(\mathbf{v}, a_1\right) \le 0}$.Because of $\dot{V}_2 \le 0$ and $V_2(0) > 0$, The Lyapunov function satisfies $V_2(t) \le V_2(0), t \in [0, \infty)$.This implies $0 < \dfrac{k_1}{2V_2(0)} \le \tilde{\mathbf{p}}_{\mathrm{o}}^{\mathrm{T}}\tilde{\mathbf{p}}_{\mathrm{o}} - r_{\mathrm{o}}^2$, that is, the pseudo control $\mathbf{u}$ can guide the multicopter avoid obstacle.

1. Fully-Autonomous Control

☐ Path Planning

$$\mathbf{u} = -\frac{k_0}{k_2}\mathrm{sat}_{\mathrm{gd}}\left(\tilde{\mathbf{p}}_{\mathrm{wp}}, a_0\right) + \frac{k_1}{k_2\left(\tilde{\mathbf{p}}_{\mathrm{o}}^{\mathrm{T}}\tilde{\mathbf{p}}_{\mathrm{o}} - r_{\mathrm{o}}^2\right)^2}\tilde{\mathbf{p}}_{\mathrm{o}} - \frac{1}{k_2}\mathrm{sat}_{\mathrm{gd}}\left(\mathbf{v}, a_1\right)$$

（3）Obstacle avoidance

3）Algorithm design

Furthermore, $\dot{V}_2 = 0$ if and only if $\mathbf{v} = 0_{3\times1}$. Now $\mathbf{v} = 0_{3\times1}$ implies that $\mathbf{u} = \mathbf{0}$, that is, $a\tilde{\mathbf{p}}_{\mathrm{wp}} + b\tilde{\mathbf{p}}_{\mathrm{o}} = 0$ （2） where

$$a = -\frac{k_0}{k_2}\kappa_{a_0}\left(\tilde{\mathbf{p}}_{\mathrm{wp}}\right), b = \frac{k_1}{k_2\left(\tilde{\mathbf{p}}_{\mathrm{o}}^{\mathrm{T}}\tilde{\mathbf{p}}_{\mathrm{o}} - r_{\mathrm{o}}^2\right)^2}, \kappa_a\left(\mathbf{x}\right) = \begin{cases} 1 & , \|\mathbf{x}\|_\infty \le a \\ \dfrac{a}{\|\mathbf{x}\|_\infty} & , \|\mathbf{x}\|_\infty > a \end{cases}$$

Thus, the invariant set theorem indicates that the system converges globally to $(\mathbf{p}, \mathbf{v})$, where $\mathbf{p}$ is the solution to equation (2) and $\mathbf{v} = 0_{3\times1}$. The parameters k_0, k_1, k_2 will achieve a trade-off convergence between convergence to the goal waypoint and obstacle avoidance.

1. Fully-Autonomous Control

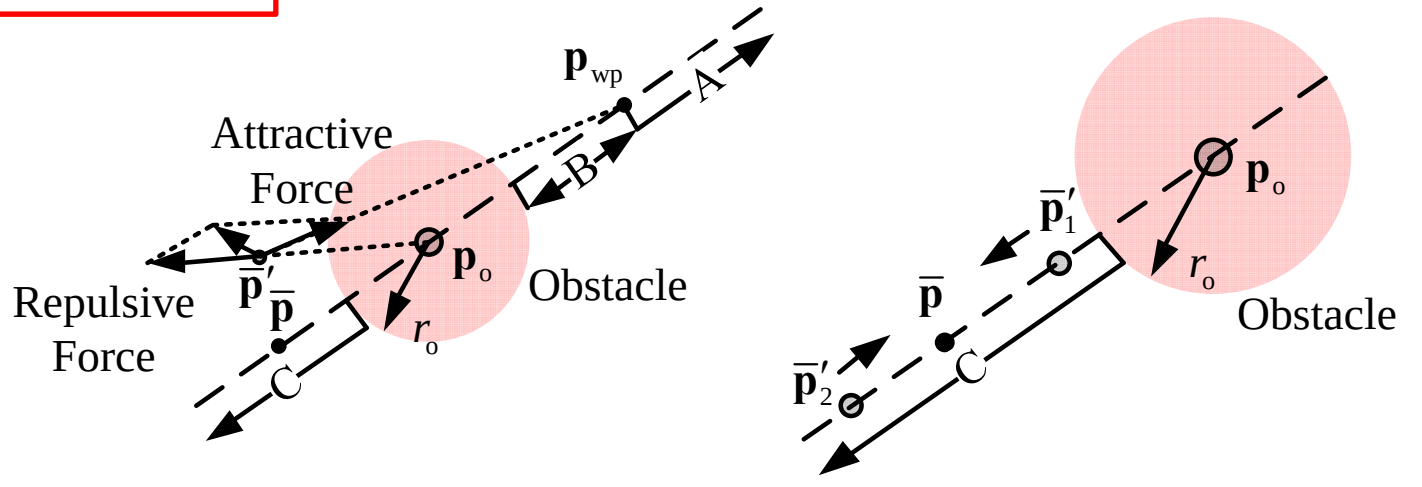
□ Path Planning

$\bar{\mathbf{p}}$ is unstable equilibrium point

$\mathbf{p}_{wp}$ the only stable equilibrium point

（3）Obstacle avoidance

$$a\tilde{\mathbf{p}}_{wp} + b\tilde{\mathbf{p}}_{o} = 0 \quad (2)$$



(a) Multicopter not in “C half-line”　　(b) Multicopter in “C half-line”

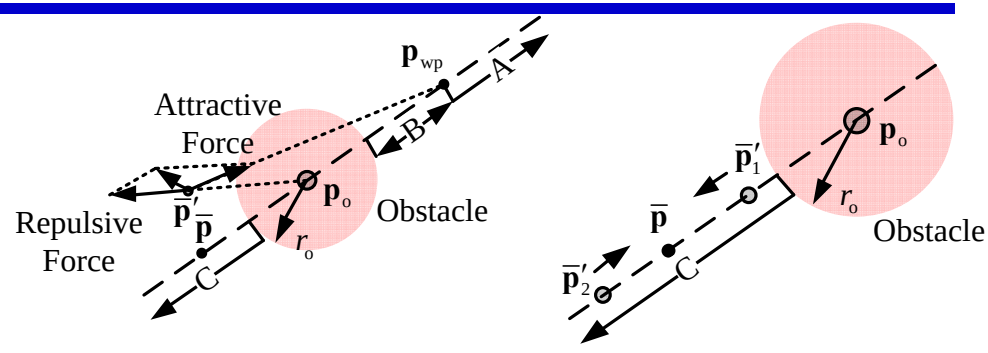
Figure 13.14 Schematic illustration of equilibrium points

1. Fully-Autonomous Control

☐ Path Planning

（3） Obstacle avoidance

3） Algorithm design



(a) Multicopter not in “C half-line” (b) Multicopter in “C half-line”

Figure 13.15 The physical meaning of $\mathbf{p}_d$

The pseudo control input can be written as a PD controller as

$$\mathbf{u} = -\frac{k_1'}{k_2}(\mathbf{p}-\mathbf{p}_d) - \frac{1}{k_2}\mathrm{sat}_{gd}(\mathbf{v}, a_1)$$

where

$$\mathbf{p}_d = \mathbf{p} + \frac{k_0}{k_1'}\mathrm{sat}_{gd}(\mathbf{p}_{wp}-\mathbf{p}, a_0) - \frac{k_1}{k_1'}\frac{1}{\left((\mathbf{p}-\mathbf{p}_o)^T(\mathbf{p}-\mathbf{p}_o)-r_o^2\right)^2}(\mathbf{p}_o-\mathbf{p})$$

Let $k_0/k_1' = k_1/k_1' = 1$, the physical meaning of $\mathbf{p}_d$ is shown in Figure 13.15.

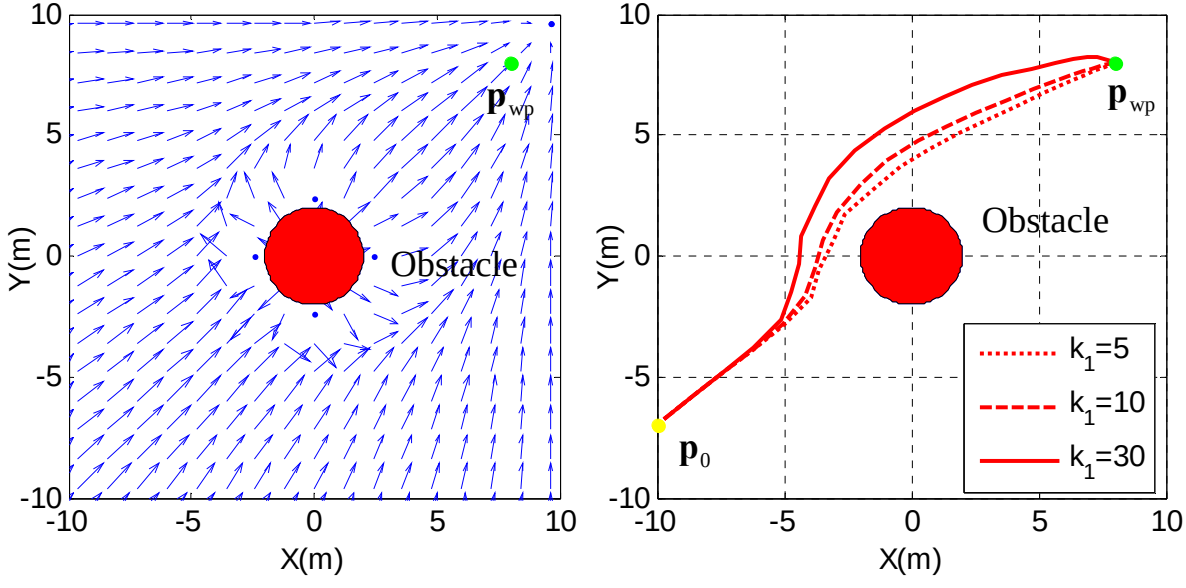
1. Fully-Autonomous Control

☐ Path Planning

（3） Obstacle avoidance

4） Simulation

A higher k_1 makes the multicopter circumvent the obstacle much faster!



(a) APF

(b) Three obstacle avoidance trajectories from $\mathbf{p}_0$ to $\mathbf{p}_{wp}$

Figure 13.16 Obstacle avoidance by the APF method

1. Fully-Autonomous Control

☐ Synthesis

In practice, a multicopter always needs not only to follow the desired path but also to avoid both fixed and moving obstacles. The algorithm can be obtained by the superposition of potential fields of the path, the goal waypoint and obstacles. The details of the synthesis algorithm please see the reference book.

2. Semi-Autonomous Control

☐ Three Modes of SAC Manner

In fact, the SAC manner consists of Automatic Control (AC) and Radio Control (RC), and a multicopter in the SAC manner is controlled by either AC or RC. Generally, according to the degree of the AC, a multicopter in SAC manner can be in one of three main modes:

- Stabilize Mode
- Altitude Hold Mode
- Loiter Mode

2. Semi-Autonomous Control

☐ Three Modes of SAC Manner

Generally, according to the degree of the AC, a multicopter in SAC manner can be in one of three main modes：

- Stabilize Mode
- Altitude Hold Mode
- Loiter Mode

- Under RC, an RC transmitter is used to control its roll/pitch and then drive the multicopter to tilt towards the desired direction. When the remote pilot releases the roll and pitch control sticks, the multicopter automatically switches itself to AC. Then, its attitude will be stabilized but the position drift will occur. During this process the remote pilot will need to regularly give roll, pitch and throttle commands to keep the multicopter in place as it is pushed around by wind.
- If the remote pilot puts the throttle completely down, then the motors will operate at their minimum rate and if the multicopter is in the air it will lose altitude control and tumble.

2. Semi-Autonomous Co

☐ Three Modes of SAC Manner

Generally, according to the degree of the AC, a multicopter in SAC manner can be in one of three main modes：

- Stabilize Mode
- Altitude Hold Mode
- Loiter Mode

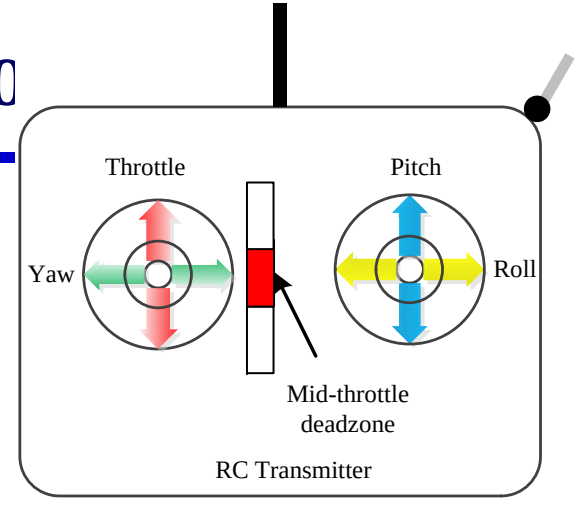


Figure 13.17 Schematic illustration of sticks in RC transmitter

- As shown in Figure 13.13, When the throttle control stick is in the mid-throttle deadzone (40% ～60%), the multicopter automatically switches itself to AC. Then the throttle is automatically controlled to maintain the current altitude but the horizontal position drift will occur. The remote pilot will need to regularly give roll and pitch commands to keep the multicopter in place.
- Going outside of the mid-throttle deadzone, the multicopter will enter RC, that is, the multicopter will descend or climb depending upon the deflection of the control stick. The altitude hold mode needs the support of height sensors, such as barometers and ultrasonic rang finders.

2. Semi-Autonomous Control

☐ Three Modes of SAC Manner

Generally, according to the degree of the AC, a multicopter in SAC manner can be in one of three main modes：

- Stabilize Mode
- Altitude Hold Mode
- Loiter Mode

- The loiter mode automatically attempts to maintain the current position, heading and altitude. When the remote pilot releases the roll, pitch and yaw control sticks and pushes the throttle control stick to the mid-throttle deadzone, the mul ticopter will automatically switch itself to AC and maintain the current location, heading and altitude. Precise GPS position, low magnetic interference on the compass and low vibrations are all important in achieving a good hovering performance.
- The remote pilot can control the multicopter's position once by pushing the control sticks out of the mid- points. The loiter mode needs the support from both the height sensors and position sensors like GPS and cameras.

2. Semi-Autonomous Control

☐ Radio Control (RC)

- Define $(\cdot)_{\mathrm{d}}, (\cdot)_{\mathrm{drc}}$ to be desired values and RC values, respectively. In the SAC manner, the throttle/yaw control sticks and roll/pitch control sticks are manipulated to specify the desired total thrust $f_{\mathrm{d}} = f_{\mathrm{drc}}$, the desired yaw rate $\dot{\psi}_{\mathrm{d}} = \dot{\psi}_{\mathrm{drc}}$, the desired roll angle $\phi_{\mathrm{drc}} = u_{\phi}$ and the desired pitch angle $\theta_{\mathrm{drc}} = u_{\theta}$.
- In a direct-type RC transmitter, the throttle control stick can stop at any position when it is not pushed and the total thrust is proportional to the deflection of throttle control stick.
- In addition, some multicopters use the increment-type throttle to control the total thrust. In increment-type throttle transmitter, the control stick can turn back to the midpoint automatically if it is released and the throttle control stick position is proportional to the desired vertical speed or thrust rate instead of the desired total thrust.

2. Semi-Autonomous Control

☐ Radio Control (RC)

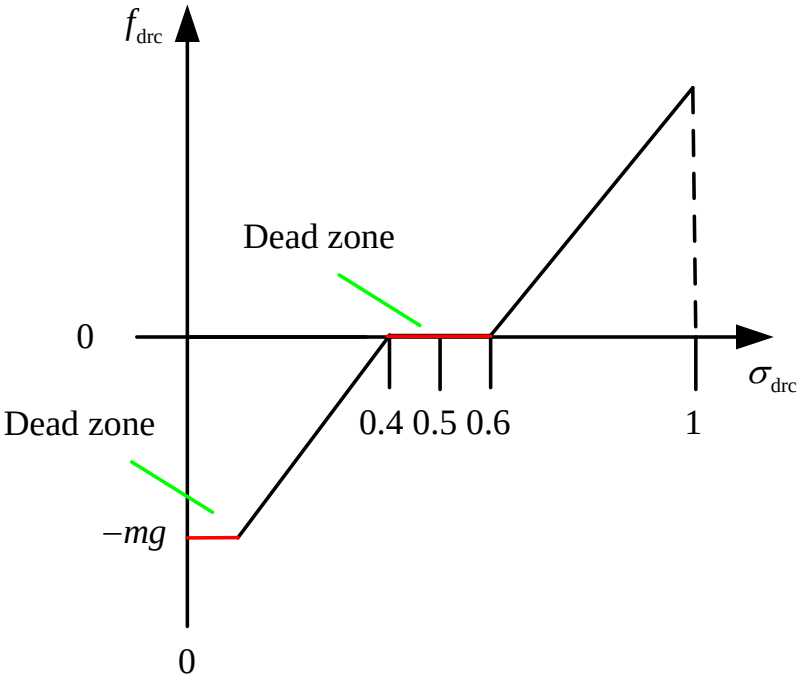


Figure 13.18 The relationship between the position percentage and the throttle control value

Here, $\sigma_{drc} \in [0,1]$ is the deflection of throttle control stick, where $\sigma_{drc} = 0.5$ represents the midpoint. If $\sigma_{drc} \in [0.4, 0.6]$, then $f_{drc}(\sigma_{drc}) = 0$. Then, AC starts to introduce the feedback in altitude for altitude hold. Here, the feedforward mg has been given by AC, so f_{drc} starts from $-mg$ as shown in Figure 13.11. The dead zone is used to reduce the effect by slight change of the throttle control stick. Similarly, other control sticks should also have dead zones.

2. Semi-Autonomous Control

☐ Automatic Control (AC)

- When all control sticks are close to their midpoints, the AC takes over the control of the multicopter. In fact, no matter which mode of SAC manner is active, the decision-making module will produce the desired hover position $\mathbf{p}_{\mathrm{dac}}$ and yaw ψ_{dac}.
- On the other hand, the state estimation module will produce the position estimate $\hat{\mathbf{p}} = \begin{bmatrix} \hat{p}_x & \hat{p}_y & \hat{p}_z \end{bmatrix}^{\mathrm{T}}$ and attitude estimate $\hat{\mathbf{\Theta}} = \begin{bmatrix} \hat{\phi} & \hat{\theta} & \hat{\psi} \end{bmatrix}^{\mathrm{T}}$. The AC aims to drive the multicopter so that

$$\lim_{t\to\infty} \left\| \hat{\mathbf{p}}(t) - \mathbf{p}_{\mathrm{dac}}(t) \right\| = 0 \text{ and } \lim_{t\to\infty} \left\| \hat{\psi}(t) - \psi_{\mathrm{dac}}(t) \right\| = 0$$

are satisfied. Thus, AC structures for the three modes of SAC could be the same. However, due to different sensors are used, the estimation accuracies are different for the three modes.

2. Semi-Autonomous Control

☐ Automatic Control (AC)

（1） Stabilize Mode

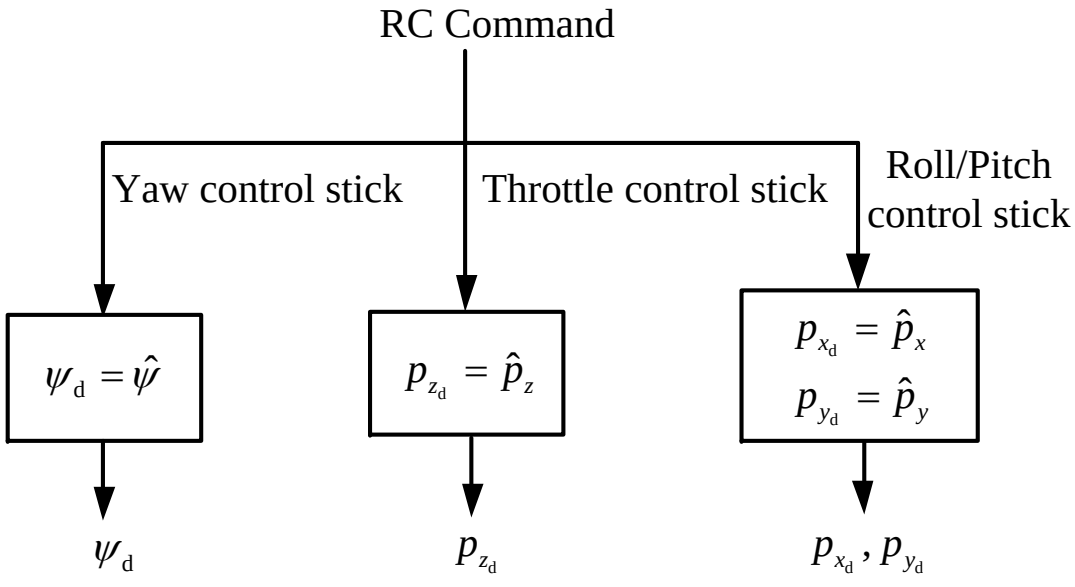


Figure 13.19 The principle of producing the desired position and yaw angle in stabilize mode

The stabilize mode produces the desired thrust and moments according to the desired position $\mathbf{p}_d = \hat{\mathbf{p}}$ and desired yaw $\psi_d = \hat{\psi}$.

As shown in Figure 13.19, the autopilot can produce the desired position $\mathbf{p}_d$ and yaw angle ψ_d according to the RC commands.

2. Semi-Autonomous Control

☐ Automatic Control (AC)

（1） Stabilize Mode

By recalling the controllers proposed in (11.14) and (11.19) in Lesson 11, the horizontal position controller is

$$\Theta_{\mathrm{hd}} = -g^{-1}\mathbf{A}_{\psi}^{-1}\left(-\mathbf{K}_{\mathbf{p}\mathrm{hd}}\dot{\hat{\mathbf{p}}}_{\mathrm{h}} - \mathbf{K}_{\mathbf{p}\mathrm{hp}}\left(\hat{\mathbf{p}}_{\mathrm{h}} - \hat{\mathbf{p}}_{\mathrm{hd}}\right)\right)$$

and the altitude controller is

$$\boxed{f_{\mathrm{d}} = -m\left(-k_{p_z\mathrm{d}}\dot{\hat{p}}_z - k_{p_z\mathrm{p}}\left(\hat{p}_z - p_{z_{\mathrm{d}}}\right)\right)}$$

Since $\mathbf{p}_{\mathrm{d}} = \hat{\mathbf{p}}$, the horizontal position controller and altitude controller become

$$\boxed{\begin{aligned}\Theta_{\mathrm{hd}} &= g^{-1}\mathbf{A}_{\psi}^{-1}\mathbf{K}_{\mathbf{p}\mathrm{hd}}\dot{\hat{\mathbf{p}}}_{\mathrm{h}}\\ f_{\mathrm{d}} &= mg + mk_{p_z\mathrm{d}}\dot{\hat{p}}_z\end{aligned}}$$

2. Semi-Autonomous Control

☐ Automatic Control (AC)

（1） Stabilize Mode

Generally, let $\mathbf{\Theta}_{\mathrm{hd}} = [\phi_{\mathrm{d}} \quad \theta_{\mathrm{d}}]^{\mathrm{T}} = \mathbf{0}_{2\times1}$, because $\dot{\hat{\mathbf{p}}}_{\mathrm{h}}$ may be unavailable or inaccurate, or the magnetometer is unavailable. This implies that AC can make the multicopter self-level. Moreover, AC cannot hold the altitude anymore but just controls the vertical speed to zero. A simple yaw controller has the form as

$$\tau_z = -k_{\dot{\psi}}\dot{\psi}$$

Stabilize mode cannot make the multicopter hover steadily due to lack of feedback of the horizontal position signal. This mode is often used when without GPS and height sensors or they fail.

2. Semi-Autonomous Control

☐ Automatic Control (AC)

（2） Altitude Hold Mode

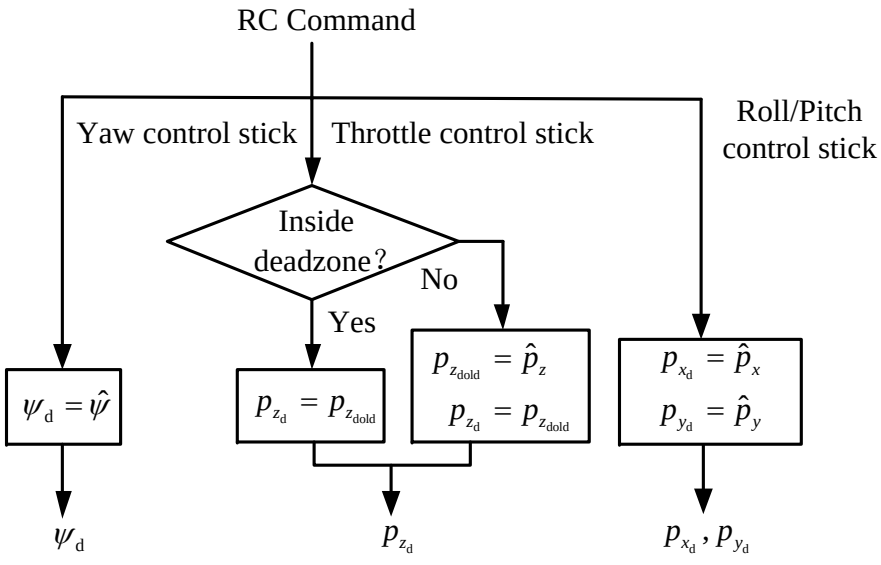


Figure 13.20 The principle of producing the desired position and yaw angle in altitude hold mode

The altitude hold mode produces the desired thrust and moment according to the desired altitude $p_{z_d} = p_{z_{dold}}$, horizontal position $\mathbf{p}_{hd} = \hat{\mathbf{p}}_h$ and yaw angle $\psi_d = \hat{\psi}$ where $\mathbf{p}_{hd} = \hat{\mathbf{p}}_h$ implies $\theta_d = 0, \phi_d = 0$

The time, denoted by t_d is recorded when the throttle control stick turns back to the midpoint, then, the altitude estimate $\hat{p}_z(t_d)$ is saved as $p_{z_{dold}} = \hat{p}_z(t_{zd})$.

2. Semi-Autonomous Control

☐ Automatic Control (AC)

（2） Altitude Hold Mode

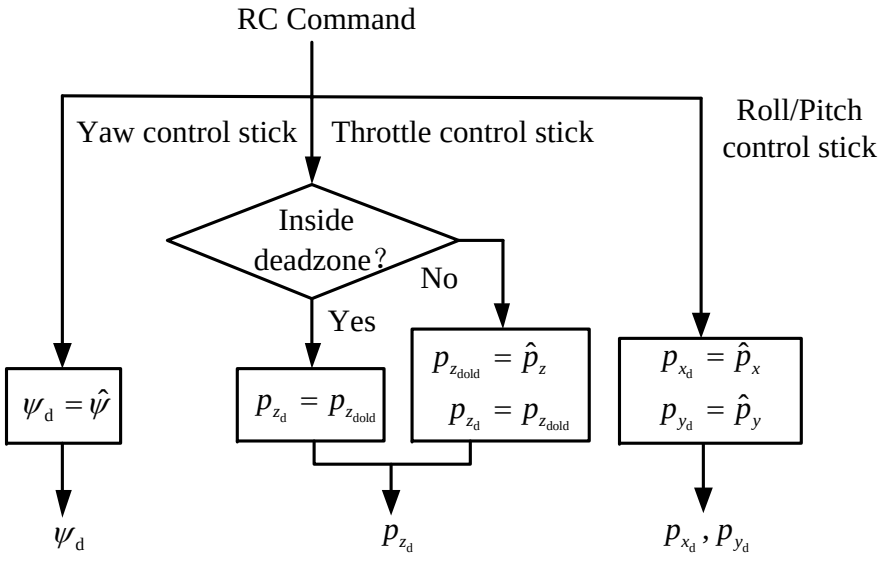


Figure 13.21 The principle of producing the desired position and yaw angle in altitude hold mode

At the same time, altitude hold mode starts to hold the multicopter's altitude at $p_{z_d} = p_{z_{dold}}$. Just like the stabilize mode, the altitude hold mode cannot make the multicopter hover for lack of feedback in the horizontal position. The altitude hold mode is often used when the height sensors are available while position sensors are missing or electronic compasses are unavailable.

2. Semi-Autonomous Control

☐ Automatic Control (AC)

（3）Loiter Mode

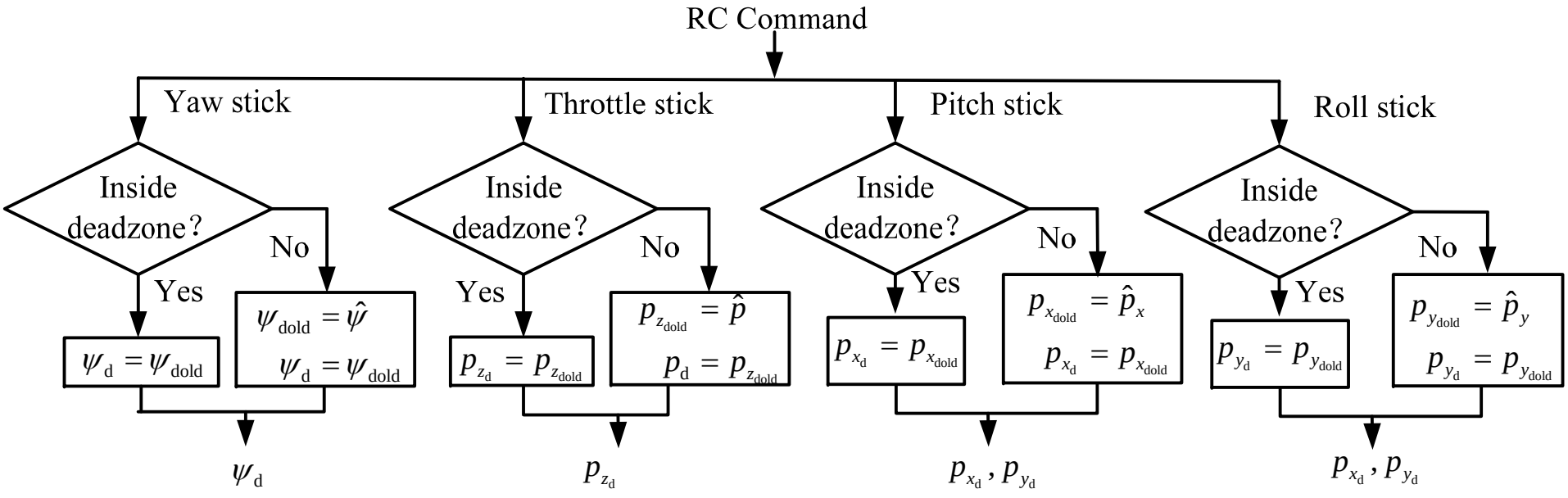


Figure 13.22 The principle of producing the desired position and yaw angle in loiter mode

2. Semi-Autonomous Control

☐ Switching Logic between RC and AC

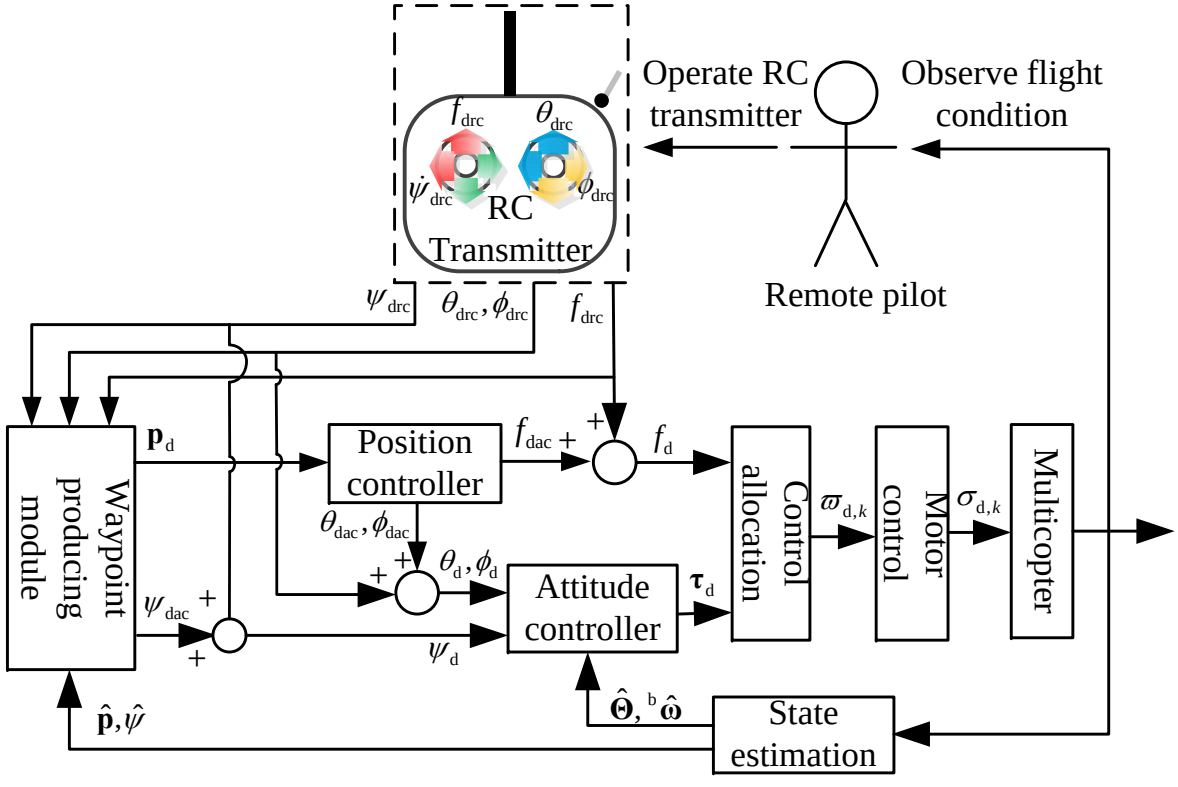


Figure 13.23 The closed loop control block diagram in the SAC manner

（1） Yaw command switching logic

$$\psi_d = \psi_{dap} + \psi_{drc}$$

$\psi_{dap} = \hat{\psi}$ $\quad$ $\psi_{drc} = \dot{\psi}_{drc}\Delta t$

or $\psi_{dac} = \psi_{dold}$ $\quad$ **RC command**

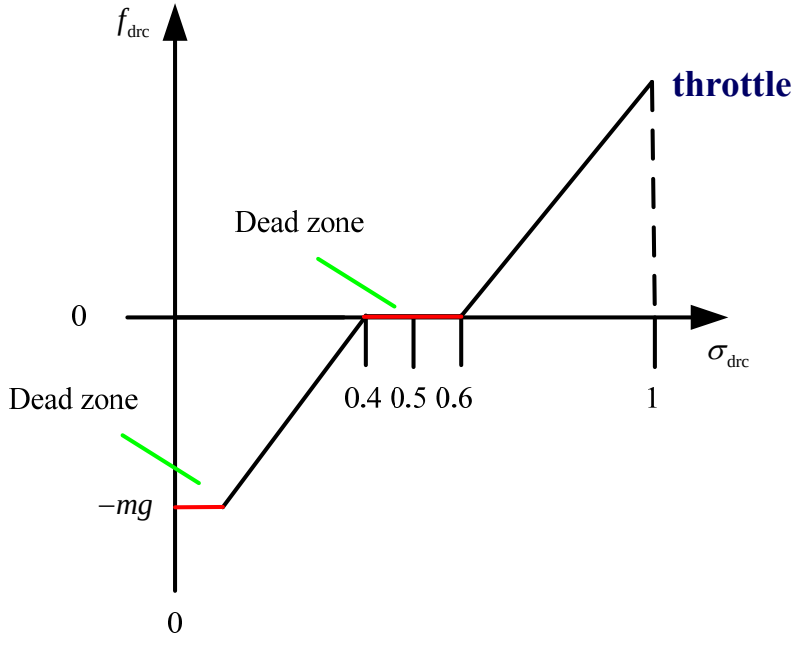
2. Semi-Autonomous Control

☐ Switching Logic between RC and AC

（2） Throttle command switching logic

$$f_{\mathrm{d}} = f_{\mathrm{dap}} + f_{\mathrm{drc}}\left(\sigma_{\mathrm{drc}}\right)$$

AC command **RC command**



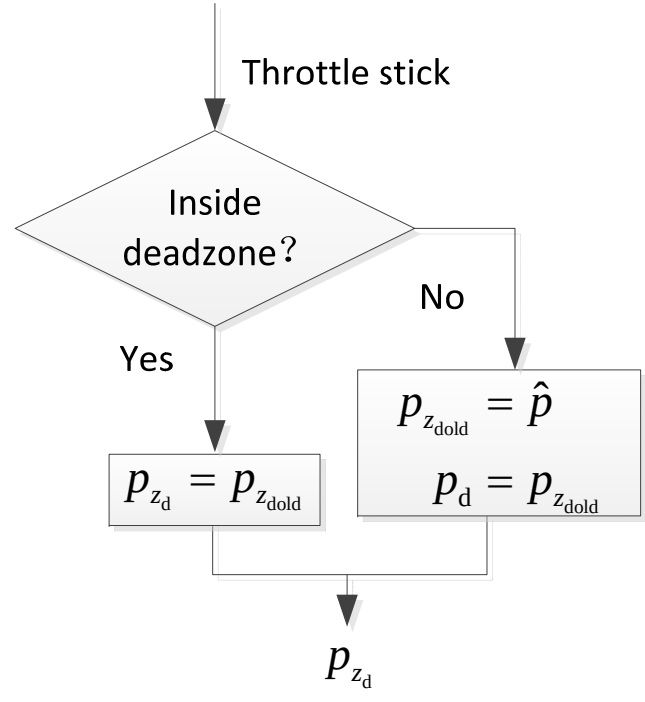


Figure 13.24 Switching logic of desired altitude

2. Semi-Autonomous Control

☐ Switching Logic between RC and AC

（3） Roll/Pitch command switching logic

$$\boxed{\begin{aligned}\theta_{\mathrm{d}} &= \theta_{\mathrm{dac}} + \theta_{\mathrm{drc}} \\ \phi_{\mathrm{d}} &= \phi_{\mathrm{dac}} + \phi_{\mathrm{drc}}\end{aligned}}$$

- As shown in Figure 13.18, the total roll/pitch command is

  where θ_{dac} and ϕ_{dac} are produced by AC in autopilot, and θ_{drc} and ϕ_{drc} represent the command from the RC transmitter.
- Take the pitch control stick as an example. When the pitch control stick is at its mid-point, $\theta_{\mathrm{drc}} = 0$, the autopilot will control the pitch to θ_{dac} depending on which mode the autopilot is in.
- Once the pitch control stick leaves its midpoint, $p_{x_{\mathrm{d}}} = \hat{p}_x$. Then the AC does not offer the feedback in horizontal location except for velocity feedback. This implies that RC will take over the control of the horizontal channel completely.

3. Conclusion

1. Mission planning or automatic flight control for single multicopter is relatively simple.
2. In recent years, researchers have successfully presented the cooperative control among multiple multicopters in a controlled laboratory environment.
3. In order to realize the full-autonomous mission planning, the following prerequisites have to be satisfied:

（1） Each multicopter is adequately reliable;

（2） Position and attitude of each multicopter are estimated accurately;

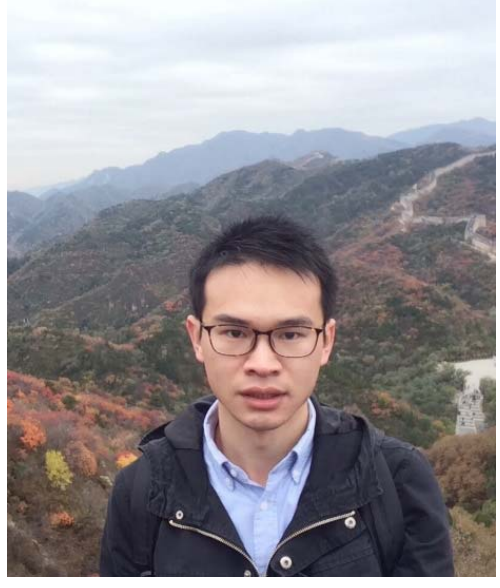
（3） Endurance of flight is long enough and each multicopter has Battery Management System to evaluate its health;

（4） Fast-charging stations are built and the charging is accomplished automatically.

Acknowledgement

Deep thanks go to

Yan Jiang



Xunhua Dai

for material preparation.

Thank you!

All course PPTs and resources can be downloaded at
http://rfly.buaa.edu.cn/course

For more detailed content, please refer to the textbook:

Quan, Quan. Introduction to Multicopter Design and Control. Springer, 2017. ISBN: 978-981-10-3382-7.

It is available now, please visit http://
www.springer.com/us/book/9789811033810