Automatic Flight Path Control of Small Unmanned Aircraft with Delta-wing ICCAS 2004

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Abstract: It is known that an aircraft with delta-wings which are attached to the body at a large angle like a kite or a hang glider has a measure of maneuverability and stability. Aircrafts of this kind can fly stably. Even if engine trouble occurs, it will not fall and might be able to land. In this paper, one of the conventional control methods, PID control, is applied to the aircraft with local control block. This is based on an idea that the aircraft flies so stably that the automatic control system might be realized by a simple controller. The proposed PID controller consists of several sub-controllers which are constructed to each system neglecting the interference. In addition, the L control is involved as a local loop of the aileron and rudder control in order to increase stability of the attitude when circling.

The effectiveness of the proposed method is shown through 3D computer simulations and experiments of the flight path control.

Keywords: Unmanned Aircraft, Automatic flight control, Delta-wing, PID control, 3D simulation

1. INTRODUCTION

Observing environmental conditions or weather patterns as well as checking disasters zones quickly for victim or damage are very important jobs. Usually, these jobs are almost always carried out with aircrafts controlled by human pilots. This is not adequate because pilots are forced to be in danger and the operating cost of piloted aircraft is also generally expensive. On the other hand, unmanned aircrafts (UMA) that are remotely controlled, for example operated by radio control, have a big advantage because there are no risks to human life. However, there are several problems to overcome to make UMA more practical. First, as the aircraft must be operated within a operator’s sight, the search field is limited. Second, it requires skill to operate one. An automatic flight control system is one solution for both of these problems.

In the field of automatic flight control, many studies are proposed with regard to auto navigation of commercial airplanes or military reconnaissance planes. These papers emphasized that the robust control is needed for automatic control of aircrafts because aircrafts are coupled MIMO systems and unstable and extremely nonlinear. Most of these papers researched aircrafts with rectangular wings. Aircrafts with rectangular wings have the advantages of high maneuverability and resist wind disturbance. However, once an engine stops, those aircrafts fall immediately, while, airships almost never fall but have a disadvantage of maneuverability.

It is known that an aircraft with delta-wings which are attached to the body at a large angle like a kite or a hang glider overcomes the above disabilities, i.e. it has a measure of maneuverability and stability. Aircrafts of this kind can fly stably. Even if engine trouble occurs, it will not fall and might be able to land. The aircraft has a strong relationship between its speed and altitude, that is, a specific speed determines a corresponding altitude in a certain fixed condition. It is difficult to follow the desired trajectory whose position(longitude, latitude and altitude) and speed are settled at the same time. Therefore, in this paper, it is considered that the aircraft is controlled to follow the desired flight path which does not define speed but position.

In the above mentioned, many papers of automatic flight control were proposed. Most of those applied 2 or \( H_\infty \) control method and sliding mode control method which are based on robust control theory. In this paper, one of the conventional control methods, PID control, is applied to the aircraft with local control block. This is based on an idea that the aircraft flies so stably that the automatic control system might be realized by a simple controller.

The equation of motion for an airplane is complex 6 D-O-F nonlinear equation with 4 inputs of throttle operation, elevator angle, aileron angle and rudder angle and 4 outputs of direction, altitude, longitude and latitude. Although these inputs and outputs are strongly coupled to each other, the equation can be analyzed into the longitudinal system and lateral system by linearization. Altitude control systems for the longitudinal system, Horizontal position control system and Direction control system for lateral system are independently constructed. In addition, the L control is involved as a local loop of the aileron and rudder control in order to increase stability of the attitude when circling.

The effectiveness of the proposed method is shown through 3D computer simulations and experiments of the flight path control.

2. KITEPLANE

Figure 1 shows an aircraft with delta-wings which is the focus of this paper. We call this aircraft a kiteplane. The kiteplane is 2,280mm at full length, the wing span is 2,780mm, the height is 1,130mm, and it has four control inputs which are engine thrust: \( T[N] \) and three angles of rudder: \( \alpha[\text{rad}] \), elevator: \( \alpha_\phi \), ailerons: \( \alpha_\psi \). The engine thrust controls the speed and altitude of the kiteplane. The elevator controls up and down. The rudder and ailerons control circling. The ailerons on the right and left side also are set to move symmetrical. Horizontal positions and altitude are detected by GPS. The direction of the nose is measured by the magnetometer, and the gyroscope measures angle speed. Automatic control systems are built on PC-104 type CPU boards operated by ART-Linux OS and control programs using C language.

3. EQUATION OF MOTION FOR KITEPLANE

3.1 D-O-F equation of motion

Here the equations of motion for the kiteplane are considered. Cartesian coordinate system(it will be referred to as body axis from now) attached to the kiteplane pass through the center of gravity of the aircraft are shown in Fig.2. Each state value is...
With regard to Drag and Lift, it is known that the next equations are given by Bernoulli’s theorem.

\[
L = \frac{1}{2} C_L V^2 S, \quad D = \frac{1}{2} C_D V^2 S
\]

where

\[
L: \text{ Lift [N]} \quad D: \text{ Drag [N]}, \quad C_L: \text{ Lift coefficient,} \quad C_D: \text{ Drag coefficient}, \quad V: \text{ Kite velocity [m/s]}, \quad S: \text{ Area of wing [m}^2], \quad \rho: \text{ Air density [kg/m}^3]\]

Here \( C_L \) can be approximated by the first order transfer function of the angle of attack: \( \beta \). Hence,

\[
C_L = a\beta + b, \quad \beta = \alpha - \phi_0 \tag{6}
\]

\[
\alpha: \text{ mounting angle,} \quad \phi_0 = -\tan^{-1}\frac{V_p}{V_v}, \quad V_p: \text{ following velocity of wing,} \quad V_v: \text{ crossing velocity of wing}
\]

and from the relationships between Lift coefficient and Drag coefficient, we can write

\[
C_D = cC_L^2 + dC_L + e \tag{7}
\]

where a,b,c,d and e are constant values depending on the shape of the wing. Furthermore, Lift and Drag and , for example in the main wing, are related with as follows.

\[
\alpha = \text{Rot}(y,\phi)\begin{bmatrix} d_m & 0 \\ -d_m & 0 \end{bmatrix}^T \tag{8}
\]

From these equations (6),(7) and (8), the equations of motion for the kiteplane including its inputs: \( T, \alpha, \alpha, \alpha \) are obtained. Velocities in inertial axis can be calculated by coordinate transformation(C.T.) from the body axis to the inertial axis with Euler angles: \( \Phi, \Theta, \Psi \).

### 3.2 Linearization of equation of motion

It is known that the equations of motion for the kiteplanes given in the previous sections are 6 D-O-F complex nonlinear equations. Then, in order to design the controller, the equations should be better linearized. The equations are linearized by considering small-perturbations from an equilibrium state. Here, considering straight steady flying without sideslip, the following equations are derived from (1) and (2).

\[
m(\dot{U} + R') = -mg \sin \Theta + + (1) \\
m(\dot{V} + RU - P_a) = mg \cos \Theta \sin \Phi + + (1) \\
m(\dot{W} - RV - P_a) = mg \cos \Theta \cos \Phi + + (1)
\]

\[
I_{xx} \dot{\phi} - I_{xx}(\dot{\phi} + \dot{\theta}) + (I_{xx} - I_{yy})R_a = L(1) \\
I_{yy} \dot{\phi} + I_{xx}(\dot{\phi} + \dot{\theta})R_a + I_{yy}(P_a - \dot{\theta}^2) = M(1) \\
I_{zz} \dot{\phi} - I_{zz}(\dot{\phi} + \dot{\theta}) + (I_{zz} - I_{yy})P_a = N(1)
\]

With regard to Euler-angles, the next equations are derived.

\[
\begin{bmatrix}
\dot{\Phi} \\
\dot{\Theta} \\
\dot{\Psi}
\end{bmatrix} = E[P_a \begin{bmatrix} \dot{R}_a \\ \dot{\phi} \\ \dot{\theta} \end{bmatrix}],
\]

\[E = \begin{bmatrix}
\cos \Psi \cos \Theta & \cos \Psi \sin \Theta & -\sin \Psi \\
-\sin \Psi \cos \Theta & \sin \Psi \sin \Theta & \cos \Psi \\
\end{bmatrix}
\]

On the other hand, aerodynamic terms and momentums in (1) are generated by the engine thrust and the air resistance force divided into Drag and Lift which are dependent on the wing form and the angle of attack of each wing measured from the direction of movement. Here, force and moment which affect the main wing, rudder, elevator, and aileron are indicated by \( w, r, e, a, \) respectively. These variables are written as follows.

\[
\begin{bmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{bmatrix} = \begin{bmatrix}
f_{xx} + f_{xy} + f_{xz} + f_{xx} + T \\
f_{yy} + f_{yz} \\
f_{zz} + f_{zx} + f_{zz}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{bmatrix} = \begin{bmatrix}
f_{xx} + f_{xy} + f_{xz} + T \\
f_{yy} + f_{yz} \\
f_{zz} + f_{zx} + f_{zz}
\end{bmatrix}
\]
\[ I_{xy} \dot{q} = \Delta M(\ ) \]  
\[ I_{yz} \dot{r} - I_{y} \dot{\theta} = \Delta N(\ ) \]
\[ \dot{\phi} = p + r \tan \theta_0 \]
\[ \dot{\theta} = q \]
\[ \dot{\phi} = r \sec \theta_0 \]

where lowercase characters and the symbol of \( \Delta \) indicate small-perturbations. Moreover, concerning aerodynamic terms and moments, the following equations are obtained.

\[ \Delta A(\ ) = \frac{\partial}{\partial u} u + \frac{\partial}{\partial w} w + \frac{\partial}{\partial T} T \]
\[ \Delta A(\ ) = \frac{\partial}{\partial p} p + \frac{\partial}{\partial r} r + \frac{\partial}{\partial \alpha_r} \alpha_r \]
\[ \Delta Z(\ ) = \frac{\partial}{\partial u} u + \frac{\partial}{\partial w} w + \frac{\partial}{\partial q} q + \frac{\partial}{\partial \alpha_q} \alpha_q + \frac{\partial}{\partial \Delta T} T \]
\[ \Delta L(\ ) = \frac{\partial}{\partial \alpha_r} \alpha_r + \frac{\partial}{\partial \Delta T} T \]
\[ \Delta M(\ ) = \frac{\partial}{\partial w} w + \frac{\partial}{\partial \alpha_e} \alpha_e + \frac{\partial}{\partial \Delta q} q \]
\[ \Delta N(\ ) = \frac{\partial}{\partial \alpha_e} \alpha_e + \frac{\partial}{\partial \Delta q} q \]

Equations (9) and (10) represent that the equations between altitude and horizontal position are not coupled. The first equation is called the longitudinal system which has inputs of throttle \( T \) and elevator: \( \alpha_r \), and the second is called the lateral system which has inputs of aileron: \( \alpha_e \) and rudder: \( \alpha_s \). These systems are given as follows.

\[ \begin{align*}
\dot{s}_s & = s + \\
& = (\theta, u, w, a)^T
\end{align*} \]
\[ \begin{align*}
\dot{s}_s & = s + \\
& = (T, \alpha_e)^T
\end{align*} \]
\[ \begin{align*}
\dot{s}_s & = s + \\
& = (u, w, r, \alpha_e)^T
\end{align*} \]
\[ \begin{align*}
\dot{s}_s & = s + \\
& = (\theta, \psi, \alpha_e)^T
\end{align*} \]

where equation (11) represents that there is some interrelation between its speed and altitude. In fact, it is confirmed that the kiteplane has a strong interrelation to them by calculating a parameter matrix of \( A \).

4. DESIGN OF CONTROL SYSTEM

As shown in the previous chapter, the equations of motion for an aircraft can be divided into the longitudinal system and lateral system by linearization, where it may be possible that conditions of linearization are satisfied because the kiteplane, which has delta-wings, can fly stably. Therefore, it can be expected that control systems give an available control performance even if they are constructed to the longitudinal system and the lateral system independently. This idea can be adequate for purposes of this paper because a small-UMA does not need to control high performance like commercial airplanes.

Now considering the design of the controller, we want to make clear the purpose of control. In the above mentioned, the kiteplane has a strong interrelation between its speed and altitude, that is, a specific speed determines a corresponding altitude in a certain fixed condition. It is difficult to follow the desired trajectory whose position (longitude, latitude and altitude) and speed are settled at the same time. Then the flight path control which does not define speed but position is considered. Here the flight path is defined as follows. First, target points which the kiteplane must pass through some limits are settled in 3D space by a user. The flight path is defined as straight line(s) (in fact, parallel to the earth) connecting these points. Therefore, there are three errors which should be controlled. The first two errors are the altitude error and the horizontal position error from the connecting path lines between the previous target point and the present target point to the current position of the kiteplane, and also the third error is the direction error between flying direction and the direction from current position to present target point. In this paper, the control systems constructed for each error are called altitude control systems, horizontal position control systems and directional control systems, respectively. Here it is noticed that flight path control does not control the velocity of the kiteplane. Thus the forward and backward positions of the kiteplane on flight path are not controlled.

At this point, to simplify the calculation of the controller, the following 3D coordinates for each target point are introduced. For every change of the target point, the current coordinate is transformed into the new coordinate which has the origin of the previous target point and a x-axis equal to the current path. Therefore, flight path s y-axis components are equal to zero on the new transformed coordinates. Next a perpendicular line to the flight path from the current position of the kiteplane is calculated. It is clear that the directional error is equal to y-axis component of the current position of the aircraft and the altitude error is also equal to the length on z-axis of the calculated perpendicular line. The directional error is given as an angle between a vector from current position of the kiteplane to the current target point and a directional vector of the nose.

On the other hand, Altitude control systems for the longitudinal system, Horizontal position control system and Direction control system for lateral system are independently constructed as in figure 3. Any interference in the two linearizing systems is ignored when these PID control systems are structured, and the conditions of linearization might not be satisfied when circling because it is difficult to characterize the motion as small-perturbations from an equilibrium state. Therefore in order to stabilize it more when circling, the L local loop is attached to the lateral systems as in figure 4. The kiteplane can be stabilized more by the L local loop, and it is possible to regard the kiteplane as a linear system to a certain degree.

5. 3D SIMULATION

The 3D numerical simulation is used to illustrate the effectiveness of the proposed control system, and the non-linear equation (1) is used in it. The kiteplane’s automatic control is started from a certain position at where the aircraft is flying in the equilibrium state, and the aircraft will follow in order four target points which are on the same plane as shown in fig.5(a). The target points are changed at the time the aircraft arrives in a globe with a radius
Altitude control system

Horizontal position control system

Direction control system

Fig. 4 Block diagram of LQ local feedback loop

*) x, y, z: Aircraft s 3D position on inertial axis

Fig. 3 Block diagram of PID control systems

of 70m from the target point. In fig.5(a) the direction of nose is North.

With regard to the tuning of control parameters in longitudinal systems, first throttle gains are adjusted and second elevator gains are adjusted. In lateral systems, there are two control systems: direction control system and horizontal position control system, and each control system includes two inputs of rudder and aileron. In this paper, the rudder input is mainly used for the direction control, on the other hand the aileron input is mainly used for the horizontal position control. Figure 5 shows simulation results where the altitude control in longitudinal system and only the direction control in lateral system are carried out with no wind, and figure 6 shows simulation results when the horizontal position control is added to fig. 5. Projections of the aircraft or simulated flight path to the xy, xz and yz plane are shown in these figures, and control parameters in this simulation are shown in table 1 and graphs of control errors and control inputs of fig.6 are also shown in fig.7. It is confirmed in fig.5 that the direction control is working well to change the target points, and the altitude is also controlled very well. Comparing fig.5 and fig.6, it is obvious that the aircraft was controlled to follow the flight path well.

On the other hand, it is supposed that an aircraft with big wings like a kiteplane is strongly influenced by wind in practical flights. Therefore a case with wind that is 10m/s and blowing from the west is simulated in order to confirm the impact of wind. Control parameters are the same as in table 1. Figure 8 shows this simulation result, and figure 9 shows the control error and control inputs for fig.8. It is described in fig.8, 9 that the aircraft is flowing on a complex path in a west-south direction, and control errors are bigger than in the no wind case. However, the aircraft arrives at each target point satisfactorily. Thus it is possible to say that the proposed method accomplishes a measure of control performance without considering wind disturbances.

6. EXPERIMENTAL RESULT

Experiments should confirm the effectiveness of the proposed method. Therefore the experiment with the actual kiteplane is carried out. Figure 10 shows the target points and the desired flight path at the experiment. The target points are arranged as in a triangle with sides 300m long, and the desired paths are three straight lines between those points. The reason one side of the triangle is short 300m compared with the simulation is that the area of the experiment is restricted by the range of manual radio command control. The target points are changed when the aircraft arrives in a globe with a radius of 75m from the target point.

The experiment was carried out as follows. First the aircraft climbed up to about the altitude of the target points by manual control, next the automatic flight path control was started at the
(a) 3D view of controlled kiteplane

(b) 3D view of controlled path

**Fig.** Simulation results with direction and horizontal position control

**Table 1** Control parameters at the simulation

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<td><strong>Altitude control system</strong></td>
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**Table 2**

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appropriate position, and the aircraft was controlled to follow one circuit of the desired path. Figure 10 and 11 show the experimental results and table 2 describes parameters of the experiments. A wind of 8~10m/s was blowing from the west on the day. In this experiment, the reason the control parameters are still smaller than simulations is that this experiment was carried out only a few times and the parameters were not able to be adjusted at the time. Figure 11(a) and 11(b) represent that the aircraft is driven from the desired path by the wind, and is meandering in the adverse wind, i.e. the aircraft is going to the west. These figures also show that there are errors of 100m in the altitude control system. It is the reason why the errors of the altitude control are due to GPS system which has a feature of a first-order transfer function with a large time constant of a few minutes. With regard to meandering in the
adverse wind, it is considered that an oscillation occurs by an insufficiency of adjusting parameters in PID control systems. Therefore the control performance in the position control will be improved by parameter adjustment in an experiment, and we are going to prepare these next experiments.

Here we compare the experimental results and the simulation. In the altitude control, it is mentioned that the experiment has large errors than the simulation. In the position control, it looks like the experimental errors are larger than the simulation errors, but it is found from fig.9(a) and fig.12(a) that they are almost same. These experimental results suggest the proposed method is effective for automatic control of an aircraft with delta-wings.

7. CONCLUSIONS

This paper proposed that automatic control systems for small unmanned aircrafts with delta-wings are possible to be structured with conventional PID controller because of the stability of aircrafts of this kind, and the effectiveness of the proposed method were confirmed by simulations and experiments. The equations of motion for the aircraft are 6 D-O-F complex nonlinear differential equations. However the equations can be divided into two independent linear systems of the longitudinal system and the lateral system by considering small-perturbations from an equilibrium state. The altitude control system is structured in the longitudinal system and the position control system is also structured in the lateral system, where the most common control method of PID is employed. Simulation results show the effectiveness of the proposed method even with wind disturbance, and the experimental result indicates simulation results are reliable, and shows effectiveness of the proposed automatic control system.

REFERENCES