TRAJECTORY GENERATION AND CONTROL FOR PERCHING MANEUVERING WITH QUADROTOR

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Abstract

Micro quadrotors have great applications in the area of military events, civil use and scientific research due to its tiny size, agility and portability. However, miniaturization reduces the space of energy storge, leading to the loss of endurance and deterioration of deployment performance. Perching maneuvering, originating from birds perching, is a hot topic for exploring the solution for extending the endurance of micro quadrotor. This method aims to take the advantage of maneuverability to achieve perching the quadrotor on the inclined or vertical surface with the help of perching mechanism. When perching, interaction force from vertical surface could afford the gravity of quadrotor and there is no need to maintain the aerodynamics. Therefore, motors could be turned off and energy consumption would be much less than flight. Perching maneuvering involves complex problems such as motion control. In this paper, perching control is solved by trajectory generation and track control. First, dynamics model is built to describe the motion of perching quadrotor and the model is further simplified into longitudinal model. Then, planning trajectory is generated and initial state is set with reference to the perching restrictions. Finally, geometry control method is applied to achieve the tracking control and modified method is also brought up to make the track more precisely, which is verified in the Simulink experiments.

Keywords: Micro Quadrotor, Perching Maneuvering, Trajectory Generation, Tracking Control.

1. Introduction

1.1 Background

Micro quadrotor, a current hot topic, has great applications in military events, civil use and scientific research. In military events, quadrotors could be equipped with squad or soldiers, executing the tasks of inspection and destruction. For civil use, quadrotors play the role as mapping, monitoring, data gathering or air camera. In scientific research, quadrotors turn into an ideal platform for multidisciplinary integration, including concept design, flight control, sensor, navigation, MEMS technology, et al. Although bringing advantages in maneuverability and portability, miniaturization also causes shrinking energy storge space, leading to discount in endurance and deterioration of performance. There-fore, there is great need to explore the solution to extend the endurance of micro quadrotor with tiny size.

Originated from bird perching behavior, perching maneuvering is an effective method to extend the endurance for micro quadrotor. This bionic strategy, imitating the bird landing on the ground or branches, give quadrotor the ability to perch on the surface of room and buildings with the aid of perching mechanism. When perching, resting quadrotor no longer requires thrust from rotor because the gravity will be afforded by the interaction force from the surface. Therefore, rotors could be turned off in perching, which means much less energy consumption and longer endurance.

1.2 Research status of perching quadrotor

Domestic and foreign study about perching maneuvering concentrates on perching mechanism, motion planning and control design. To generate the attachment force, researchers develop the mechanism that could make use of macroscopic interaction, van der Waals force and atmosphere pressure. Morgan from Stanford combined the quadrotor with micro spines and developed the multi-modal robot that could fly, perch and climb on outdoor surface. Hawkes developed the dry adhesive pad, utilizing the van der Waals force. Directional adhesive comes when shear force is applied in the

correct direction to turn the adhesive "ON". In order to support normal loads without shear, the grasper must use multiple tiles of directional adhesive which are loaded with internal shear forces in opposing directions. Wopereis designed the passive vacuum cups and achieved perching on smooth surfaces using aerial impacts. In detachment, a servomotor pulls the wire allowing air to leak under the vacuum cup. This enables the system to detach. For motion planning, Justin Thomas present con-trol and planning algorithms for maneuvering to land on specified surfaces while satisfying constraints on actuation and sensing. Daniel Mellinger developed a family of trajectories defined as a sequence of segments, each with a controller parameterized by a goal state. Each controller is developed from the dynamic model of the robot and then iteratively refined through successive experimental trials to account for errors in the dynamic model and noise in the actuators and sensors. For controller design, GRASP Laboratory of University of Pennsylvania proposed trajectory planning algorithm using the property of differential flatness and geometry tracking con-troller that could guide the quadrotor to fly along the desired trajectory. Daniel Mellinger defined perching as a sequence of segments and developed controller for each segment, which greatly lowers the level of difficulty in control design.

1.3 Arrangement

In this paper, we focus on the quadrotor perching maneuver, exploring the solution to successful perching. First, dynamic equations are derived to describe longitudinal motion in perching. Then, trajectory generation method is proposed based on the open-loop response. Finally, we introduce the theory of geometry tracking control and put forward the modified control algorithm. Simulation results are also provided to validate the proposed techniques.

2. Modeling of Perching Quadrotor

2.1 Concept of Quadrotor Perching

Perching maneuvering, shown in Fig1 describes a process that quadrotor flies to the vertical surface while pitches itself up to orient the perching mechanism toward the surface. When the quadrotor touches the surface, it will pitch up to 90 degrees and perching mechanism will attach itself to the vertical surface tightly in some manner. When perching, quadrotor could execute the mission such as inspection, data gathering or communications relay. If quadrotor finishes the task, it will detach the surface and take off to fly again.
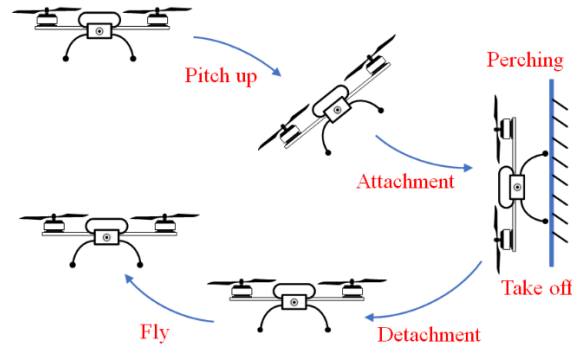

Fig. 1 Illustration of Quadrotor Perching on Vertical Surface

2.2 Parameters of Quadrotor

The quadrotor we use in this paper is a custom-made robot. Its parameters are listed in Table 1.

Table 1 Parameters of Quadrotor

Name	Symbol	Parameter	Unit
Mass	m	0.235	kg
Inertia	I	0.002	$kg \cdot m^2$
Length	L	0.075	m
gravitational acceleration	g	9.82	N/kg
Coefficient of thrust	C_F	0.0015	$N \cdot s^2$
Coefficient of moment	C_M	0.0002	$N \cdot s^2$

2.3 Motor Modeling

Quadrotor has four rotors and each rotor has its own angular speed   and generates thrust   and moment according to

$$F_i = C_F \omega_i^2, i = 1, 2, 3, 4,$$

$$M_i = C_M \omega_i^2, i = 1, 2, 3, 4,$$

C_F and C_M are the coefficient of thrust and moment. Experiment with a fixed motor at steady state shows that C_F and C_M could be treated as constant.

The results from system identification point out that the rotor speed is related to the command speed by a first-order differential equation, written as

$$\dot{\omega}_i = k_m \left(w_i^{des} - w_i \right).$$

This motor gain, k_m, is found to be 20s^{-1} by matching the performance of the simulation to the real system. The desired angular speed, w_i^{des}, is limited to the minimum and maximum value of the electric motor through the experiments.

2.4 Coordinate System

To describe the motion of perching, ground coordinate system and body coordinate system are used in this paper, as shown in Fig 2. Two coordinate systems are defined as follows:

(1) Ground coordinate system $O_g x_g y_g z_g$: This system is fixed on the earth and original point of this coordinate, O_g, is located on the position we concern. x_g, y_g and z_g will be set by the law of right-handed coordinate system.

(2) Body coordinate system $O_b x_b y_b z_b$: This system is fixed on the body of quadrotor and original point of this coordinate, O_b, is located on the center of gravity. x_b points to the front of quadrotor and y_b points to left. z_b is arranged by the law of right-handed coordinate system.
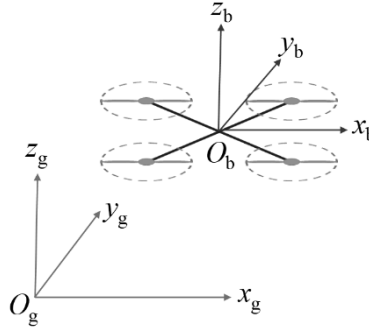

Fig. 2 Coordinate Systems for Quadrotor Dynamics Modeling

The relationship between these two coordinate systems can be expressed with position and attitude angel. The displacement vector, x, is defined as the coordinate of quadrotor barycenter in ground coordinate system, which can be written as the form of component, (x, y, z). Attitude angel is used to describe the rotation transformation between two systems, which can be expressed with roll(ϕ), pitch(θ) and yaw(ψ). Time rate of displacement vector, $\dot{x}$, will be written as (U, V, W) in ground coordinate systems and angular speed vector, Ω, will be written as (p, q, r) in body system or ($\dot{\theta}$, $\dot{\phi}$, $\dot{\psi}$) in ground system.

2.5 Longitudinal Dynamic Model

In this paper, perching maneuver is thought to be 2-D motion, especially the longitudinal motion in x_g - z_g coordinate plane, as shown in Fig 3. We model the quadrotor as rigid body and its longitudinal dynamic equations can be expressed as

$$F_x = \left(\sum F_i \right) \sin \theta = m \left(\partial U / \partial t \right),$$

$$F_z = \left(\sum F_i \right) \cos\theta - mg = m(\partial W / \partial t)$$

$$M = (F_3 + F_4 - F_1 - F_2) \cdot L / 2 = I(\partial q / \partial t) + Iq^2 .$$

m is the mass of quadrotor and I is the inertia according to the y_b. F_1 - F_4 represents thrust of four rotors and L is the distance between two rotors, half of which is the arm of rotor thrust.
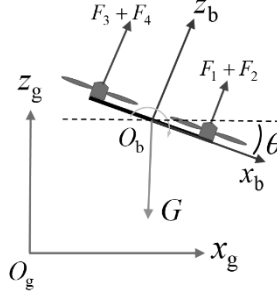

Fig. 3 Longitudinal Motion of of Perching Quadrotor

3. Method of Perching Trajectory Generation

Perching trajectory generation aims to find the feasible trajectory that could achieve the perching maneuver with constraints satisfied. This feasible trajectory will be the reference input for the controller. In this paper, feasible trajectory will be generated based on the guideline of open-loop trajectory and setting the initial states.

First, constraints such as maximum thrust of rotor and speed of attachment, are discussed so that following design could refer to these constraints. Next, to generate the open-loop trajectory, we bring up the estimation of time of flight and establish the time sequence of pitch and total thrust because acceleration is decided only by pitch and total. Then, trajectory is generated by marching with time and integrating. Finally, we could read the variation of different physical quantity. What we concern is the speed and pitch angle. Therefore, we solve the quantity that we concern and set the initial states in starting point with reference to the constraints.

In this chapter, we will explain the procedure in detail, including the constraints, flight time estimation, establish of time sequence of pitch and total thrust, and initial states arrangement.

3.1 Constraints of Perching Trajectory

To achieve successful maneuver, constraints need to be satisfied such as velocity and pitch angel. The concerned constraints are explained as below.

(1) Pitch and angular velocity at the moment of contact

At the moment of contact, quadrotor needs to pitch up to 90degrees to orient its perching mechanism towards the surface. Moreover, to reduce the vibration load in contact, quadrotor would be expected to land with negligible angular velocity. The constraints are expressed as

$$\theta_{contact} = \pi / 2 ,$$

$$\dot{\theta}_{contact} = 0 .$$

(2) Normal velocity at the moment of contact

At the moment of contact, perching mechanism needs to contact the wall with appropriate normal contact speed. The impact speed is required to land in the envelope of perching mechanism, because smaller speed will cause disabled perching, while larger speed may produce dynamic load that exceeds the capacity of mechanism. The constraints are expressed as

$$U_{min} \leq U_{contact} \leq U_{max} .$$

(3) Tangential velocity at the moment of contact

At the moment of contact, perching mechanism is expected to contact the wall with zero tangential speed, because in the test of Justin Thomas, it is shown that tangential speed will narrow the section of available normal contact speed. The constraints are expressed as

$$W_{contact} = 0 .$$

(4) Maximum thrust of rotor

Perching maneuver means quadrotor needs to manipulate itself to pitch up. The manipulation moment comes from the thrust and the maneuverability depend on the maximum thrust of rotor. To satisfy the requirement of perching, we need to select the type of rotor with enough thrust to execute the control output.

3.2 Perching Trajectory Generation

Flight Times Estimation

To generate the time sequence of pitch and thrust, we need to estimate the time of flight, first. The maximum thrust of single rotor is F_{max} and the maximum angular acceleration can be expressed as

$$\beta_{max} = 2 * F_{max} * L / I .$$

If the quadrotor pitch itself to 90 degrees with maximum angular acceleration, the time of flight can be expressed as

$$T = \sqrt{\pi / \beta_{max}} .$$

However, quadrotor won't pitch with maximum angular acceleration all the time, so the time will be longer than T. In this paper, we estimate the real time by multiplying a coefficient, S. T_{est} could be written as

$$T_{est} = S \cdot T$$

Times Sequence of Pitch Angel and Total Thrust

The motion of quadrotor is determined by its acceleration at each moment and dynamics equations show that the acceleration depend on the pitch and total thrust. Therefore, we need to form the time sequence of pitch and total thrust to generate the trajectory.

For the time sequence of pitch, it will be taken into consideration that the constraints of pitch and rate of pitch. At the contact moment, pitch angle is $\pi/2$ and rate of pitch is 0. In the moment of start, pitch angle is zero and rate of pitch is 0. In this way, the time sequence could be obtained by interpolation, and what we use here is spline functions. Next, we need to set the thrust, but to keep things simple, total thrust will be set as constant all the time, whose value is equal to the gravity of quadrotor.
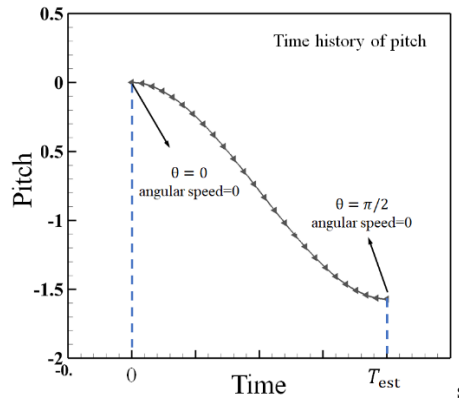

Fig. 1 Time history of pitch angle

Trajectory Generation

From the dynamic equations, expression of acceleration could be written as

$$\partial U / \partial t = -g \sin \theta ,$$

$$\partial W / \partial t = g \cos \theta - g .$$

Velocity, taking the form of integration, can be expressed as

$$U(t) = U_0 + \int_0^t \frac{\partial U}{\partial t} dt ,$$

$$W(t) = W_0 + \int_0^t \frac{\partial W}{\partial t} dt ,$$

where U_0 and W_0 are the horizontal and vertical velocity at the moment of start.

The position of quadrotor, taking the form of integration, can be expressed as

$$x(t) = x_0 + \int_0^t U dt ,$$

$$z(t) = z_0 + \int_0^t W dt .$$

where x_0 and z_0 are the horizontal and vertical coordinate at the moment of start.

Setting The Initial States

From the equations above, we still don't know the initial states of perching trajectory, including U_0, W_0, x_0 and z_0, so we need to solve the initial states. referring to the constraints.

In the process of trajectory generation, we could derive the displacement and velocity variation, which can be written as

$$\Delta x = \int_{t=0}^{t=T_{\text{est}}} U dt ,$$

$$\Delta z = \int_{t=0}^{t=T_{\text{est}}} W dt ,$$

$$\Delta U = \int_{t=0}^{t=T_{\text{est}}} \frac{\partial U}{\partial t} dt ,$$

$$\Delta z = \int_{t=0}^{t=T_{\text{est}}} \frac{\partial W}{\partial t} dt .$$

The initial states could be written as

$$U_0 = U_{\text{des}} - \Delta U ,$$

$$W_0 = W_{\text{des}} - \Delta W ,$$

$$x_0 = x_{\text{des}} - \Delta x ,$$

$$z_0 = z_{\text{des}} - \Delta z - W_0 \cdot T_{\text{est}} .$$

where U_{des}, W_{des}, x_{des} and z_{des} are the desired contact velocity and target position.

3.3 Perching Trajectory Generation

For the quadrotor we use in this paper, we set that the maximum thrust of rotor is 1.8 times the thrust in hover. Therefore, the maximum angular acceleration can be expressed as

$$\beta_{\text{max}} = (2 \cdot F_{\text{max}} - 2 \cdot 0) * 0.5 L / I = 77.72 / \text{s}^2 .$$

The flight time is 0.4s where S is selected to be 2.

With the estimated time, we can obtain the time sequence of pitch, as shown in Fig. An the moment of start, pitch angel is 0 and rate of pitch is zero. At the end, pitch grows to $\pi/2$ and rate of pitch approaches zero again.
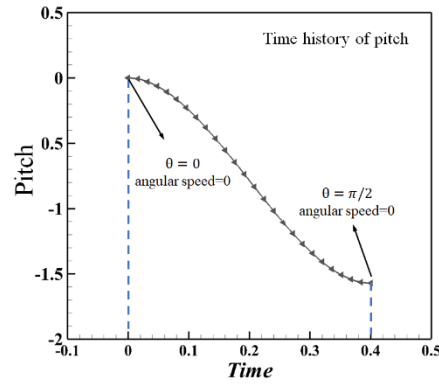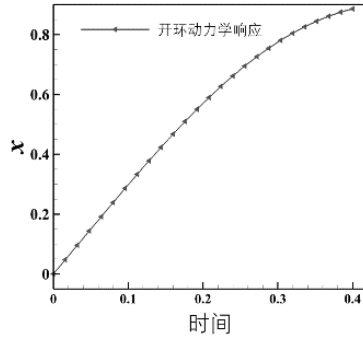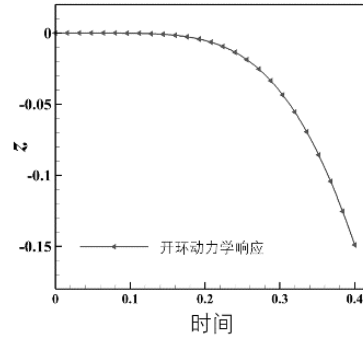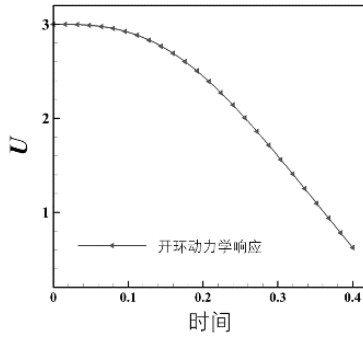
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Fig. 2 Time history of pitch angle

With time sequence of pitch and total thrust equaling to the gravity all the time, we can generate the trajectory by marching and integrating. The results are shown below.
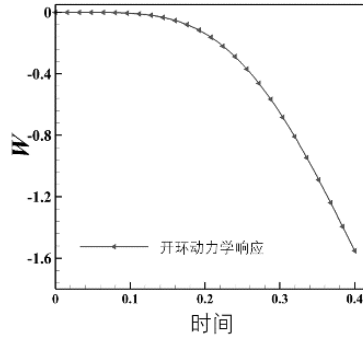

（1）Time history of horizontal position

（2）Time history of vertical position

（3）Time history of horizontal velocity

（4）Time history of vertical velocity

Fig. 3 Open-Loop Dynamics Response for Given Input

4. Perching Control Design and Simulation

The difficulty of control design for perching lays on the point that quadrotor needs to track the position and pitch angel simultaneously. In this paper, we choose the geometry tracking control used in [29] and bring up a modified algorithm to make this method more suitable for the control of perching quadrotor. In this chapter, theory of geometry tracking control is introduced first and simulation results point out that this method is not completely suitable for the control of under-actuated quadrotor with coupled motion. So, we explain the reason from the aspects of system and control method and put forward the improved algorithm. This improvement is further verified in Simulink experiments.

4.1 Geometry Tracking Control

Geometry tracking control produces the control of total thrust and moment with input of position error and attitude error. Total thrust control aims to eliminate the position error between desired position and current position. We define the position error as $e_p = x - x_d$ and define the velocity error as $e_v = \dot{x} - \dot{x}_d$, where x and $\dot{x}$ are the position and velocity at the current moment, x_d and $\dot{x}_d$ are the position and velocity in the tracking trajectory at the current moment. By taking the form of negative feedback, errors of position and velocity form the thrust vector, pointing from the current barycenter to the desired on, which can be written as

$$f_{des} = -k_p e_p - k_v e_v + mg \cdot z_g + m\ddot{x}_d ,$$

where k_p and k_v are the positive gains of feedback, and $\ddot{x}_d$ is the acceleration of the desired trajectory at current moment.

To solve the total thrust, we need to project the thrust vector, f_{des} , into the vector that is perpendicular to the plate of rotor. The total thrust can be written as

$$F = f_{des} R e_3$$

where R is the matrix of projection and e_3 is a unit vector, written as [0, 0, 1]T.
Next, we need to solve the moment, aiming to eliminate the error of attitude angle. We define the angle error as $e_\theta = \theta - \theta_{des}$ and define the rate error as $e_\Omega = \dot{\theta} - \dot{\theta}_{des}$. The commanded moment is expressed as

$$M = -k_\theta e_\theta - k_\Omega e_\Omega + \dot{\theta} \times I\dot{\theta} ,$$

where k_θ and k_Ω are positive gains.

4.2 Simulation Results of Geometry Tracking Control

To check the control ability of geometry tracking control, simulation frame is built in Simulink, the frame is shown in Fig 7. This frame cover 3 main modules, including nominal trajectory input, dynamics model of quadrotor and controller. The dynamics comes from the model in chapter 2 and nominal trajectory is the result from chapter 3. In order to check the ability of this method, different cases with initial state error are set and recorded in Table 1.
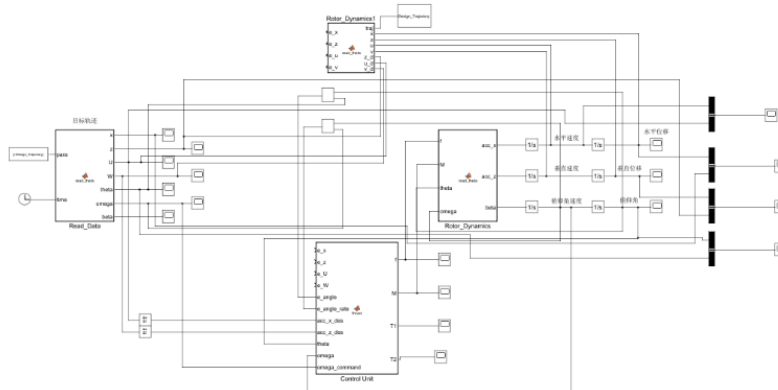

Fig. 1 Geometric Control Simulation based on Simulink

Table 2 Parameters of Simulation Experiments

Case Name	z	U_0	W_0
Nominal Trajectory	0	3	0
Case1	0	3.2	0
Case2	0	2.8	0
Case3	0	0	0.2
Case4	0	0	-0.2
Case5	0.02	0	0
Case6	-0.02	0	0

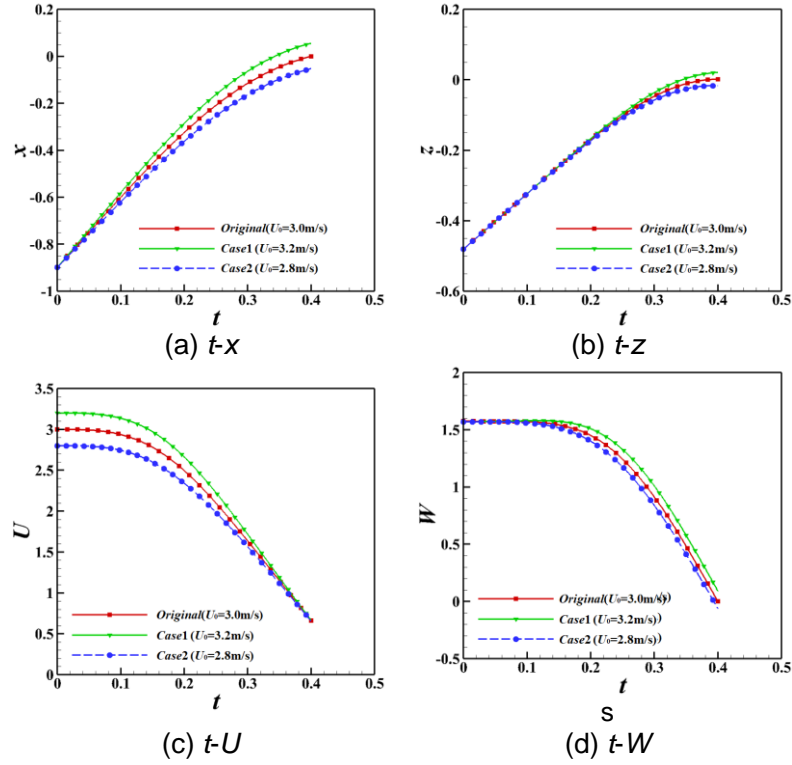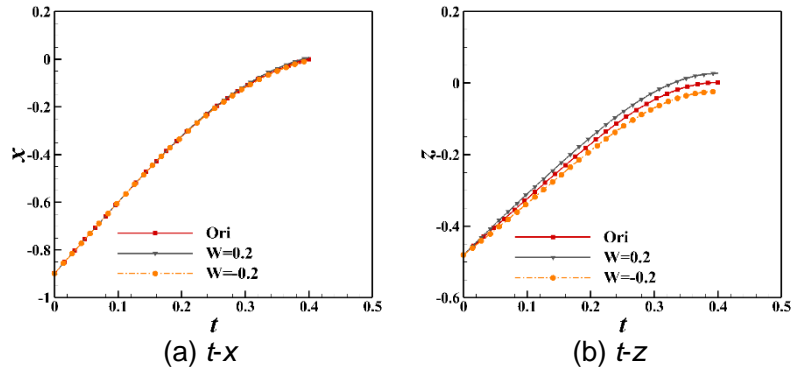Case1 and Case2 set error on the initial horizontal velocity. The results in tracking control are shown in Fig2

(a) t-x (b) t-z

(c) t-U (d) t-W

Fig. 2 Control Results with horizontal velocity error

(a) t-x (b) t-z

(c) *t-U*   (d) *t-W*
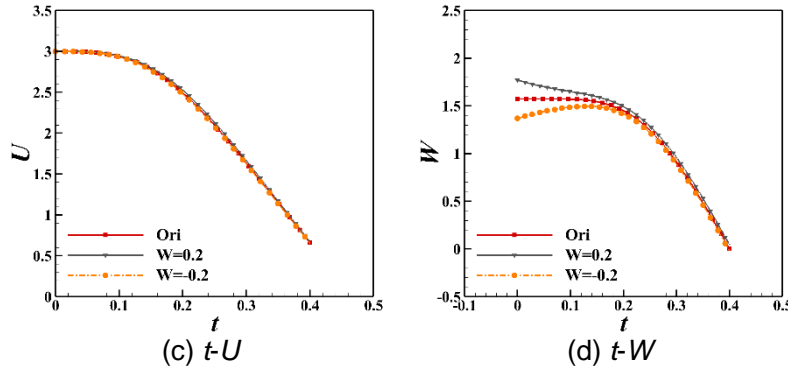
Fig. 3 Control Results with vertical velocity error

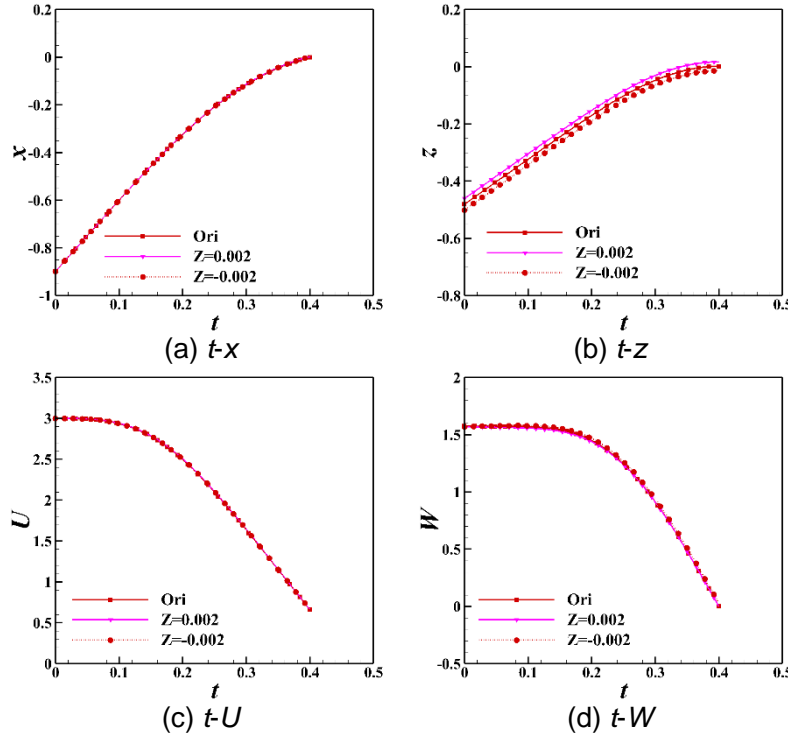(a) *t-x*   (b) *t-z*

(c) *t-U*   (d) *t-W*

Fig. 4 Control Results with vertical velocity error

4.3 Modified Tracking Control Method for Perching

The test of geometry tracking control in subsection 3.2 shows that geometry tracking control could achieve tracking control of nominal trajectory, but this method is not completely suitable for this problem. For instance, in case1, a slight increase of initial horizontal velocity leads to higher average velocity and early cut-off in trajectory. In case1, the time of contact is 0.343s, which is less than the estimated time. However, the normal contact velocity arises from 0.659m/s to 1.263m/s and tangential contact velocity grows to 0.244m/s, which is unexpected for successful perching. Therefore, original geometry tracking control is not entirely appropriate for the task of perching.

In order to improve the control effects, we review the theory of geometry tracking control and the characteristics of quadrotor perching again. It is found that quadrotors with different initial states fly across the same distance in perching while trajectory tracking algorithm executes with error signal at current moment and doesn't response to current position feedback. Thus, current tracking algorithm can only deal with the convergence of velocity in finite time but can't achieve convergence of displacement. That's why the tracking algorithm will finish ahead of schedule or exceed the estimated time.

In this paper, we modify the control method by setting the position and velocity feedback based on position interpolation instead of time interpolation. The flow chart of modified method is shown as blow. The results of modified control method are shown in Fig 13.
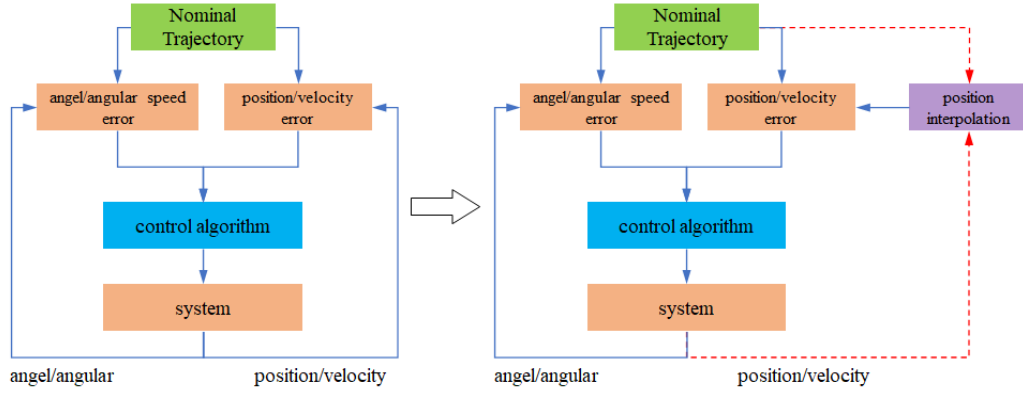
Fig. 5 Flow chart of modified control method

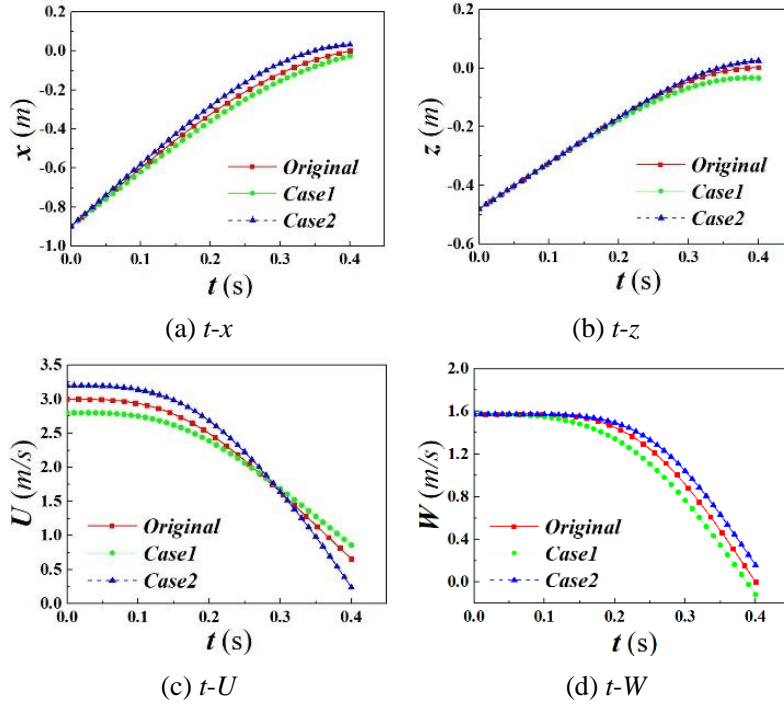(a) *t-x*

(b) *t-z*

(c) *t-U*

(d) *t-W*

Fig. 6 Control Results with horizontal velocity error for modified control method

In Table 3, simulation results of different cases are shown with geometry tracking control and modified control method. The name, original, shows the result of planning trajectory. The name, case, shows the parameter setting in Table 2. The suffix, GTC, means geometry tracking control used in simulation while Mod means modified method.

In the simulation of Case0, both methods achieve precise tracking control with no initial error. While in case1 and case2, modified control method has better performance in converging the disturbance of initial velocity. In case1, initial horizontal velocity has increment of 0.2m/s and geometry tracking control lands the quadrotor with 1.263m/s, while modified could reduce the contact speed to 1.010m/s.

Table 3 Simulation Results for Modified Control Method

Case Name	T_{att}	z	U	W	θ
Original	0.4	0.002	0.659	0.000	-1.571
Case0-GTC	0.4	0.002	0.661	0.012	-1.573
Case0-Mod	0.4	-0.005	0.618	0.009	-1.557
Case1-GTC	0.343	0.000	1.263	0.344	-1.515
Case1-Mod	0.348	0.004	1.010	0.109	-1.509
Case2-GTC	0.4	-0.017	0.655	-0.063	-1.555
Case2-Mod	0.4	-0.034	0.858	-0.115	-1.514

Case3-GTC	0.39	0.026	0.769	0.143	-1.573
Case3-Mod	0.385	0.013	0.765	0.182	-1.551
Case4-GTC	0.4	-0.024	0.653	-0.019	-1.568
Case4-Mod	0.393	-0.025	0.711	0.051	-1.555
Case5-GTC	0.397	0.017	0.691	0.027	-1.572
Case5-Mod	0.389	0.012	0.737	0.110	-1.554
Case6-GTC	0.399	-0.013	0.671	0.037	-1.572
Case 6-Mod	0.389	-0.024	0.738	0.121	-1.554

5. Conclusion

Perching maneuvering is an effective way for quadrotors to extend its mission endurance. In this paper, trajectory planning and tracking control are applied in perching the quadrotor on vertical surface. In trajectory planning, we set the open-loop trajectory and solve the initial states referring to the constraints and trajectory displacement. Then, tracking control method is applied to guide the quadrotor to achieve precise landing.

In the simulation of geometry tracking control, it is found that initial velocity disturbance will lead to termination in tracking ahead of time, resulting in excursion in desired landing states. Reviewing the basic principles of geometry tracking control and the features of perching maneuvering, we find that tracking control respond to trajectory error in time while the termination is decided by position. Hence, geometry tracking control is not completely suitable for the problem of perching. Therefore, based on analysis above, modified method is brought out by replacing the time-domain error feedback by position interpolation for position and velocity. Simulation experiments show that modified method could achieve better tracking results.

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