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Autonomous homing control of a powered parafoil with insufficient altitude

Jin Tao [a,b], Qing-lin Sun [a,b,*], Pan-long Tan [a,b], Zeng-qiang Chen [a,b], Ying-ping He [c]

[a] Intelligent Robots Key Lab of Tianjin, Nankai University, Tianjin 300350, China
[b] College of Computer and Control Engineering, Nankai University, Tianjin 300350, China
[c] Aerospace Life-Support Industries Ltd., Aviation Industry Corporation of China, Xiangyang 441003, China

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ABSTRACT

In order to realize safe and accurate homing of a powered parafoil under the condition of insufficient initial altitude, a multiphase homing path is designed according to the flight characteristics of the vehicle. With consideration that the traditional control methods cannot ensure the quality of path following because of the nonlinear, large inertial and longtime delay existed in the system and strong disturbances in a complex environment, a homing controller, composed of the vertical and horizontal trajectory tracking controllers, is designed based on active disturbance rejection control (ADRC). Then autonomous homing simulation experiment of the powered parafoil with insufficient altitude is carried on in a windy environment. The simulation results show that the planned multiphase homing trajectory can fulfill the requirements of fixed-point homing and flare landing; the designed homing controller can overcome the influences of uncertain items of the internal and external disturbances, track the desired homing path more rapidly and steadily, and possesses better control performances than traditional PID controllers.

1. Introduction

Powered parafoils have existed in their current form since 1983, when the basic concept was introduced at the Sun'n Fun aviation event by the ParaPlane Corporation [1]. The powered parafoil is a very unique kind of flexible vehicle, which is composed of a parafoil canopy and a payload with a propeller. It has the same flight characteristics of traditional unpowered ram-air parafoil systems: gliding without manipulation, turning by pulling left or right steering rope connected to the rear of its trailing edge, and flare landing through pulling both of the steering ropes symmetrically and rapidly. When the engine of the propeller is shut off, the vehicle can be regarded as an unpowered parafoil system. Once the engine flared, thrust will be produced, such that the vehicle can be equated with a flexible wing aircraft. Because of the propelling unit, the vehicle can cruize at a constant altitude, even climb. The slow flight and large payload characteristics of the powered parafoil make it a practical platform for application such as military reconnaissance, crop-dusting and advertizing. In recent years, with the introduction of GPS navigation technology and the development of measurement technology and control science, the autonomous flight of powered parafoils has made favorable progress [2,3].

Control is one of key technology for autonomous homing of powered parafoils. For the existence of various kinds of disturbances in a real flight environment, if there are no proper control systems to restrain interferences, it is impossible for the vehicle to perform precize homing. Nowadays, the autonomous homing control of powered parafoils is still a challenging task. In recent years, a variety of control methods designed for unpowered parafoil systems have been reported. Slegers [4] applied the model predictive control method (MPC) to control a parafoil-payload system. Xiong [5] built the linear time-variable error equations based on Frennet frame, and designed the traditional PD controller and gain-scheduling fuzzy PD controller to realize path following of a parafoil system. Jiao [6] and Gao [7] tackled the problem of path tracking by using ADRC, and achieved some positive results. For powered parafoils, recently, there have been some meaningful results. Aoustin [8] proposed a nonlinear control law based on the partial feedback linearization, for controlling the longitude motion of a powered parafoil. However, the homing control of powered parafoils is seldom introduced, especially under the condition of insufficient initial altitude, that unpowered parafoil systems are unable to perform precise homing successfully [5].

* Corresponding author at: Intelligent Robots Key Lab of Tianjin, Nankai University, Tianjin 300350, China.
E-mail addresses: jack.taojin@mail.nankai.edu.cn (J. Tao), sunql@nankai.edu.cn (Q.-l. Sun), 296055178@qq.com (P.-l. Tan), chenzq@nankai.edu.cn (Z.-q. Chen), heyingping01@163.com (Y.-p. He).

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In this paper, on the basis of previous studies, an eight degree of freedom (DOF) dynamic model of a powered parafoil is established in terms of the Kirchhoff motion equation. And then, with consideration that the vehicle is given priority to steady movements in the process of homing, and with the situation of insufficient initial altitude, a multiphase homing trajectory of the powered parafoil is designed accordingly. The planned homing path gives full consideration to homing principles of upwind flare landing and closing to the destination, therefore, the problem of autonomous homing control of the powered parafoil is transformed into the desired homing path following problem. Consequently, ADRC controllers are designed separately for vertical and horizontal trajectory tracking. Simulation results justify the feasibility of the homing trajectory planning method and the validity of ADRC based path following controllers.

This paper is organized as follows: in Section 2, an eight DOF dynamic model of the powered parafoil is established briefly. In Section 3, the insufficient altitude multiphase homing trajectory planning scheme is proposed. In Section 4, regarding the system as two single input single output systems, ADRC controller for each channel is designed separately. In Section 5, simulation experiments are carried out to certify the feasibility of homing trajectory planning method and the performance of the designed controllers. In the last Section, the research work is summarized.

2. Dynamic model of the powered parafoil

The dynamic model of the powered parafoil is presented with eight DOF in this paper, including three inertial position components of the parafoil mass center, three Euler orientation angles of the parafoil, and the relative pitching and yawing motions between the parafoil and the payload. In order to facilitate analysis, some reasonable hypotheses [2] are made as follows:

(1) After the parafoil has been inflated completely, its aerodynamic configuration keeps steady without maneuver.

(2) The mass center of the parafoil overlaps the aerodynamic pressure center, but does not overlap the gravity center.

(3) The lift force of the payload is ignored, only its aerodynamic drag force is considered.

(4) The ground is plane.

2.1. Motion equations of the payload

The payload is treated as a rigid body of revolution, so that the momentum and the angular momentum theorems are applied to formulate motion equations of the payload. The forces acting on payload are the aerodynamic drag force, gravity, tension of the suspension line and thrust produced by the propeller. The gravity and thrust are assumed to act upon the mass center of the payload. The angular momentum caused by gravity and thrust is ignored. The motion equations are described as:

$$\frac{\partial P_p}{\partial t}+W_p\times P_p=F_p^{aero}+F_p^t+F_p^G+F_p^{th} \tag{1}$$

$$\frac{\partial H_p}{\partial t}+W_p\times H_p=M_p^{aero}+M_p^f+M_p^t \tag{2}$$

where $V_p=[u,\ v,\ w]^{\mathrm{T}}$ and $W_p=[p,\ q,\ r]^{\mathrm{T}}$ are vectors of velocity and angle velocity of the payload's mass center, respectively. F and M with subscript P denote the forces and moments acting upon the payload, respectively. The superscript *aero* denotes the aerodynamic force, t denotes tension of suspension lines, G represents gravity, th represents thrust and f represents friction. P_p and H_p denote the momentum and angular momentum of the payload, respectively, which are formulated as:

$$\begin{bmatrix} P_p \\ H_p \end{bmatrix}=\begin{bmatrix} m_p & 0 \\ 0 & J_p \end{bmatrix}\begin{bmatrix} V_p \\ W_p \end{bmatrix} \tag{3}$$

where m_p denotes the mass of the payload and J_p represents the matrix moment of inertia of the payload.

2.2. Motion equations of the parafoil

Motion equations of the parafoil are described under the consumption that the parafoil have been completely inflated in the air. Then forces acting on the parafoil include the aerodynamic force, gravity and tension of lines. The motion equations of the parafoil are described as:

$$\frac{\partial P_s}{\partial t}+W_s\times P_s=F_s^{aero}+F_s^G+F_s^t \tag{4}$$

$$\frac{\partial H_s}{\partial t}+W_s\times H_s+V_s\times P_s=M_s^{aero}+M_s^f+M_s^G+M_s^t \tag{5}$$

where V_s and W_s denote vectors of the velocity and the angular velocity of the parafoil's mass center, respectively. The subscript s denotes the parafoil, and other symbols are defined similar with Eqs. (1) and (2).

The powered parafoils is lightly loaded vehicle with flexible flight wing. It is significantly important to take the apparent mass into consideration when building its motion equations. The quantity of the apparent mass, as we know, is associated with motion directions. However, the traditional rigid body dynamics equations often obscure changes of the apparent mass under different coordinates, which may lead to incorrect results. Consequently, Kirchhoff motion equation is adopted to describe dynamic equations of the parafoil.

The total momentum P_s and the angular momentum H_s are composed of two parts, one is produced by the real mass A_r, and the other is generated by the apparent mass A_a, which are shown as:

$$\begin{bmatrix} P_s \\ H_s \end{bmatrix}=[A_a+A_r]\begin{bmatrix} V_s \\ W_s \end{bmatrix} \tag{6}$$

2.3. Constraints of the velocity and the angular velocity

The parafoil and the payload both have six DOF. But their velocities and angular velocities are not independent from each other. Let C be the middle of two connection points between the parafoil and the payload. Then, constraints of the velocity and the angular velocity satisfy with:

$$V_p+W_p\times L_{p-c}=V_s+W_s\times L_{s-c} \tag{7}$$

where L_{p-c} and L_{s-c} denote the distance from the mass center of the payload to C and the distance from the parafoil's mass center to C, respectively.

As for the relative rotation of two bodies, the equation can be written as:

$$W_p=W_s+\tau_s+\kappa_p \tag{8}$$

where $\tau_s=\begin{bmatrix} 0 & 0 & \psi_r \end{bmatrix}$ and $\kappa_p=\begin{bmatrix} 0 & \theta_r & 0 \end{bmatrix}$ stand for the relative yaw angle and the relative pitch angle between the parafoil and the payload, respectively.

2.4. Dynamic model of powered parafoil

Let $x=\begin{bmatrix} V_p^T & W_p^T & V_s^T & W_s^T & \psi_r & \theta_r \end{bmatrix}^T$ be the state vector of the dynamic model of the powered parafoil. Then x is a 14×1 vector with eight independent parameters. Combining Eqs. (1)–(2), (4)–(5),