Real-Time Data Acquisition and Model Identification for Powered Parafoil UAV

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Abstract. Powered Parafoil UAV (PPUAV) is a kind of different aircraft from common UAVs. It consists of parafoil canopy, payload and suspension lines and has the adventages of simple structure, low cost and high load weigh ratio, which is suitable for large-area and long-time surveillance and airdrop missions. This type of UAV has the problems of adding mass and flexible connection, and it is not easy to build the accurate model, which brings challenges to theoretical study and practical applications. This paper designs the structure of PPUAV and real-time data acquisition system, obtains flight data for modeling, identifies and validates the transfer functions using Matlab System Identification Toolbox. Finally the model of PPUAV is obtained, which gives a practicable method of PPUAV modeling and does a preliminary work for the following controller design and mission planning.

Keywords: Powered parafoil · UAV · Data acquisition · Transfer functions · System identification · Modeling

Nomenclature

la	left brake deflection
ra	right brake deflection
T	thrust
S	symmetric brake deflection
v_x	longitudinal velocity
v_z	vertical velocity
w	yaw rate

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1 Introduction

1.1 The Characteristics of PPUAV

With the development of society and economy, Unmanned Aircraft Vehicles (UAVs) have been more and more widely used in varied domains. Compared with common UAVs which have rigid contact surface, Powered Parafoil UAV (PPUAV) has a soft wing called parafoil, which is connected to the payload by suspension lines and provides lift for the system. This type of UAV can takeoff from the ground or be released from a plane and has the ability to perform long-time surveillance. When landing, it impacts the ground with low velocity. It is suitable for field investigations, search and rescue, and cargo delivery [1]. The system has the characteristics of complexity, uncertainty, nonlinearity, time variation, large delay and large inertia, and is easily affected by the atmospheric environment [2]. The system is usually treated as a rigid body, with the models built in 6 degree of freedom (DOF), 8DOF, etc. The researches make contributions to theoretical study, with approaches to data acquisition, flight tests designing, model analysis discussed inadequately, which causes challenges to practical applications. This paper discusses the structure, control mechanisms, fight test design, data acquisition and model analysis of the PPUAV, which provides a method of PPUAV modeling and flight test and does a preliminary work for PPUAV modeling and control design. The PPUAV system is shown in Fig. 1.

Fig. 1. PPUAV system

1.2 The Structure of Powered Parafoil UAV

Powered Parafoil UAV consists of parafoil canopy, payload, suspension lines and GN&C system. The GN&C system consists of winches, global position system (GPS), magnetic compass, inertial measurement unit(IMU), pitot tube, flight computer and data-transmit module to uplink commands and downlink data.

The structure of the system is shown in Figs. 2-3: 1 Powered Parafoil system, 2-1 GPS, 2-2 data acquisition board, 2-3 data-transmit module, 2-4 magnetic compass 3, 4 IMU, 5-1 canopy lines, 5-2 hanging lines, 5-3 manipulating lines, 6 GPS and magnetic compass, 7 oil tank, 8-1 pitot tube, 8-2 airspeed calculating module, 9 data-transmit module, 10 flight computer, 11 IMU, 12 cradle head, 13 winches, 14 wheels, 15 tachometer, 16 engine, 17 propeller, 18 protection ring, 20 fuselage.

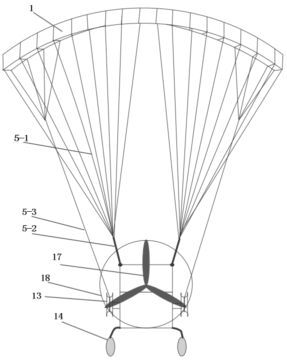
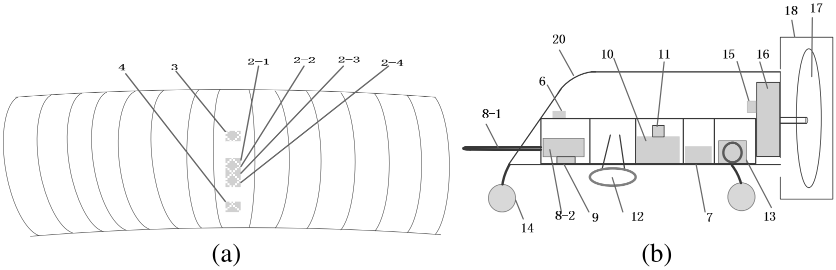


Fig. 2. Powered Parafoil UAV structure



(a) (b)

Fig. 3. (a) Parafoil canopy structure. (b) Payload vehicle structure

1.3 Control Mechanisms of Powered Parafoil UAV

PPUAV consists of ram-air-inflated fabric wing, payload and suspension lines.

The predominant control mechanism for powered parafoil UAV is left and right brake deflection and thrust provided by the engine. For most parafoils, deployment of the right brake causes a significant drag rise and a small lift increase on the right side of the canopy with slight right tilt. The overall effect causes the parafoil to turn right when a right brake is deployed. With a engine installed on the back of the payload, the system can adjust its longitudinal and vertical velocity [3-8].

To improve the accuracy of the parafoil system, several new flight control mechanisms have been created. One new control mechanism is called the dynamic incidence angle control. It is realized by changing the rigging length between the parafoil and the payload dynamically in flight, thus to realize direct glide slope control [3,9]. Another new control mechanism is realized by dynamically opening vent holes on the upper surface of the canopy to create a virtual aerodynamic spoiler. Symmetric activation of canopy spoilers yields longitudinal control while asymmetric activation creates lateral control [10].

Over the past few decades, a lot of models of different parafoil system were developed to address the varied issues, including 3DOF [11] (degrees-of-freedom), 6DOF [12], 8DOF [13], 9DOF [14] and 12DOF [15] models. In order to develop the GN&C successfully, reasonably accurate dynamic models that exhibit similar nonlinear behaviors with the actual airdrop systems are required. Thus several methods of system identification were developed [16-20].

In the paper, we consider the system as a rigid body, left brake deflection *la*, right brake deflection *ra*, symmetric brake deflection *S* and thrust *T* as inputs and longitudinal velocity v_x, vertical velocity v_z and Eular angles as outputs. The PPUAV model is obtained with lateral motion taken into account.

2 Real-Time Data Acquisition and Flight Tests Design

2.1 Real-Time Data Acquisition

Sensors and Structure of the System

The sensors installed on the aircraft consists of inertial measurement unit (IMU), global position system (GPS) , magnetic compass, tachometer and pitot tube.

The platform, on which a 3-axis gyro, a 3-axis acceleration sensor, a compass, and a GPS are installed, can store the data of velocities, angular rates, Euler angle accelerations, and positions into an SD card through an ARM processor. An Extended Kalman Fliter is used to estimate the sensors' values.

The sensors installed on the lower surface of the canopy are used to accurately measure the movement of the canopy, to reduce the error caused by the soft structure of the system, thus to control the system more accurately with the system's stability enhanced. The sensors installed on the vehicle measure the movement of the payload. Thus the total movement of the system is measured, which provides the basis for flight control.

Data Communication

The data acquisition module on the canopy is used to acquire the data from IMU, GPS and magnetic compass and transmit them to the flight computer.

The data acquisition module on the vehicle is used to acquire the data from IMU, GPS, magnetic compass and pitot tube and transmit them to the flight computer. As the communication is established, the onboard avionics transmits the system's flight status, including GPS position and 3axis compass information, aircraft attitude data, filtered and estimated velocities and acceleration data, control inputs and outputs and task management information to the ground control station (GCS) . After parsing incoming data packets, GCS displays the flight trajectory, waypoints, target location, as well as the battery and gas level, engine temperatures and revolutions. The GCS also uploads task information to the onboard controller, such as task waypoints, target location, and payload control commands.

2.2 Flight Test Design for the PPUAV Modeling

Three flight tests are needed. The objective of the first test is to gather aerodynamic data during manual flight by executing planned longitudinal and lateral maneuvers, and to analyze the main relationship between inputs and outputs, thus to obtain the aerodynamic characteristics of the system. In the second flight test, the powered parafoil is flown to a suitable altitude and the flight computer is switched to automatic mode to verify the correctness and the effectiveness of the model and the controller. The third flight test is autonomous. Fig. 4 shows the flight simulation in Matlab.

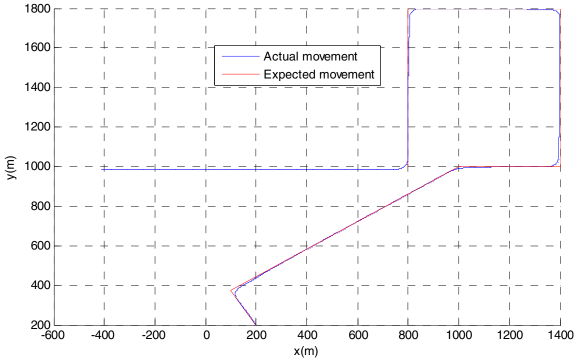


Fig. 4. Flight simulation in Matlab

2.3 Flight Test Arrangement for Mathematical Modeling

Manual flight test requires a windless environment. The powered parafoil was flown to the altitude of 200 m, then the maneuvers were executed after it flied stably. The maneuvers are presented by the percentage of the maximum value of left and right deflection and thrust. Each maneuver is held for a pre-determined time to ensure that the dynamics induced as the result of the maneuver have been damped out as shown in Table 1.

Table 1. Maneuvers of the flight test

Left deflection(%)	Right deflection(%)	Thrust(%)	Duration(s)
10	0	0	5
20	0	0	5
30	0	0	5
40	0	0	5
50	0	0	5
0	10	0	5
0	20	0	5
0	30	0	5
0	40	0	5
0	50	0	5

(*Continued*)

Table 1. (*Continued*)

Left deflection(%)	Right deflection(%)	Thrust(%)	Duration(s)
10	0	0	10
20	0	0	10
30	0	0	10
40	0	0	10
50	0	0	10
0	10	0	10
0	20	0	10
0	30	0	10
0	40	0	10
0	50	0	10
10	10	0	5
20	20	0	5
30	30	0	5
40	40	0	5
50	50	0	5
10	10	0	10
20	20	0	10
30	30	0	10
40	40	0	10
50	50	0	10
0	0	10	10
0	0	30	10
0	0	50	10
0	0	10	15
0	0	30	15
0	0	50	15

3 System Identification of Powered Parafoil UAV

3.1 Matlab System Identification Toolbox

Modern engineering of airdrop systems leans heavily on flight dynamic modeling and simulation to predict a multitude of drop events virtually so that guidance, navigation, and control (GN&C) software can be developed and tested in a cost efficient manner [21]. Matlab System Identification Toolbox is used to construct mathematical models of dynamic systems from measured input-output data. The toolbox also provides algorithms for embedded online parameter estimation. The tools simplifies the calculation and make the process concise and direct [22].

3.2 Identification and Verification of the Transfer Functions

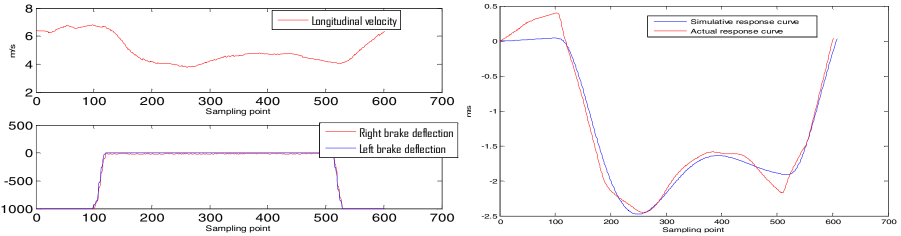
The Powered Parafoil UAV is a kind of underactuated aircraft and the variation of a single input will lead to variations of multiple outputs.

Increasing or decreasing the thrust *T* provided by the engine power affects the longitudinal and vertical velocity. Deflecting the right or left trailing edge of the parafoil turns the aircraft right or left. If the trailing edge of the wing is pulled on both sides at the same time, the longitudinal velocity of the aircraft will decrease and the vertical velocity will increase. The data is acquired 50 times per second.

Symmetric Brake Deflection-Longitudinal Velocity

The flight data was imported to the Matlab System Identification Toolbox to obtain the transfer function from symmetric brake deflection to longitudinal velocity. Fig. 5 shows the curves of input and output and the transfer function was verified. The transfer function is as follow:

$$\frac{-0.0002958s-0.002586}{s^2+0.775s+1.357} \tag{1}$$



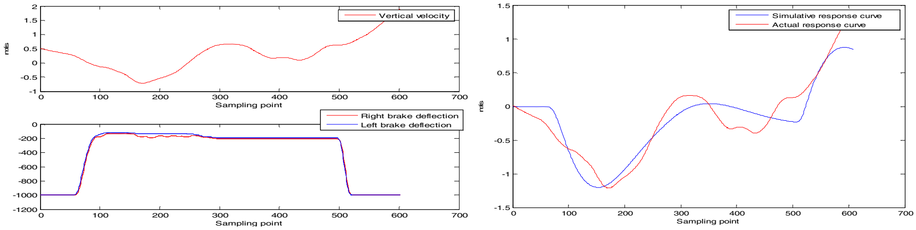
(a) (b)

Fig. 5. (a) Curves of inputs and outputs. (b) Transfer function verification

Symmetric Brake Deflection-Vertical Velocity

Fig. 6 shows the curves of input and output and the transfer function was verified. The transfer function is as follow:

$$\frac{-0.002016s-0.0002064}{s^2+0.8429s+0.8064} \tag{2}$$



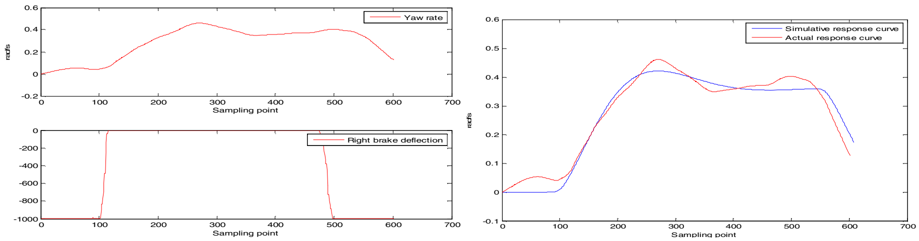
(a) (b)

Fig. 6. (a) Curves of inputs and outputs. (b) Transfer function verification

Right Brake Deflection-Yaw Rate

Fig. 7 shows the curves of input and output and the transfer function was verified. The transfer function is as follow:

$$\frac{0.0001213s+0.0002496}{s^2+0.9468s+0.9751} \tag{3}$$



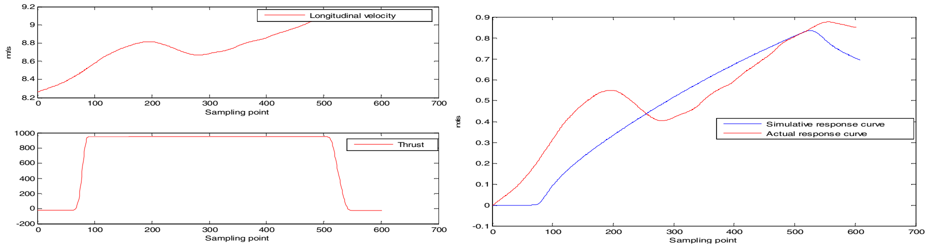
(a) (b)

Fig. 7. (a) Curves of inputs and outputs. (b) Transfer function verification

Thrust-Longitudinal Velocity

Fig. 8 shows the curves of input and output and the transfer function was verified. The transfer function is as follow:

$$\frac{0.0002851s+0.0002664}{s^2+2.159s+0.533} \tag{4}$$



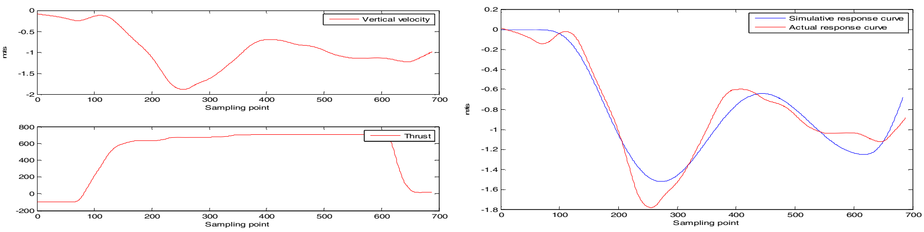
(a) (b)

Fig. 8. (a) Curves of inputs and outputs. (b) Transfer function verification

Thrust-Vertical Velocity

Fig. 9 shows the curves of input and output and the transfer function was verified. The transfer function is as follow:

$$\frac{-0.0003046s-0.001045}{s^2+0.2243s+0.8359} \tag{5}$$



(a) (b)

Fig. 9. (a) Curves of inputs and outputs. (b) Transfer function verification

4 Model Analysis of the PPUAV

4.1 Analysis of the Transfer Functions

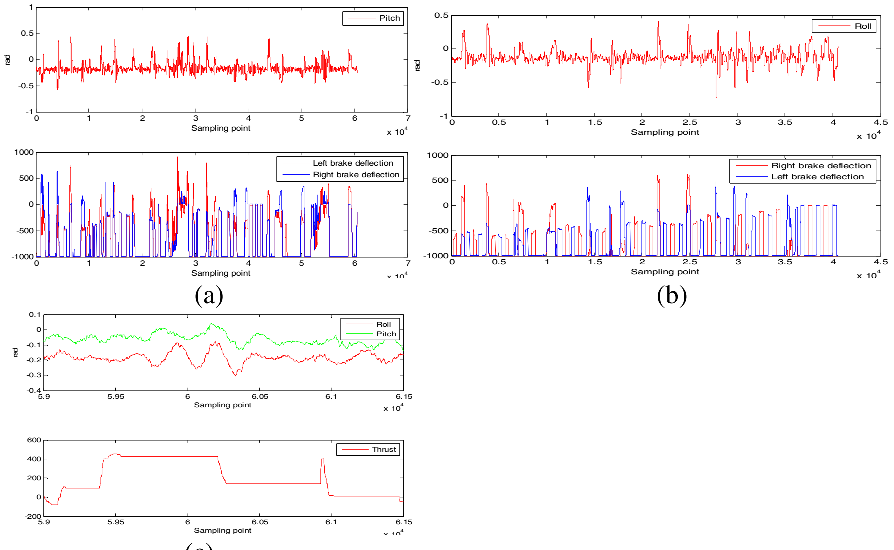
The transfer functions' cutoff frequencies, pole-zero location, rise time and settling time have been analysed, as shown in Table 2.

Table 2. Analysis of the transfer functions

Channel	Cutoff frequency (Hz)	Rise time (second)	Settling time (second)	Zero	pole
S - v_x	0.28	1.5	7	-8.74	-0.338+1.11j; -0.338-1.11j
S - v_z	1.4	0.5	8	-0.102	-0.421+0.793j; -0.421-0.793j
ra -*w*	0.13	1.7	6	-2.06	-0.473+0.867j; -0.473-0.867j
la-w	0.13	1.5	10	-2.15	-0.202+0.98j; -0.202-0.98j
T- v_x	0.016	35	40	-0.934	-0.0735; -2.09
T- v_z	0.1	1	18	-3.43	-0.112+0.908j; -0.112-0.908j

4.2 Analysis of the Effects of the Input on Secondary Factors

The influences from brake deflection to pitch, asymmetric brake deflection to roll, thrust to pitch,and thrust to roll are analysed, as shown in Fig. 10. The figure shows that brake deflection and thrust have minor effects on pitch and roll.



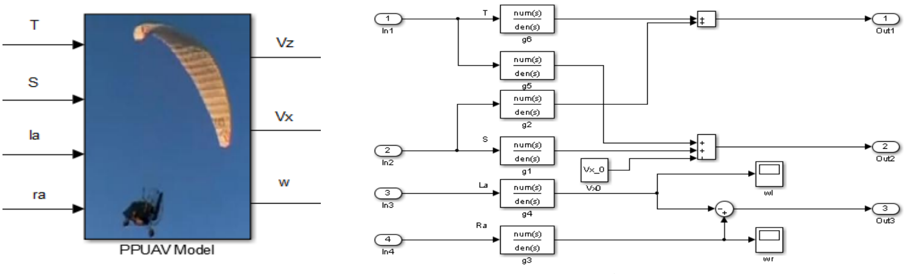
(a) (b)

(c)

Fig. 10. (a) Curves of brake deflection and pitch. (b) Curves of asymmetric brake deflection and roll. (c) Curves of thrust, pitch and roll

5 Model of the PPUAV

Using the transfer functions, a mathematical model of Powered Parafoil UAV is obtained, which is used for trim control of the system. Fig. 11 shows the model and the specific expression of the model using transfer functions.



(a) (b)

Fig. 11. (a) Inputs and outputs of PPUAV. (b) Transfer functions expression of the model

6 Conclusion

The PPUAV is an excellent platform for surveillance, search and rescue and cargo delivery. The platform is nonlinear, time-varing and strongly coupled. Thus modeling of the PPUAV system is of great significance.

The model has been built by designing and conducting flight tests, analyzing the main relationship between inputs (left brake deflection, right brake deflection, symmetric brake deflection and thrust) and outputs (longitudinal velocity, vertical velocity, yaw rate, etc.), identifying transfer functions, analysing the effects of inputs on the secondary factors.

As an important future prospect, the model can be used for the design and analysis of new guidance and control approaches for parafoil systems as well as the design of new software tools for mission planning.

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