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Research article

Design of a fuzzy adaptive controller for a ducted fan (UAV)

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Abstract

Unmanned Aerial Vehicles (UAVs) are of great interest among mobile robots. Recently, a lot of researches aimed at promoting the technology of such robots, especially abilities of them in different applications like discovering missions, search and rescue, surveillance, academic researches, etc. The main focus of this paper is on a specific class of the UAVs, in which a fuzzy adaptive controller is developed to control a ducted fan. VTOL vehicles, blimps, rockets, hydroplanes, ships and submarines are generally underactuated which makes the control stage sever and requires more complex controllers. Herein, a fuzzy controller is employed to overcome this problem. Moreover, the design procedure for controller of a ducted VTOL mobile robot is presented.

Keywords: Doublet mechanics; Ducted fan UAV; Fuzzy controller; Dynamic model

1- Introduction

Nowadays, many governments and institutes are focusing on the small UAV for its low cost, small volume, low weight and flexible flight. There are few limits to its rise and fall. Thus, it can adapt to complicated environment, and also can be used in target recognition and localization. The technology of small UAV has brought a big challenge to the traditional control theory. Besides, for its high flexibility and strong adaptability, it has wide application prospect in both military and civil fields. In civil field, its high sensitivity, high accuracy and dependability in flight makes the small UAV competent in many applications, such as city traffic control, sowing and medicine for crops and forests, survey and drawing for complicated topographies [1, 2].

Ducted fans not only vertically take off and land, but can also hover and are controlled provided by the two counter rotors and four control surfaces (vanes) submerged in the slipstream flow from ducted fans [3, 4]. Making control surfaces fully submerged in the propeller slipstream from ducted fan is a critical technology to successfully achieve longitudinal transition. The conventional aircraft cannot achieve this transition because when they are climbing vertically at low speed, without a big enough free flow over their elevators which control pitching attitude, naturally the longitudinal transition is not able to be fulfilled in conventional aircraft as well as the UAVs [5]. For this reason, the prediction of the propeller slipstream effects is critical to the successful simulating of the full-scale UAV aerodynamic characteristics [6].

The major difference between ducted fan and other UAVs are a strong coupling effect and existence of a duct surrounding the rotor. When ducted fan UAV hovers, the vehicle is very unstable because of a strong coupling effect. Existence of a duct has some advantages for the vehicle. First of all, a duct guarantees safety more than any rotorcraft without it. The unshrouded propeller operating with high speed can do damage to somebody directly. On the other hand, if the craft bump into anything while it is operating, it can be damaged seriously by breaking the rotor. Secondly, a duct produces more efficient thrust with the same power. The thrust of a craft with a duct is increased approximately 21percent comparing with a ductless craft [7].

A typical ducted fan just has two actuators with three or six degree of freedom dependent of the desire of the operator; but generally ducted fan is an underactuated mechanical system. This feature makes the controlling method sever for a ducted fan to be tracked or stabilized. Also the interactions of the vehicle with the surrounding fluid are often difficult to model precisely whereas they may significantly influence and perturb its motion.

In recent years, there has been attention paid to ducted fans for propulsion of some special air vehicles which can achieve vertical taking-off and landing.

Ducted fans have a number of superioreties over open propellers in several technical aspects, e.g. fewer design compromises are required, the effective range of the ducted fan is larger than its physical range, and most of the noise is absorbed because of enclosing the propeller in a duct. Therefore, the associated technology as propulsion system is widespread in use of low speed VTOL (Vertically Take off and Land) aircraft and air-cushion vehicles. Finally, simulations and animations confirm these abilities of proposed controller.

2- Mechanical structure

A schematic view of a ducted fan prototype is shown in Fig. 1. As it is obvious in this figure, this vehicle is composed of a main duct, driving engine, propeller, and anti-torque and control rudders and landing legs. Increasing motor speed, we can increase the trust and adjust the vehicle altitude. Under the propeller, there are two levels of rudders with different structures. The first level rudders which rotate altogether but binary converse neutralize the motor torque. The second level rudders which are placed under the first level ones and outside the duct rotate together in the same direction to control the vehicle in the xy− plane. The major difference between ducted fan and other UAVs are a strong coupling effect and existence of a duct surrounding the rotor. When ducted fan UAV hovers, the vehicle is very unstable because of a strong coupling effect. Existence of a duct has some advantages for the vehicle. First of all, a duct guarantees safety more than any rotorcraft without a duct. The unshrouded propeller operating with high speed can do damage to somebody directly. On the other hand, if the craft bump into anything while it is operating, it will be damaged seriously by breaking the rotor. Secondly, a duct produces more efficient thrust with same power. The thrust of a craft with a duct is increased approximately 21 percent comparing with a ductless craft [8]. The unshrouded propeller has tip loss by escaping tip vortex at the blade tip. It results in rapid decrease in the lift at the tip. In addition, the duct tends to prevent air at the tip from escaping so that more thrust efficiency could be generated by lower energy loss. As a disadvantage of a duct, there are momentum drag and righting torque that disturb the forward flight at higher speeds [8]. As the craft forces the incoming flow in the duct to align it to downward, a reaction force is created, known as momentum drag. This force is same the mass flow of the air flow added crosswind velocity.

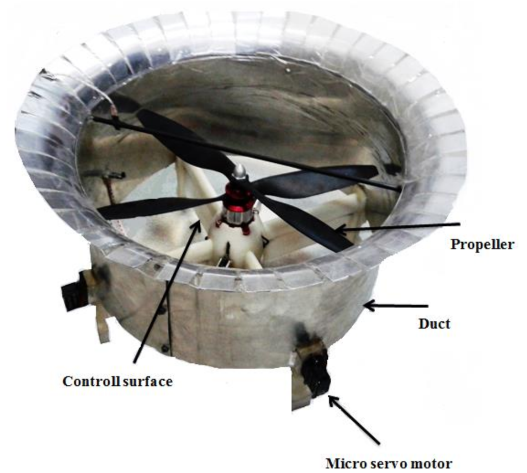

Fig. 1 Schematic of Ducted Fan unmanned aerial robot (made in labratoary control and robotic systems, Department of Electrical Engineering, Amirkabir University of Technology)

2- Dynamic model

Dynamic Model of a ducted fan can be derived from the concepts of fluid mechanic and by using the Bernoulli's equation [5]. Bernoulli's equation is a statement of Newton's law for an in viscid incompressible flow with no body force, which was not only derived from the momentum equation, but also derived from a general equation. Hence, an application of the Bernoulli's equation is in considering how the energy is changed with flow through a duct, such as that sketched in. The element theory of rotor blades [3] is defined as the blade divided into an infinite micro-blade, analyzing aerodynamic force and moment of each micro-blade and discovering the relationship among geometry specialty, motion and aerodynamic characteristics. Then, by integrating every blade and entire rotor, the total thrust and power can be calculated. Finally the dynamic equations of a ducted fan can be written as following:

$$\begin{aligned} X - mgS_\theta &= m(\dot u + qw - rv) \\ Y + mgC_\theta S_\phi &= m(\dot v + r - pw) \\ Z + mgC_\theta C_\phi &= m(\dot w + pv - qu) \end{aligned} \tag{1}$$

$$\begin{aligned} L &= I_x \dot p - I_{xx}\dot r + qr(I_z - I_y) - I_{xx} pq \\ M &= I_y \dot q + rp(I_x - I_z) + I_{xz}(p^2 - r^2) \\ N &= -I_{xz}\dot p + I_z \dot r + pq(I_y - I_x) + I_{xz} qr \end{aligned} \tag{2}$$

$$\begin{aligned} p &= \dot\phi - \dot\psi S_\theta \\ q &= \dot\theta C_\phi + \dot\psi C_\theta S_\phi \\ r &= \dot\psi C_\theta C_\phi - \dot\theta S_\phi \end{aligned} \tag{3}$$

$$\begin{aligned} \dot\theta &= qC_\phi - rS_\phi \\ \dot\phi &= p + qS_\phi T_\theta + rC_\phi T_\theta \\ \dot\psi &= (qS_\phi + rC_\phi)(\frac{1}{C_\theta}) \end{aligned} \tag{4}$$

where m represents the vehicle mass, g is the gravity, X, Y and Z are forces exerted to the vehicle L, M and N torques to the vehicle, u, v and w linear velocities and p, q and r angular velocities of the vehicle respectively in the body attached frame.

ϕ, θ and ψ are respectively roll, pitch and yaw angles of the ducted fan. S_x and C_x respectively stand for $\sin x$ and $\cos x$.
The external forces to the UAV are as below:

$$
\begin{aligned}
X &= \rho c_L S^{l2} \alpha_x V_e^2 \\
Y &= \rho c_L S^{l2} \alpha_y V_e^2 \\
Z &= T - \rho c_D (2S^{l1} + 4S^{l2}) V_e^2 + \\
&\rho (c_D S^{l2} (\alpha_x + \alpha_y) + 4 c_D S^{l1} \alpha) V_e^2
\end{aligned} \tag{5}
$$

In these equations, ρ is air density, c_L lift coefficient, c_D drag coefficient, α angle of attack of first level (anti torque) rudders, α_x and α_y the angle of attack of second level (control) rudders respectively in x and y directions, T the motor trust and S^{l1} and S^{l2} respectively are area of each of the first and second rudders. V_e Is the exiting wind velocity from the bottom of the duct which can be calculated as:

$$
V_e = \sqrt{\frac{2T}{\rho S_{disk}}} \tag{6}
$$

where S_{disk} represents the cross section area of the duct. Like the external forces, the external torques can be classified as:

$$
\begin{aligned}
L &= -Xd \\
M &= Yd \\
N &= 4c_L (S^{l1} / S_{disk}) d_T T \alpha + k_N \omega_P^2
\end{aligned} \tag{7}
$$

where d and d_T respectively are the distance from pressure center of the second level rudders to the vehicle center of mass and the distance between pressure centers of each of two contrary control rudders (see Fig. 1). ω_P Is the angular velocity of the propeller and k_N is a constant coefficient. It is noteworthy to say that in these equations, the drag force caused by horizontal motion of the vehicle, wind forces, drag forces of the rudders and also momentum drag of the duct are assumed to be zero. These assumptions are sufficiently correct for indoor hovering flights of the ducted fan UAV [9, 10].

4- Control algorithm

Feedback linearization techniques for nonlinear control system design have been developed in the last two decades [11], [12]. However, these techniques can only be applied to nonlinear systems whose parameters are known exactly. If the nonlinear system contains unknown or uncertain parameters then the feedback linearization is no longer utilizable. In this situation, the adaptive strategies are used to simplify the problem and to allow a suitable solution. At present, a number of adaptive control design techniques for nonlinear systems based on the feedback linearization can be found in literature [13]. These approaches simplify the nonlinear systems by assuming either linearly or nonlinearly parameterized structures. However, these assumptions are not sufficient for many practical applications. Recently, the fuzzy systems have been employed successfully in the adaptive control design problems of nonlinear systems.

Fuzzy logic controllers are in general considered being applicable to plants that are mathematically poorly understood and where the experienced human operators are available [14]. In indirect adaptive fuzzy control, the fuzzy logic systems are used to model the plant. Then a controller is constructed assuming that the fuzzy logic system approximately represents the true plant.

In this paper three fuzzy logic controllers (FLC) are designed for the navigation computer in order to control the altitude of a ducted fan. This controller acting in combination enables the navigation of the ducted fan aerial vehicle.

FLC is conceived as a better method for sorting and handling data but has proven to be an excellent choice for many control system applications because of non-linearity, complex mathematical computation and real-time computation need. It can be built into anything from small, hand-held products to large computerized process control systems. It uses an imprecise but very descriptive language to deal with input data more like a human operator. It is very robust and forgiving of operator and data input and often works when first implemented with little or no tuning. If the fuzzy controller types in literature are reviewed, it can be seen that there are two main classes of fuzzy controllers: one is position-type fuzzy controller which generates control input u from error e and error rate $\dot{e}$, and the other is velocity-type fuzzy logic controller which generates incremental control input from error and error rate. In the developed controller the same approach has been chosen and error and derivation of error are the inputs of the fuzzy controller. Fig. 2 presents a schematic of the proposed algorithm. Fig. 3 presents the membership functions of the error and derivation of the error. Fig. 4 shows the linguistic rules designed for the controller.

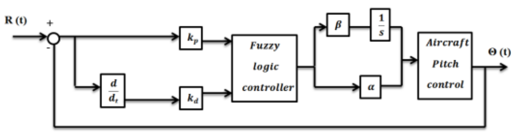

Fig. 2 Scheme of the proposed algorithm

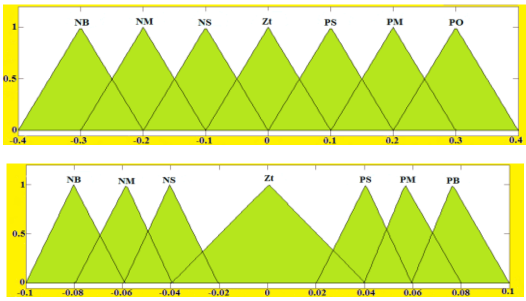

Fig. 3 The membership function of the error and derivation of the error

e \ e'	NB	NM	NS	Z	PS	PM	PB
NB	NVVB	NVB	NB	NM	NS	NVS	Z
NM	NVB	NB	NM	NS	NVS	Z	PVS
NS	NM	NS	NVS	Z	PVS	PS	PM
Z	NS	NVS	Z	PVS	PS	PM	PB
PS	NVS	Z	PVS	PS	PM	PB	PVB
PM	Z	PVS	PS	PM	PB	PVB	PVVB
PB	PVS	PS	PM	PB	PVB	PVVB	PVVB

Fig. 4 The membership function of the error and derivation of the error

5- Simulation

The performance and the potential of the proposed control approach are evaluated by using MATLAB standard configuration and the Aerosim Aeronautical Simulation Block Set, the aircraft simulated being Aerosonde UAV. Flight-Gear Flight Simulator is deployed in order to get visual outputs that aid the designer in the evaluation of the controllers. Despite the simple design procedure, the simulated test flights indicate the capability of the approach in achieving the desired performance. The numeric value of the simulated ducted fan is presented in TABLE I. In this simulation, the goal is to send the robot to different altitudes and keep it in that point. Results are depicted in Fig. 5 which shows the good ability of the proposed controller to track the reference point.

Table 1: constants of the simulated ducted fan

UAV's Constant	
Parameter	**Value**
m	0.8kg
I_{xx}	0.017
I_{yy}	0.017
I_{zz}	0.08
I_r	$6.5e^{-5}$
d	$3.13e^{-5}$
d_r	$7.5e^{-5}$
S_1	0.0981
S_l	0.23
S_{disk}	0.65

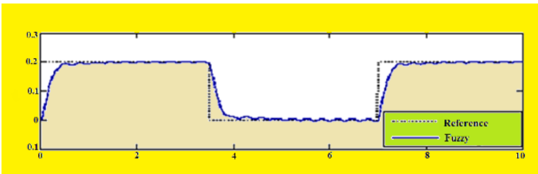

Fig. 5 Ability of proposed algorithm to track a reference point.

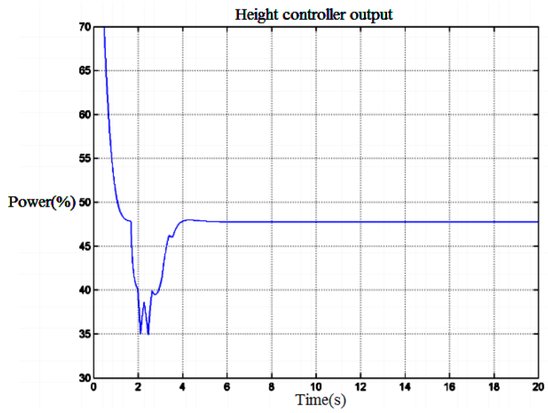

Fig. 6 Ducted fan altitude

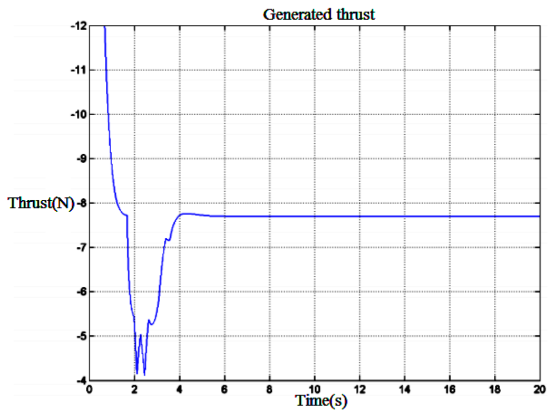

Fig. 7 Time history of the trust

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