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# Way Point Tracking of Fixed-Wing Unmanned Aerial Vehicles Using Backstepping Controller and Fuzzy Logic

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## ABSTRACT

***Keywords***: *Backstepping controller, Fuzzy guidance, Way point tracking, Unmanned aerial vehicles*

*Nowadays, operational usage of Unmanned Aerial Vehicles (UAVs) in various missions is increasing, considering their capabilities. Provided that there is coordination between the UAV, navigation and control system, the operational capability of the UAVs increases. Since there is no pilot in UAVs, the task of guidance and control of the UAV for carrying out the mission depends on the ability of the autopilot and guidance system. This paper regards the control and the guidance as separate entities in the waypoint tracking problem. To do so, the outer loop generates the backstepping controller design for the inner loop to track the commands. The outer loop is designed based on fuzzy logic. The proposed system uses standard Mamdani fuzzy controllers that provide autopilot speed, heading, and flight path angle references. Nonlinear six-degree-of-freedom equations of motion are used to model the vehicle dynamics. Simulations were carried out to verify the performance of the system. The results indicate the ability of the waypoint tracking system to track the desired set of waypoints.*

## NOMENCLATURE

| | |
|---|---|
| $C_D$ | Drag coefficient |
| $C_L$ | Lift coefficient |
| g | acceleration of gravity |
| m | Mass |
| p, q, r | roll, pitch, yaw rates |
| $\varphi,\theta,\psi$ | Euler Angles (roll, pitch, yaw angles) |
| $\beta$ | sideslip angle $\alpha$ angle of attack |
| χ | aerodynamic heading angle |
| $I_X, I_y, I_z$ | Moment of inertia |
| $I_{xz}$ | Product of inertia |
| $I_1$ to $I_9$ | combination of moments of inertia |
| D, L, Y | aerodynamic force |
| T | trust force |
| $l_{aero}, m_{aero}, n_{aero}$ | rotational moment |
| V | velocity of aircraft |
| $\delta_a, \delta_e, \delta_r$ | Control Surfaces |
| $\delta_t$ | Throttle Deflection |

## Introduction

The advances in the design and application of various types of UAVs and improvement of their operational capabilities require technological advances in different fields (aerodynamics, structure, material, propulsion, guidance and flight control, etc.). Since there is no pilot in the UAVs, the task of guidance and control of the UAV for carrying out the mission depends on the ability of

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the autopilot and guidance system. The rapidly growing use of UAVs has focused on the need for autonomous attitude and trajectory tracking [1].

There are two approaches for trajectory tracking of autonomous vehicles [2, 3]. One method separates the guidance and control problems into an outer guidance loop and an inner control loop. The inner loop controls the vehicle so that it can follow the commands generated by the outer loop. The other method uses an integrated approach wherein the inner and outer loops are designed simultaneously. In this case, a number of modern control design techniques can be applied, such as the gain-scheduling technique [4], receding horizon [5], differential flatness [6], and neural network-based adaptive controls [7]. In actual flight applications, the separate inner and outer loop approach is more commonly taken because it is usually simpler, and well-established design methods are available for inner-loop vehicle control.

Several nonlinear approaches have been proposed for the guidance of unmanned vehicles. In [8] and [9], a vector field-based path following guidance law was developed. Straight lines and circles were employed to validate the algorithm, and Lyapunov stability arguments were also presented. In [10], a Lyapunov approach was used to control the vehicle velocity vector to ensure convergence to a limit cycle. The algorithm combines both trajectory-tracking and path-following objectives using the Lagrange multiplier method. The controller was developed using a Lyapunov-based backstepping technique employed in [11 to 13]. Reference [14] presents an approach that can accommodate large cross-track or heading deviations from a straight-line path between waypoints. In [15], a five-dimensional guidance law is proposed for the trajectory tracking problem in which fuzzy controllers are used to produce smooth and bounded commands; however, the flight path angle is not followed, and no coordination between generated commands is considered.

Various control approaches have been studied to design an autopilot in UAVs. Neural networks have recently been proposed as an adaptive controller for nonlinear systems [16]. Using their universal approximation capability, the adaptive controller based on neural networks can be designed without significant prior knowledge of the system dynamics. In flight control problems, the applications of adaptive neural networks can be found in [17, 18]. An adaptive scheme is redesigned in which the controller can handle low-level autopilot parametric uncertainties [19]. In [20], a kinematic tracking controller is proposed for fixed-wing UAVs. In this control design, the assumed control inputs are the command references of the UAV's airspeed, heading, and altitude control systems. Moreover, only the heading control dynamic model is used in the control design. In [21], the tracking control framework is extended to an adaptive scheme where the controller is redesigned to handle low-level autopilot parametric uncertainties.

In this paper, the procedure of the guidance system is based on a fuzzy logic controller that commands the vehicle via its autopilot to approach a specified set of waypoints. This paper proposes a backstepping controller for a nonlinear fight dynamic system in the inner loop for the controller. First, only a small subsystem is considered, for which a virtual control law is constructed. Then, the design is extended in several steps until a control law for the entire system has been constructed. Using a backstepping system, nonlinearities do not have to be cancelled in the control law. Figure 1 shows the UAV tracking control system implementation architecture.

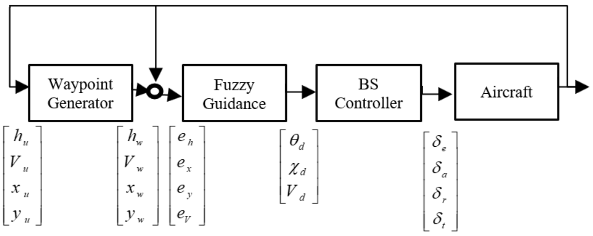

**Figure 1.** UAV tracking control system implementation architecture

## AIRCRAFT MODEL

Aircraft dynamics assuming flat ground are written by first-order nonlinear differential equations as follows [22]

$$\dot{V} = g\begin{pmatrix}\cos\phi\cos\theta\sin\alpha\cos\beta+\sin\phi\cos\theta\sin\beta \\ -\sin\theta\cos\alpha\cos\beta\end{pmatrix} + \frac{1}{m}\left(-D\cos\beta+T\cos\beta\cos\alpha\right) \tag{1}$$

$$\dot{\alpha} = q-\left(p\cos\alpha+r\sin\alpha\right)\tan\beta+\frac{1}{mV\cos\beta}\left(-L-T\sin\alpha\right) + \frac{g}{V\cos\beta}\left(\cos\phi\cos\theta\cos\alpha+\sin\alpha\sin\theta\right) \tag{2}$$

$$\dot{\beta} = p\sin\alpha-r\cos\alpha+\frac{g}{V}\cos\beta\sin\phi\cos\theta+\frac{Y\sin\beta}{mV}+ \frac{\sin\beta}{V}\left(g\cos\alpha\sin\theta-g\sin\alpha\cos\phi\cos\theta-\frac{T\cos\alpha}{m}\right) \tag{3}$$

$$\dot{p} = I_2pq+I_1qr+I_3l_{aero}+I_4n_{aero} \tag{4}$$

$$\dot{q} = I_5pr+I_6\left(r^2-p^2\right)+I_7m_{aero} \tag{5}$$

$$\dot{r} = I_8 pq - I_2 qr + I_4 l_{aero} + I_9 n_{aero} \tag{6}$$

$$\dot{\phi} = p + \left(q \sin\phi + r \cos\phi\right) \tan\theta \tag{7}$$

$$\dot{\theta} = q \cos\phi - r \sin\phi \tag{8}$$

$$\dot{\psi} = \left(q \sin\phi + r \cos\phi\right) \sec\theta \tag{9}$$

$$\begin{aligned} \dot{x} = V\ (&\left(\sin\beta \sin\phi + \sin\alpha \cos\beta \cos\phi\right) \cos\psi \sin\theta \\ &+ \cos\alpha \cos\beta \cos\psi \cos\theta - \sin\beta \cos\phi \sin\psi \\ &+ \sin\alpha \cos\beta \sin\phi \sin\psi) \end{aligned} \tag{10}$$

$$\begin{aligned} \dot{y} = V\ (&\left(\sin\beta \sin\phi + \sin\alpha \cos\beta \cos\phi\right) \sin\psi \sin\theta \\ &+ \cos\alpha \cos\beta \sin\psi \cos\theta + \sin\beta \cos\phi \cos\psi \\ &- \sin\alpha \cos\beta \sin\phi \cos\psi) \end{aligned} \tag{11}$$

$$\dot{h} = V \begin{pmatrix} \cos\beta \cos\alpha \sin\theta - \sin\beta \sin\phi \cos\theta \\ - \cos\beta \sin\alpha \cos\phi \cos\theta \end{pmatrix} \tag{12}$$

In the above equations, the first three equations specify equations of motion relative to the aircraft velocity vector. The second three equations are equations of the rotational dynamics of an aircraft. The third and second equations determine orientation relative to the gravity vector. The last three equations imply that the rotation velocity vector is relative to the inertial reference.

## Controller Design of Tracking System

Backstepping is a relative control algorithm for nonlinear systems that utilize Lyapunov synthesis to drive a stabilizing controller. The name backstepping refers to the recursive nature of the design procedure. It is a recursive procedure that interlaces the choice Lyapunov function with the design of feedback control. By exploiting the extra flexibility with the lower order and scalar systems, backstepping can often solve stabilization, tracking, and robust control under conditions less restrictive than those encountered in other methods [23]. The controller is designed using the backstepping approach, assuming all aerodynamic coefficients are fully available. Backstepping is a systematic method for nonlinear control design [24].

## Backstepping Controller Design

In this paper, with the slow states $\left[\theta, \beta, \phi\right]^T$ , the controller is designed in the outer loop, and a separated inner-loop controller is designed to make the fast states $\left[p, q, r\right]^T$ follow the outer loop's commands. By definition, the states $x_1 = \left[\theta, \beta, \phi\right]^T$ , $x_2 = \left[p, q, r\right]^T$ and $u = \left[\delta_e, \delta_a, \delta_r\right]^T$ the flight dynamic equation can be written as

$$\begin{aligned} \dot{x}_1 &= f_1 + g_1 x_2 + g_{1a} x_2 + h_1 u + f_{1g} \\ \dot{x}_2 &= f_2 + f_{2a} x_2 + g_2 u \end{aligned} \tag{13}$$

By defining error dynamics as

$$\begin{aligned} z_1 &= x_1 - x_1^d \\ z_2 &= x_2 - x_2^d \end{aligned} \tag{14}$$

## Apply for Outer Loop

By considering the Lyapunov function candidate as

$$V = \frac{1}{2} z_1^2 \tag{15}$$

To have a negative definite derivative function

$$x_2^d = g_1^{-1} \left(-k_1 z_1 - f_1 - f_{1g} + \dot{x}_1^d\right) \tag{16}$$

## Apply for Inner Loop

By considering the Lyapunov function candidate

$$V_1 = \frac{1}{2} z_1^2 + \frac{1}{2} z_2^2 \tag{17}$$

Thus,

$$u = g_2^{-1} \left(-k_2 z_2 - z_1 g_{1a} - z_1 g_1 - A\right) \tag{18}$$

$$\begin{aligned} A = f_2 + f_{2a} x_2 - \frac{\partial x_2^d}{\partial x_1} &\left(f_1 + g_1 x_2 + g_{1a} x_2 + f_{1g}\right) \\ - g_1^{-1} &\left(k_1 \dot{x}_1^d + \ddot{x}_1^d\right) \end{aligned} \tag{19}$$

## Velocity Backstepping Controller

In order to control the velocity, it is necessary to determine a control variable. In this case, a necessary thrust to track velocity is determined. By defining error dynamics and its derivative as

$$z_V = V - V_d \tag{20}$$

By considering the Lyapunov function candidate as

$$V_L = \frac{1}{2} z_V^2 \tag{21}$$

$$\dot{V}_L = z_V \begin{pmatrix} \frac{1}{m}\left(-D + Y\ \sin\beta - mg \sin\gamma + T\ \cos\beta \cos\alpha\right) \\ -\dot{V}_d \end{pmatrix} \tag{22}$$

Thus,

$$T^d = \frac{m}{\cos\beta \cos\alpha} \left(-k z_v + \frac{D}{m} + g \sin\gamma - \frac{Y}{m} \sin\beta + \frac{\dot{V}_d}{m}\right) \tag{23}$$

## Calculation of desired bank angle from yaw angle error

The yaw controller structure has two loops. Yaw angle error is minimized using bank angle in the outer loop. In order to generate an appropriate bank angle for minimizing yaw error, a proportional controller is used. If yaw angle errors exist, the controller would generate a bank angle that rotates UAV and acquire minimum heading error. The inner loop of the bank angle controller includes a backstepping controller.

### Final AL Yaw Angle for Backstepping Controller

The sideslip angle is held zero in designing backstepping controller, so the yaw angle can be assumed equal to the aerodynamic heading angle [25].

### Guidance System Design of Tracking System

The overall guidance scheme has two components: a waypoint generator and the actual fuzzy guidance system.

The selection of fuzzy systems arises primarily from specifying the desired waypoint's crossing direction because traditional proportional guidance techniques do not allow it. A fuzzy guidance system is chosen because it can reach a set of waypoints in a prescribed order, handle a sequence of waypoints, and quickly reconfigure the waypoints set, in response to changes in mission scenario.

Considering the research conducted by the authors, triangular membership functions with proper overlap are used as fuzzy membership functions with the purpose of increasing regulation speed and continuity in system response.

The aircraft guidance problem is addressed by assuming the presence of an inner autopilot loop for tracking commanded velocity, flight path, and heading angle. The outer-loop FGS generates a reference for the autopilots in order to reach the desired waypoint. The aircraft plus autopilot model is assumed to track desired velocity, flight path angle, and heading angle.

### Altitude Fuzzy Controller

In designing altitude control system, altitude error is written as follows:

$$e_H = H_w - H_u \tag{24}$$

Where $H_w$ and $H_u$ are the altitude of the waypoint and altitude of the UAV, used as an input to the control system. According to the inference method, the fuzzy system output gives the flight path angle required to reach desired conditions. In order to use the FLC, a rule base is developed. Four rules are used in this problem, corresponding Table 1.

**Table 1.** Fuzzy rule-base for altitude controller

| FLC 1 | | | | | |
|---|---|---|---|---|---|
| $e_H$ | NB | NS | Z | PS | PB |
| $f_H$ | NB | NS | Z | PS | PB |

### Velocity Fuzzy Controller

The desired velocity is achieved via the velocity controller, which computes the desired aircraft velocity depending on the velocity error as a corrective velocity term.

$$e_V = V_w - V_u \tag{25}$$

$V_w$ is desired waypoint crossing velocity and $V_u$ is the velocity of the UAV. In order to use the FLC, a rule base is developed. Three rules are used in this problem corresponding to Table 2.

**Table 2**. Fuzzy rule-base for velocity controller

| FLC 2 | | | |
|---|---|---|---|
| $e_V$ | N | Z | P |
| $f_V$ | N | Z | P |

From which the final velocity given to the backstepping controller can be obtained as follows:

$$V_{BS} = V_w + f_V\left(e_V\right) \tag{26}$$

### Heading Fuzzy Controller

The third fuzzy controller is applied to generate the desired heading angle $\chi_d$ using the position errors along the X and Y axis of the actual waypoint frame.

$$e_x = X_w - X_u \tag{27}$$

$$e_y = Y_w - Y_u \tag{28}$$

Where $X_w, Y_w$ are the position of the waypoint along the X and Y axis and $X_u$, $Y_u$ position of the UAV along the actual waypoint frame. In order to use the FLC, a rule base is developed. Twenty-five rules are used in this problem, corresponding to Table 3.

From which the final heading angle is given to the backstepping controller can be obtained as follows:

$$\chi_d = \chi_w + f_\chi\left(e_x, e_y\right) \tag{29}$$

**Table 3**. Fuzzy rule-base for heading angle controller

| FLC 3 | | $e_x$ | | | | |
|---|---|---|---|---|---|---|
| | | NL | NS | ZE | PS | PL |
| $e_y$ | NL | NL | NLL | NM | NS | NSS |
| | NS | NL | NL | NM | NSS | NSS |
| | ZE | PLLL | PLLL | ZE | ZE | ZE |
| | PS | PL | PL | PM | PSS | PSS |
| | PL | PM | PLL | PM | PS | PSS |

## Switching Between Waypoints

The desired trajectory is specified in terms of a sequence of waypoints without any requirements on the path between two successive waypoints. It is not necessary for the UAV to reach one waypoint exactly and then fly to another. In this paper, the parameter $\delta p$ is used to evaluate whether UAV reaches one waypoint or not. By considering

$$V_1 = \begin{bmatrix} w_x^{t+1} \\ w_y^{t+1} \end{bmatrix} - \begin{bmatrix} w_x^{t} \\ w_y^{t} \end{bmatrix} \tag{30}$$

$$V_2 = \begin{bmatrix} x \\ y \end{bmatrix} - \begin{bmatrix} W_x^{t} \\ W_y^{t} \end{bmatrix} \tag{31}$$

$$\eta = a\cos\left( \frac{dot\left(V_1, V_2\right)}{\left|V_1\right| . \left|V_2\right|} \right) \tag{32}$$

$$projV_2 = V_2 \cos\left(\eta\right) \tag{33}$$

$$dir = \left|V_1\right| - \left|projV_2\right| \tag{34}$$

If $dir < \delta p$ , the UAV switches to a subsequent waypoint. Figure 2 shows how the UAV passes from one waypoint to another.

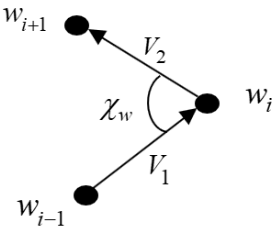

**Figure 2.** Switching between waypoints

## Simulation Results

In order to evaluate the controllers that are designed, the response of the controllers to track a set of specific waypoints is assessed. The UAV has to soar up to specific waypoints in 50 m to 1200 m with a 1000 m radius and a velocity of 20 *m/s* then track the specific waypoints in a circular path with a 1000 m radius and constant altitude of 1200 m and a velocity of 30 *m/s*.

The designed system consists of the inner loop and the outer loop controllers as well as the UAV dynamics that were tested in a scenario with a nonlinear simulation environment developed by using MATLAB®/Simulink. The simulation results in this section are based on a full six-degree-of-freedom twelve-state model equipped with low-level autopilots.

The trajectory of the UAV in the X-Y-Z plane and X-Y plane are illustrated in Figure 3 and Figure 4. Variations of control surfaces and throttle are illustrated in Figure 5. Variations of the input of the backstepping controller are illustrated in Figure 6. The red lines are the commands that must be tracked and the blue lines are the calculated vehicle response. Variations of sideslip angle, angle of attack and velocity are illustrated in Figure 7. Velocity must remain at 20 *m/s* in variable height and 30 *m/s* in fixed altitude. The velocity magnitude remains constant according to the commands.

The figures show that all of the vehicle states are tracked closely throughout the duration of the maneuver. Also, the flight path and heading angles track very closely.

As evidenced in these figures, the overall tracking performance has satisfactory results. This means that the whole control system can provide highly acceptable tracking ability.

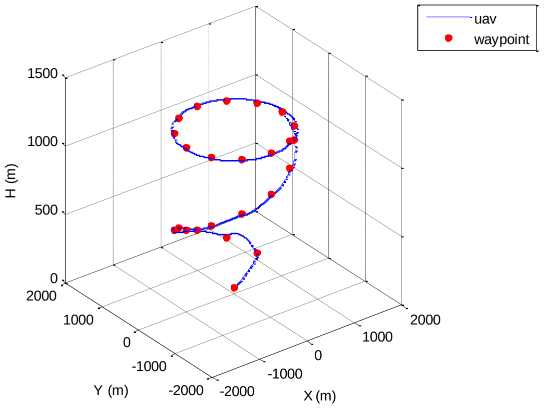

**Figure 3.** The trajectory of UAV in x-y-z plane

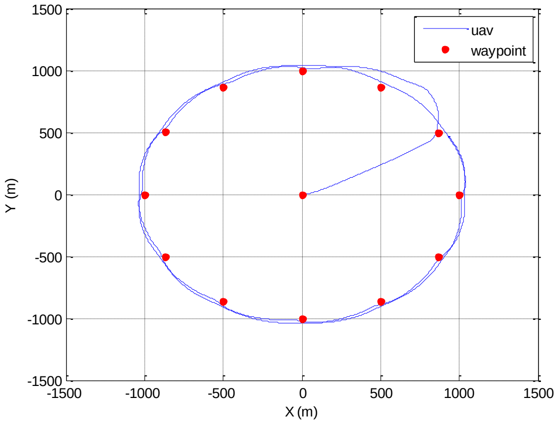

**Figure 4.** The trajectory of UAV in x-y plane

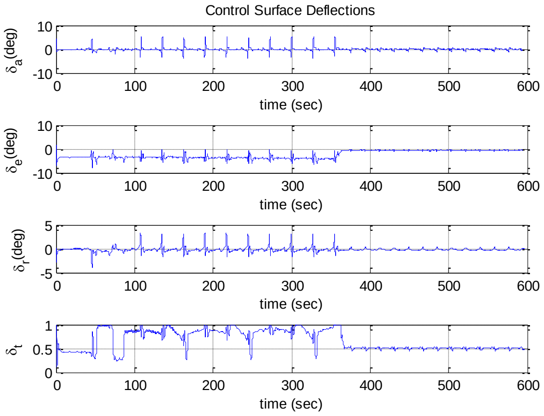

**Figure 5.** Variations of control surfaces and throttle

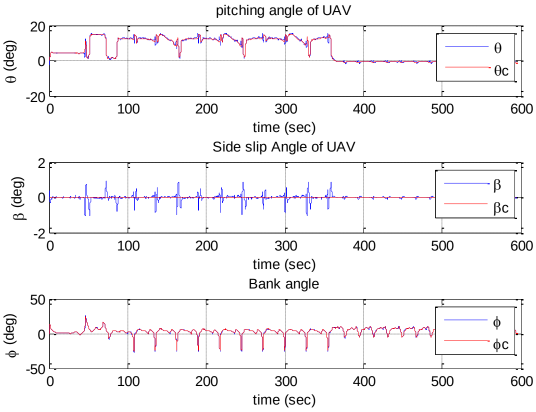

**Figure 6.** The input of the backstepping controller

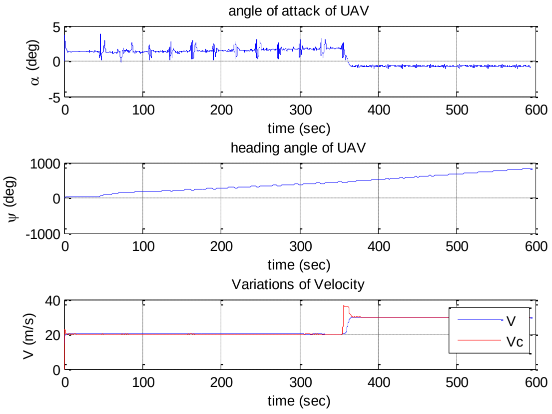

**Figure 7.** The sideslip angle, Angle of attack and Velocity

# CONCLUSIONS

In this study, for the waypoint tracking problem, the vehicle guidance and control problems are separated into an outer guidance loop and an inner control loop. A new guidance law based on the fuzzy logic was used in this paper to control the outer loop of waypoint tracking problem. In the inner loop, the backstepping controller is used to track the guidance commands with the assumption that the aerodynamic characteristics are fully understood. Aerodynamic angles horizontal and vertical flight path angles and bank angles and velocity commands are successfully controlled via the backstepping controller. In the outer loop, a fuzzy guidance system is designed to generate guidance commands for the inner loop. The simulation results are indicative of the fact that the designed controller is capable of controlling specific UAVs.

As a suggestion to continue this work, it is necessary to test the robustness of controllers in relation to parameter changes or by considering the effects of hurricanes.

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