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TECHNICAL NOTE

Designing and Modeling a Control System for Aircraft in the Presence of Wind Disturbance

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ABSTRACT

This paper proposes a switching adaptive control for trajectory tracking of unmanned aircraft systems. The switching adaptive control method is designed to overcome the wind disturbance and achieve a proper tracking performance for control systems. In the suggested system, the wind disturbance is regarded as a finite set of uncertainties; a controller is designed for each uncertainty, and a performance signal is obtained for switching between controllers through a set of visualizers. Each sub-system is robustly stable and the hysteresis logic-based switching is used to obtain the stabilization of a general system. The new system indicates more appropriate results for overcoming the air disturbance compared with the back-stepping adaptive controllers. Finally, the modeling results for the performance of the designed controller are presented.

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1. INTRODUCTION

In the past, manned vehicles have been used for performing the military or non-military actions in unknown and dangerous environments, which led to numerous casualties. In recent years, various unmanned vehicles have been designed for traveling on land, wind or even under the sea. However, unmanned aircrafts have received much more attention due to their various applications. These unmanned aircrafts are the best solution in dangerous situations and conditions, which act without the presence of a pilot and perform safe operations [1].

Today, there are various unmanned aircrafts with numerous capabilities, which are used for different applications including spy missions, mine detection, aerial surveying, being informed of and monitoring the war damages, extinguishing the forest fires, digital surveying or monitoring, research operations, collecting the information and pictures in dangerous environments, surveying the buildings, search and rescue, traffic controlling, border patrol, business tasks, etc. [1-3]. The applications (e.g., surveying, search and rescue, patrol and monitoring) need to the unmanned aircrafts so that they can track a pre-defined trajectory at a certain altitude independently [4].

The fundamental issue is that it is not easy to use the unmanned aircrafts and needs much attention. This is due to the fact that this vehicle can experience the external disturbance or its parameters undergo great variations.

To increase these unmanned aircrafts usefulness, it is necessary to apply the autonomous controllers for tacking a reference trajectory. Also, the robustness of these systems to the environmental turbulences needs to be taken into consideration. For instance, the unmanned aircrafts are considerably sensitive to the wind so that the wind size or volume can be comparable with the unmanned aircrafts velocity [2].

It is obvious that the successful performance of these unmanned aircrafts depends on the control exactness of flight controllers. Therefore, we need exact, robust and adaptive flight controllers. Although the linear controllers (e.g., PID or state feedback [5]) have simple structure and design, their performances follow the non-linear system characteristics or uncertainty and are

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influenced by temporal-varying parameters and break down. It can be said that the intelligent control systems, adaptive control systems, fuzzy systems or neural networks are a suitable solution to control the systems, such as unmanned aircrafts.

Hamidi [6] developed an adaptive control neural network and applied to the circular parts of the unmanned aircrafts wing. Johnson et al. [7] suggested a fuzzy logic control for the unmanned helicopters. Kakar [8] presented an application of an indirect adaptive fuzzy controller for controlling the unmanned aircrafts. The application of fuzzy and adaptive control methods are methods with high computational costs. In addition, tuning these controllers is considered as one of the challenges facing the adaptive fuzzy controllers design.

Liu et al. [9] used the gain scheduling control method for controlling a submarine vehicle, in which the controller is used for controlling a trajectory. In this method, six linear controllers are used for controlling the flight trajectory. Also, the external turbulence is ignored in this method. The adaptive methods are considered as appropriate alternatives when there is not an exact and suitable system model for controlling the systems with uncertainties. The Lyapunov theory based adaptive fuzzy control methods are used [10-13].

Hybrid control systems are defined as systems, which involve various types of dynamics. A variable is referred to as a “discrete variable” if it has finite values (countable) and a “continuous variable if it has values placed within the Euclidean space. The discrete states can transform their values via a parameter jump. Hybrid control systems are concerned with both these discrete and continuous dynamics. In general, it is more difficult to analyze and design the hybrid systems than pure continuous or discrete systems. The reason for this is that the discrete dynamics can influence the continuous trajectories and vice versa. The hybrid dynamics provide a suitable framework for modeling systems with various engineering applications.

In fact, switching controllers act like this: numerous flight controllers are suggested in the system and the best controller is selected among them using the switching law. The method used here differs from other regular adaptive control methods, which rely on continuous tuning. The findings indicate that a logic-based switching method can overcome the difficulties and restrictions of regular adaptive control systems [14].

Classic adaptive control methods have a set of intrinsic restrictions. If there is a state when the unknown parameters enter the control system or process in a complicated way, it is difficult to select and create a set of continuous candidate controllers. Also, it is difficult to estimate parameters in these methods. If the robustness and high-performance attributes are the main concern, this task would be more difficult.

The most important characteristics that distinguish switching adaptive controllers from regular switching adaptive controllers is the selection of controller (i.e., the logic-based switching is used for choosing the controller instead of continuous tuning, in which this is a type of the switching law).

Switching algorithms have high efficiency for evaluating the potential performance of candidate controllers. Therefore, they look for those controllers using this property [14]. They can be classified into two types: (1) those that are based on process estimation and use the confidence interval or model validation [15-18] and (2) those that are based on the direct evaluation of each candidate controller’s performance.

The idea of using switching algorithms for the adaptive control has been started, and numerous methods have been created and expanded in this regard [19-23]. The supervision and initial methods have been dealt with in the literature [24-27]. Then, these methods have been extended and analyzed [21, 28, 29].

Section 2 deals with the dynamic system modeling. In Section 3, the controllers are designed. The switching logic is presented in Section 4. Then, the simulation results are discussed in Section 5. Finally, the conclusion will be presented in Section 6.

2. SYSTEM MATHEMATICAL MODELING

It is assumed that aircrafts have the controlling systems, which have stabilized the length dynamics variables and the aircraft is flying at a constant velocity with a constant altitude. Therefore, the aircraft velocity is constant, the roll and pitch angles are small and the flight path angle is zero. Consequently, in the aircrafts dynamics and modeling, their time derivative will be ignored assuming that the roll and pitch angles are constant. With these assumptions, the control system design is only restricted to the proper direction torque (YAW) design for switching the aircraft path in terms of optimal trajectory.

For obtaining the aircraft motion equations, we use two reference coordination frameworks: The constant earth framework (FE) and constant body framework (FB). Since breadth-wise dynamics are taken into consideration, FE and FB are two-dimensional coordination systems. The FB center is placed in the center of flying object mass and its coordination axes are depicted in Figure 1. The FE framework is the inertia framework, which one of its axes is towards the North and the other one is towards the East.

In practical circumstances, the aircraft performance is influenced by various factors, such as wind disturbance. Consequently, the aircraft deviates from its normal trajectory.

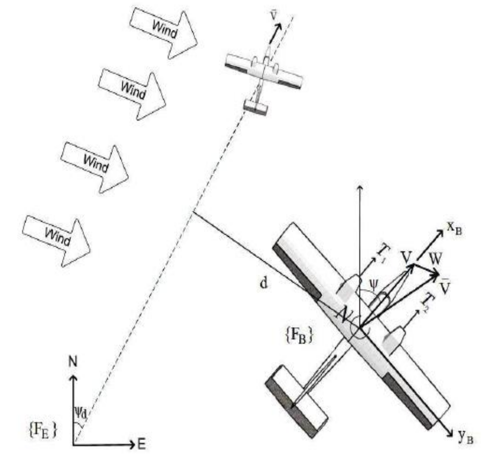

Figure 1. Aircraft position to reference frameworks [2]

The ratio of aircraft velocity to the earth can be expressed by:

$$\bar{V} = V + W \tag{1}$$

where V=$[u \quad v]T$ refers to the aircraft velocity to the local atmosphere and W represents the wind velocity to FE. It is assumed that the wind disturbance is vertical to the flight path. The wind velocity involves two functions: the W_N function is towards the North axis and W_E function is towards the East.

Assuming that $\bar{V}_8$=$[u^E \quad v^E]T$ is the aircraft velocity to the earth in the body system, Equation (2) can be derived using (1):

$$\begin{bmatrix} u^E \\ v^E \end{bmatrix} = \begin{bmatrix} u \\ v \end{bmatrix} + B_B \begin{bmatrix} W_N \\ W_E \end{bmatrix} \tag{2}$$

where B_B represents the transfer matrix from F_E framework to $F_{B.}$ Assuming that the pitch angle is constant, we obtain:

$$B_B = \begin{bmatrix} C_\theta C_\Psi & C_\theta S_\Psi \\ S_\phi S_\theta C_\Psi & S_\phi S_\theta C_\Psi + C_\phi S_\Psi \end{bmatrix} \tag{3}$$

where C_θ and S_θ indicate $Sin(\theta)$ and $Cos(\theta)$, respectively. Therefore, the differential equations for flight trajectory in F_E are as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = B_B^T \bar{V}_B \tag{4}$$

or

$$\dot{x} = u^E C_\theta C_\Psi + v^E S_\phi S_\theta C_\Psi - v^E C_\phi C_\Psi$$
$$\dot{y} = u^E C_\theta S_\Psi + v^E S_\phi S_\theta S_\Psi + v^E C_\phi C_\Psi \tag{5}$$

where,

$$u^E = u + W_V C_\theta C_\psi + W_E C_\theta S_\psi \tag{6}$$

and,

$$v^E = v + W_N S_\phi S_\theta S_\psi - W_N C_\phi S_\psi + W_E S_\phi S_\theta S_\psi - W_E C_\phi S_\psi \tag{7}$$

These equations represent the aircraft position in the inertia framework. X refers to the North axis and Y to the East axis.

Since the pitch and roll angles are considered small, we have $sin\{\theta, \phi\} = 0$ and $cos\{\theta, \phi\} = 1$. Assuming that the aircraft body is symmetrical and there is a turning rotor system, we can assume that V has a function only in the X axis. Therefore, we have:

$$v \ll 1$$
$$u \approx V \tag{8}$$

Consequently,

$$\dot{x} = VCos(\psi) + \omega Cos(\psi_\omega)$$
$$\dot{y} = VSin(\psi) + \omega Sin(\psi_\omega) \tag{9}$$

where $W_{\mathrm{N}} = \omega Cos(\psi_\omega)$ and $W_{\mathrm{N}} = \omega Sin(\psi_\omega)$‘ ω represent the wind velocity and ψ_ω indicated the wind direction. The aircraft motion to a constant trajectory in a straight line with ψ_d angle is expressed as relation (10):

$$\dot{x} = VCos(\psi - \psi_d) + \omega Cos(\psi_\omega - \psi_d)$$
$$\dot{y} = VSin(\psi - \psi_d) + \omega Sin(\psi_\omega - \psi_d) \tag{10}$$

Assuming that the aircraft engines produce the similar driving force; therefore, the rudder can be used to control the angular acceleration. The differential equation depicts this dynamics as follows:

$$\psi \approx r$$
$$\dot{r} = c\tau_\psi \tag{11}$$

where r refers to the side velocity, τ_ψ is the side, and c is a positive constant.

3. CONTROLLER DESIGN

The objective of control system design is that the aircraft can follow the ideal trajectory in the presence of wind disturbance with less error. Without simplification, we assume that the ideal trajectory conforms to the North axis and the ideal trajectory angle equals zero (ψ_d=0). Therefore, the wind is assumed as constant with slow temporal variations. Consequently, the aircraft dynamics system can be expressed by:

$$\dot{d} = \dot{y} = VSin\psi + k_\omega$$
$$\psi \approx r \tag{12}$$
$$\dot{r} = c\tau_\psi$$

where $k_\omega = \omega Sin\psi_\omega$ is considered constant with slow temporal variations. Also, *d* is the aircraft real distance from the ideal trajectory.

To design system controller, we assume that $\Theta \in R^{n\theta}$ is the uncertainty vector and involve all the system parameters which have uncertainties (e.g., system parameters and external disturbance), where n_θ is the number of unknown parameters. Assumption (1) is taken into consideration for the system controller design. The switching controller system can be depicted in Figure 2.

Assumption (1): The finite set of *P* including suggested parameters (candidates) $P = \{\Theta_1, \Theta_2, ..., \Theta_N\}$ is considered, in which the real and exact parameter Θ^* belongs to a finite set of *P* (in general, Θ^* needs to be enough close to one of the components of *P*).

We can obtain (13) applying the variable shift to the above system:

$$\begin{aligned} Z_1 &= d \\ Z_2 &= VSin\,\psi + k_\omega \\ Z_3 &= VrCos\,\psi \end{aligned} \tag{13}$$

Equation (14) can be derived by using Equation (13):

$$\begin{aligned} \dot{Z}_1 &= Z_2 \\ \dot{Z}_2 &= Z_3 \\ \dot{Z}_3 &= VuCos\,\psi - Vr^2 Sin\psi \end{aligned} \tag{14}$$

It can be turned into (15) by introducing the control law *u*:

$$u = \frac{1}{VCos\psi}(\mu + Vr^2 Sin\psi) \tag{15}$$

where μ represents the new control law. Finally, the closed-loop system is as follows (16) (i.e., feedback linearization system):

$$\begin{aligned} \dot{Z}_1 &= Z_2 \\ \dot{Z}_2 &= Z_3 \\ \dot{Z}_3 &= \mu \end{aligned} \tag{16}$$

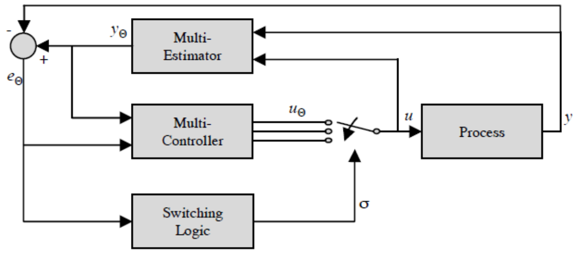

Figure 2. Switching control structure

Put it in simple words, this is a linear system that is equal to a function with transform (17):

$$G(s) = \frac{1}{s^3} \tag{17}$$

The Pole displacement control method is used for this linear system. First, it is to note whether we design μ in the way that the above system becomes stable, then the main system will change into a stable one. If Z_1 converges into zero, then *d* converges into zero and the other state variables will be restricted too. The algorithm for a linearization system in the state space will be as follows (18):

$$\begin{bmatrix} \dot{Z}_1 \\ \dot{Z}_2 \\ \dot{Z}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \mu \tag{18}$$

This system can be controlled by defining μ = -*KZ*, where *k* represents the state feedback gain vector and $Z = (Z_1, Z_2, Z_3)^T)$. Considering the above equations, Z_1 and Z_3 can be measured, but $Z_2 = VSin\psi + k_\omega$. Therefore, the only uncertainty in the feedback linearization switching system exists in variable Z_2. According to feedback linearization law (15), all the parameters are known and can be calculated for linearization of the system and the only uncertainty (k_ω) exists in state variable $Z_{2.}$ The value of this variable can be determined and calculated by using the switching law.

4. SWITCHING LOGIC

If the system can switch between various above-mentioned controllers that have been designed, it needs a proper logic for switching that guarantee the robustness and closed-loop performance. The state error of estimation is used for selecting and switching between controllers. Doing so, first, we define a performance signal based on state estimation error. The visualizer with a smaller performance signal has a more appropriate closed-loop signal. Therefore, the visualizer uses Θ parameter, which is closer to the value of vector k_ω of real parameter Θ^*. Consequently, we need to use controllers of the similar visualizer.

In this article, μ_Θ represents the performance signal and its dynamics is defined as (19):

$$\dot{\mu}_\Theta = -\lambda \mu_\Theta + \gamma_\Theta(y, d_\Theta) \tag{19}$$

where, λ represents a positive constant which is referred to as regression coefficient and γ_θ is the desired function cost. Also, μ_Θ dynamics is defined as follows (20):

$$\dot{\mu}_\Theta = -\mu_\Theta + \| \tilde{d}_\Theta \|_\infty^2 \tag{20}$$

Considering this performance signal, each visualizer with a smaller performance signal at each moment has a closer Θ to the value of real Θ and consequently, a proper controller needs to be selected for it.

5. SIMULATION RESULTS

For modeling, we assume that the aircraft flight path is in a straight line and conforms to the North axis, the wind blows with a seven velocity (meter/s) perpendicular to the flight path. The optimal flight path at 15, 40, and 60 time intervals of modeling is a straight line at 55, 110, and 160 degrees angles with the North axis. The initial circumstances can be shown as $d = 2m, \psi = -10^\circ, r = 0 rad/\sec$. Figure 3 depicts the external disturbance variation.

k_ω refers to the unknown parameter of the external disturbance of the system. This parameter is unknown but belongs to a set of P (21):

$$k_\omega \in P, P = \{-10,-9,-8,-7,-6,...,6,7,8,9\} \tag{21}$$

We assume that k_ω belongs to the set of (21) or at least has a value, which is enough close to one of the components of P and can choose one of the values of a set of P.

Therefore, there will be 20 autonomous controllers and 20 visualizers for this system. All the controllers and visualizers are parameterized in terms of k_ω. In feedback linearization controller, we place the closed-loop poles at $-5-j$ ، $-5+j$ ، -5.

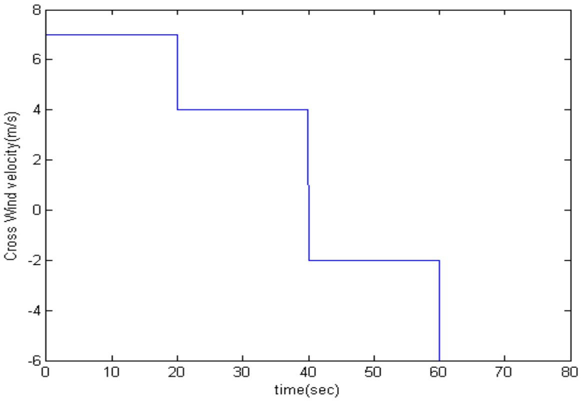

Figure 3. External disturbance variations

Consequently, the state feedback gain vector is obtained as $K = (130,76,15)$.

To compare the controller performance for tracking the optimal flight path, the adaptive step-tracking controller with disturbance estimation was designed by using the adaptation laws in terms of Equation (22).

$$\begin{aligned}
C\tau_\psi &= -\frac{e_3(L_2 + C_3) + e_2(L_3 + 1 - r^2) + e_1(L_4 + C_1 r^2)}{R} \\
&\quad - \frac{\hat{k}_{\omega 3}(L_1 + C_1 L_2) - \hat{k}_{\omega 2} C_1 L_2 - \hat{k}_{\omega 1}(L_1 - r^2)}{R} \\
\dot{\hat{k}}_{\omega 1} &= \gamma_1 e_1 \\
\dot{\hat{k}}_{\omega 2} &= \gamma_2 C_1 e_2 \\
\dot{\hat{k}}_{\omega 3} &= \gamma_3 e_3 (L_1 + C_1 L_2) \\
R &= \sqrt{V^2 - (e_2 - C_1 e_1 - \hat{k}_{\omega 1})^2}
\end{aligned} \tag{22}$$

where $L_1, L_2, L_3, L_4, C_1, C_2, C_3, \gamma_1, \gamma_2, \gamma_3$ refer to design positive coefficients and $\hat{k}_{\omega 1}, \hat{k}_{\omega 2}, \hat{k}_{\omega 3}$ represent wind estimation. Figure 4 depicts the performance of these two controllers. For a better comparison, the tracking performance of these two controllers is represented in Table 1 using various cost functions. Figure 5 represents the control effort for these two controllers.

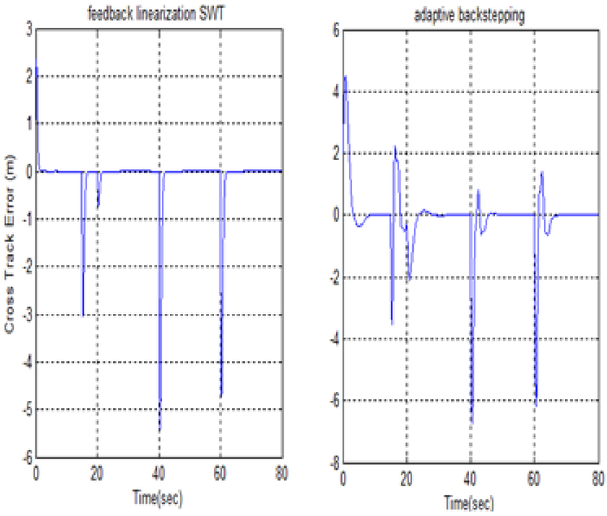

Figure 4. Comparison between two controllers tracking performance

TABLE 1. Trajectory tracking performance for two controllers

	ITSE	ISE	ITAE	IAE
Adaptive backtracking system	2847	94.3	949.5	33.71
Feedback linearization switching system	1386	34.06	420.1	11.65

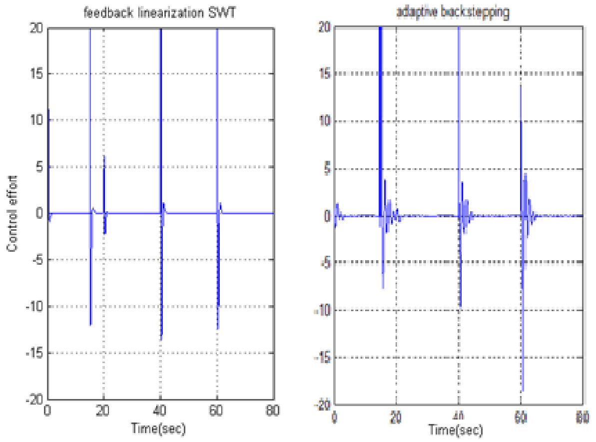

Figure 5. Comparison between control efforts of two controllers

The results indicate that the switching controller has more appropriate trajectory tracking performance. Also, this controller has a better control effort compared with other tracking controllers.

6. CONCLUSION

This article proposed a switching controller design and modeling for unmanned aircrafts in terms of a feedback linearization method. Doing so, a linear controller was designed using the state feedback linear controller. The wind disturbance was also assumed for the system. The results revealed that the switching adaptive controllers had superior trajectory tracking performance compared with back-stepping adaptive controllers.

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Logic-based Switching

چکیده

در این مقاله به کنترل سوئیچینگ هواپیمای بدون سرنشین پرداخته شده است. کنترل تطبیقی سوئیچینگ برای غلبه بر اغتشاش و بدست آوردن عملکرد مناسب برای سیستم طراحی شده است. در این روش پیشنهادی، اغتشاش باد به صورت مجموعه‌ای محدود از عدم قطعیت‌ها در نظر گرفته شده، برای هر عدم قطعیت یک کنترل‌کننده طراحی شده، سپس یک سیگنال عملکرد برای سوئیچینگ بین کنترل‌کننده‌ها با استفاده از مجموعه‌ای از رویتگرها بدست می‌آید. هر زیر سیستم پایدار بوده و برای بدست آوردن پایداری سیستم کلی، از منطق سوئیچینگ هیسترزیس استفاده شده است. در مقایسه با کنترل کننده‌های تطبیقی پسگام، نتایج مناسب‌تری برای غلبه بر اغتشاش باد حاصل شده است. نتایج شبیه سازی برای نشان دادن عملکرد کنترل‌کننده طراحی شده، ارائه شده است.

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