Trajectory Guidance and Control for a Small UAV

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Abstract

The objective of this paper is to present trajectory guidance and control system with a dynamic inversion for a small unmanned aerial vehicle (UAV). The UAV model is expressed by fixed-mass rigid-body six-degree-of-freedom equations of motion, which include the detailed aerodynamic coefficients, the engine model and the actuator models that have lags and limits. A trajectory is generated from the given waypoints using cubic spline functions of a flight distance. The commanded values of an angle of attack, a sideslip angle, a bank angle and a thrust, are calculated from guidance forces to trace the flight trajectory. To adapt various waypoint locations, a proportional navigation is combined with the guidance system. By the decision logic, appropriate guidance law is selected. The flight control system to achieve the commands is designed using a dynamic inversion approach. For a dynamic inversion controller we use the two-timescale assumption that separates the fast dynamics, involving the angular rates of the aircraft, from the slow dynamics, which include angle of attack, sideslip angle, and bank angle. Some numerical simulations are conducted to see the performance of the proposed guidance and control system.

Key Words : Flight trajectory guidance, Cubic spline, Dynamic inversion, Proportional navigation, UAV

Nomenclature

$()_e$, F_e	:	Earth fixed axis component and force.
$()_w$, F_w, V	:	Wind axis component, force and velocity.
$\mathbf{F}$	:	Body axis force.
$C()$	:	Aerodynamic coefficients and derivatives.
$K()$	:	Guidance and control gains.
α, β	:	Angle of attack, sideslip angle.
λ, γ	:	Horizontal flight path angle, Vertical flight path angle.
ϕ, θ, φ	:	Euler angles.
$\delta_a, \delta_e, \delta_r, \delta_T$	:	Deflections of aileron, elevator, rudder, and throttle setting.
$m, \mathbf{g}$	:	Mass of aircraft, gravity constant.
q_t, S	:	Dynamic pressure, Area of wing.
$()_{cmd}$	:	Commanded value.
$()_d$	:	Density.

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s	:	Laplace operator.
$\mathbf{E}()$	:	Rotation Matrix.

Introduction

Nowadays, small unmanned aerial vehicles (UAVs) play important rolls in the critical missions, such as damage inspection after disasters, observation of volcanoes and reconnaissance. Small UAVs are low risk to human operators and cost effective. In these cases, autonomous take-off, flight, landing and waypoint following are important features. For these highly nonlinear flight functions, it may be useful for the controller that flight trajectory based on the dynamic inversion[1), 2), 3), 4)]. The objective of this paper is to show the outline of this controller, and adaptability for multipurpose mission. All software is generated in the MATLAB®/Simulink® environment, and is enabled to easily mounting on the UAVs flight computer. Some numerical simulations for a runway approach shows effectiveness of the system. A right-hand orthogonal coordinate set used with the origin located at the vehicle's center of gravity. Figure1 illustrates the coordinate system.

The outline of this system will be described in Fig. 2.

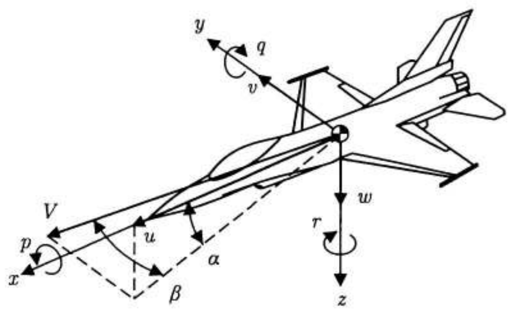


Fig. 1. Coordinate system and sign conventions

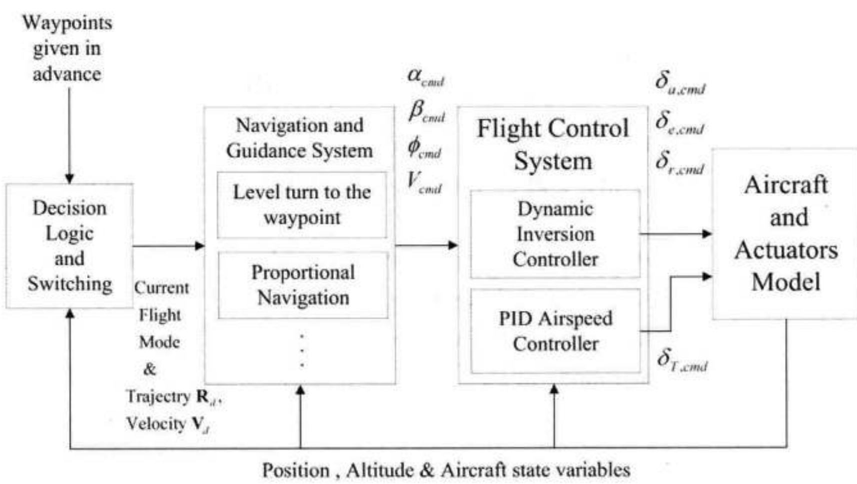


Fig. 2. The system architecture

Navigation and Guidance system

Basically, the UAV is guided by a waypoint tracking method or a trajectory following method in this study. The function of decision logic block is that calculates the suitable commanded trajectory R_d and velocity V_d. Waypoints are given by outside and have position data (latitude, longitude and the height data). Moreover, we add commanded velocity data V_{cmd} and the task information data (e.g. Pass through the point, circle around the point). In case precise control is needed, a desirable trajectory is generated automatically by an algorithm[1), 2), 3), 4)]. To pass through these points and trajectories, the suitable commanded values R_d and V_d are supplied by decision logic block. These functions are shown in Fig. 3.

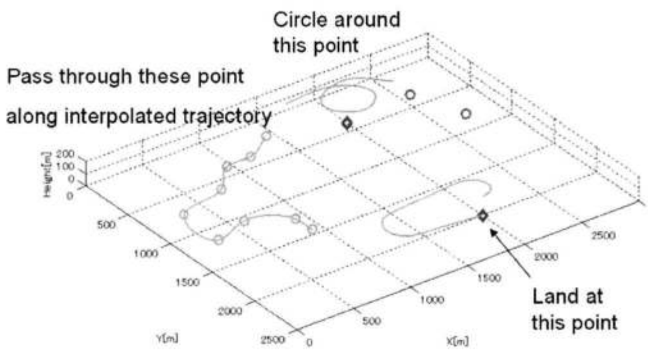


Fig. 3. Functions of the decision logic block

To generate the trajectory from a set of waypoints, we used the cubic spline interpolation because it gives the minimum curvature[4)]. In this paper, the flight distance is chosen as the independent variable. This enables us to set the airspeed to the desired constant value.

The aircraft guidance method for both trajectory tracking and waypoint following employs firstly proportional navigation expressed as Equation (1) [5)].

$$\boldsymbol{\omega}_W = \frac{\mathbf{V}_{R,W} \times \mathbf{R}_W}{R^2} \tag{1}$$

Where $V_{R,W}$ is relative velocity vector, R_W is a relative distance vector. The guidance acceleration and the corresponding force are given by

$$\mathbf{a}_W = \boldsymbol{\omega}_W \times \mathbf{V}_W = \frac{(\mathbf{V}_{R,W} \times \mathbf{R}_W) \times \mathbf{V}_W}{R^2} \tag{2}$$

$$\begin{aligned} \mathbf{F}_W &= K_n m(\boldsymbol{\omega}_W \times \mathbf{V}_W) \\ &= K_n m \frac{(\mathbf{V}_{R,W} \times \mathbf{R}_W) \times \mathbf{V}_W}{R^2} \end{aligned} \tag{3}$$

where K_n is a navigation constant.

Command values

A conventional aircraft has four control variables, which are an elevator angle, an aileron angle, a rudder angle and a throttle. Therefore, the airplane is given the four commanded values which are the angle of attack, the sideslip angle, the bank angle and thrust in this paper. The guidance force components are converted wind axis into body axis.

$$\mathbf{F}=\mathbf{E}(\phi,\theta,\varphi)\cdot\mathbf{E}^{-1}(0,\gamma,\lambda)\mathbf{F}_w \tag{4}$$

The desired side force and lift yields

$$\begin{aligned} F_{Y,d} &= F_y\cos\Delta\phi_d + F_z\sin\Delta\phi_d \\ F_{L,d} &= \left(F_y\sin\Delta\phi_d - F_z\cos\Delta\phi_d\right)\cos\alpha \end{aligned} \tag{5}$$

where

$$\Delta\phi_d=\sin^{-1}\left(\frac{F_y}{\sqrt{F_y^{\,2}+F_z^2}}\right)\qquad\left(-\frac{\pi}{2}\le\Delta\phi_d\le\frac{\pi}{2}\right) \tag{6}$$

And then the angle of attack and the sideslip are defined by

$$\begin{aligned} \alpha_d &= \frac{1}{C_{L\alpha}}\left(\frac{-F_{L,d}}{q_t S}-C_{L0}\right) \\ \beta_d &= \frac{1}{C_{Y\beta}}\left(\frac{F_{Y,d}}{q_t S}\right) = 0 \end{aligned} \tag{7}$$

No side slip is desired in this study.

Flight Control System

As we deal with a various curved path, a nonlinear flight control system is designed. Though many design techniques for the nonlinear flight control have been proposed, the dynamic inversion approach is one of the most popular and useful methods. Therefore the flight control system to achieve the commands is designed using the dynamic inversion approach. For this controller, we use the 2−time scale assumption that separates the fast dynamics from the slow dynamics. The slow mode consists of α, β and ϕ. And the fast mode consists of p, q and r. A block diagram representation of the 2−time scale approach is shown in Fig. 4.

The nonlinearities are cancelled by static feedback and the dynamics are replaced with desired linear dynamics. For both fast and slow mode desired dynamics block, we used Proportional−Integral controllers as shown in Fig. 5[6]. The block diagram for the PI form corresponds to the desired dynamics in Eq. (8).

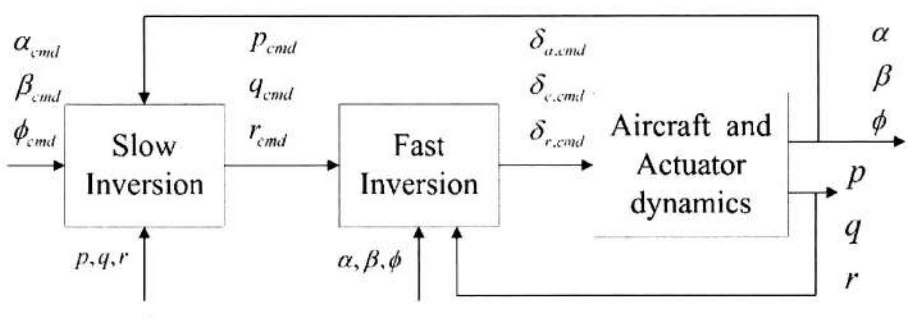


Fig. 4. Block diagram of the 2−time scale approach

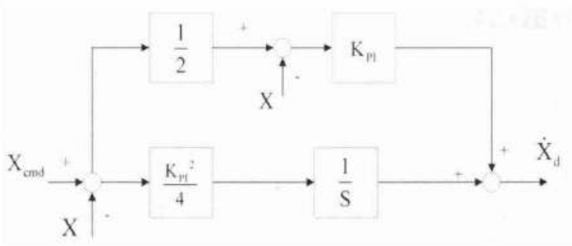


Fig. 5. PI desired dynamics block diagram

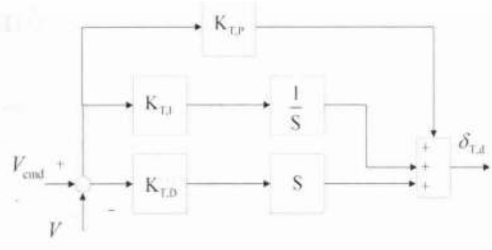


Fig. 6. PID throttle controller block diagram

$$\dot{X}_{des} = K_{PI}\left(\frac{1}{2}X_{cmd} - X\right) + \frac{K_{PI}^2}{4s}(X_{cmd} - X) \tag{8}$$

where K_{PI} is PI-gain and X is the control variable (slow mode: α, β and ϕ / fast mode: p, q and r). These dynamics have a closed-loop transfer function of

$$\frac{x}{x_{cmd}} = \frac{\frac{1}{2}K_{PI}}{s + \frac{1}{2}K_{PI}} \tag{9}$$

which place a pole at $s = -0.5K_{PI}$ for any real constant K_{PI}.

Fig. 6 illustrates the block diagram for throttle control. For speed control, we applied Proportional-Integral-Derivative method to the throttle controller.

6-DOF Rigid Body Model

For simulation purposes, we built a full nonlinear 6-degree-of-freedom rigid body model in the MATLAB®/Simulink® environment[7), 8)]. The model includes Simulink blocks for the equations of motion, aerodynamics, propulsion, inertia, standard atmosphere, and the WGS-84 Earth model. The airplane inertia model is fixed mass model.

The target aircraft is the Aerosonde UAV[9)]. The look of the Aerosonde is shown in Fig.7. Aerosonde is a small autonomous airplane designed for the long-range weather data acquisition. It was developed especially for the reconnaissance over oceanic and remote areas. The aerodynamics and propulsion models extracted from the existing Aerosonde simulator[10)].

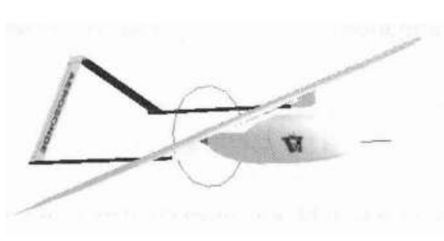


Fig. 7. Aerosonde UAV

Simulations

To show the effectiveness of the proposed guidance and control system, some numerical simulations are performed. In this paper, we show three types of simulation results: terrain following, runway approach and total simulation that combined these features.

First, we conducted the terrain following simulation in a certain lay of land shown in Fig. 8. Some waypoints are set along with desired trajectory and interpolated by the cubic spline.

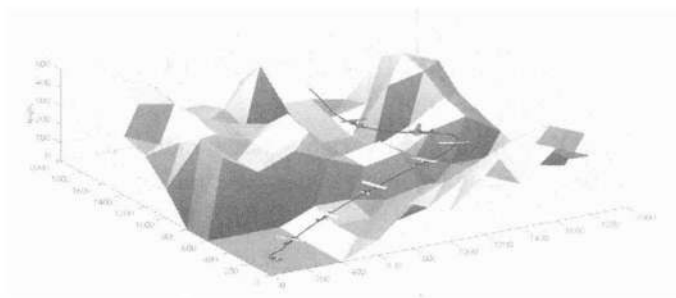


Fig. 8. Terrain following in certain lay of land

The simulation results are depicted in Fig. 9 and Fig. 10, Fig. 9 shows tracking performance while Fig. 10. is velocity control performance. In each figure, the thick broken line is actual path, and the thin one is the commanded value. The UAV is precisely guided to the generated trajectory. And it remains desired velocity well.

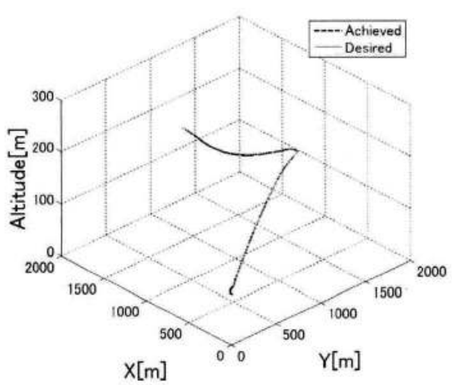


Fig. 9. Tracking performance

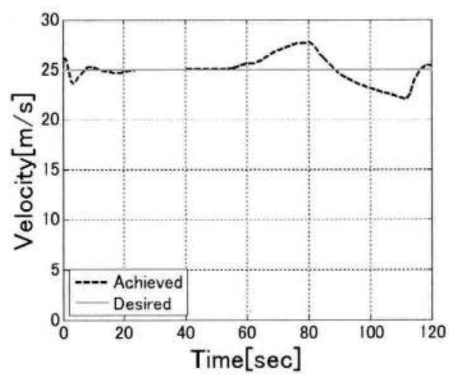


Fig. 10. Velocity control performance

Next, the runway approach simulation was carried out. In the simulation, the UAV start turning above the touchdown point. This method of landing is called "360 degree overhead approach" as shown in Fig.11. The earth fixed origin is taken at the touchdown point. Points are along the approach trajectory, and the desired trajectory is generated by using cubic spline. To reduce the descend rate at the touchdown point, the flare path is also generated. Figure 12 depicts that the vehicle is guided well by the trajectory controller. A descend rate time history is shown in Fig.13. Before vehicle touches the ground, descend rate is made small enough to touch down by the flare movement.

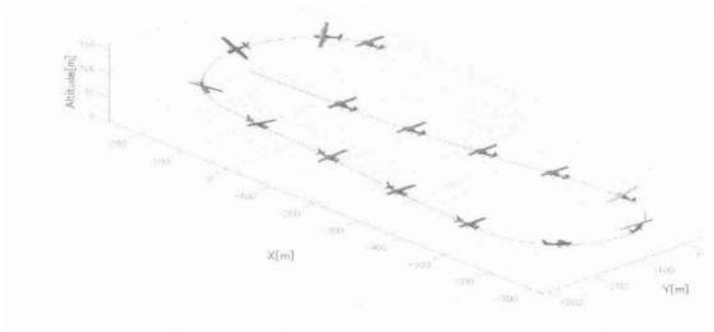
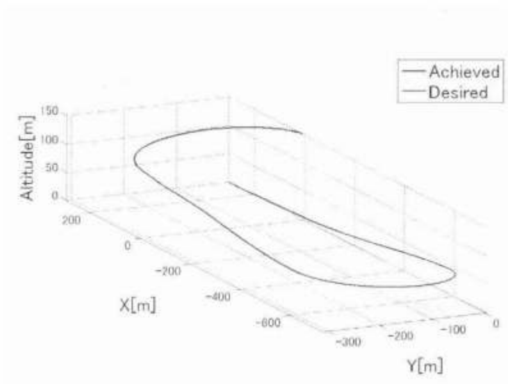


Fig. 11. 360 degree overhead approach



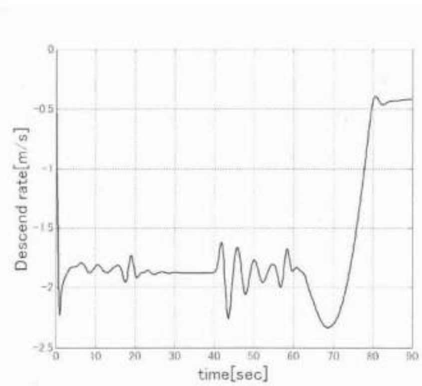


Fig. 12. Tracking performance in the trajectory Fig.13. The time history of the descend rate

At last, we considered the mission represented in Fig. 14. The UAV is commanded to circle around the mission point in the figure left side of the figure, fly through the corridor in the bottom of the figure, and land at the point in the right side of the figure.

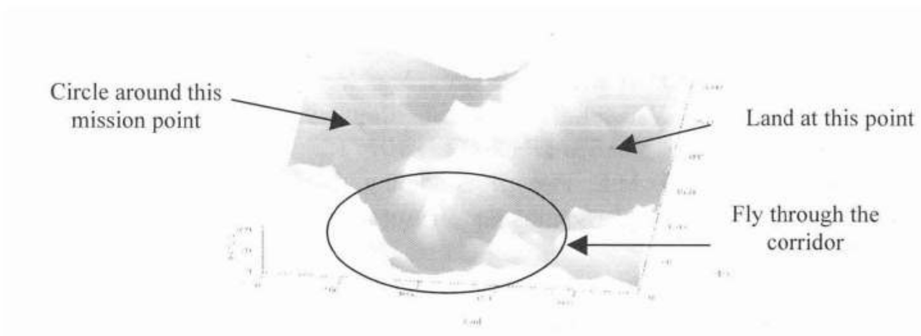


Fig.14. The mission in a certain ray of land

The total simulation result is described in Fig.15. We put some waypoints to approach these mission points. And to avoid a terrain collision, we set some points in the corridor for cubic−spline interpolation. Flight trajectory is generated automatically. The thick solid line is the actual simulate path. We could guide the UAV over narrow complicated terrain.

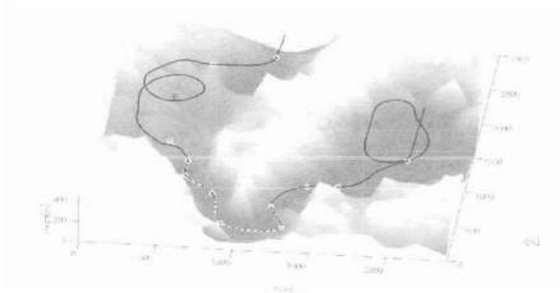


Fig. 15. The mission in a certain ray of land

Conclusion

In this paper, we present the trajectory guidance and control system using an aircraft model, which is nonlinear 6-DOF rigid body model. The vehicle is controlled via the dynamic inversion method, guided along the trajectory that generated with the cubic spline, using proportional navigation guidance. All system is developed in the MATLAB®/Simulink® environment. The simulation results confirm the effectiveness of the system.

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