# Guidance Law for Vision-Based Automatic Landing of UAV

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## Abstract

In this paper, a guidance law for vision-based automatic landing of unmanned aerial vehicles (UAVs) is proposed. Automatic landing is a challenging but crucial capability for UAVs to achieve a fully autonomous flight. In an autonomous landing maneuver of UAVs, the decision of where to landing and the generation of guidance command to achieve a successful landing are very significant problem. This paper is focused on the design of guidance law applicable to automatic landing problem of fixed-wing UAV and rotary-wing UAV, simultaneously. The proposed guidance law generates acceleration command as a control input which derived from a specified time-to-go ($t_{go}$) polynomial function. The coefficient of $t_{go}-$ polynomial function are determined to satisfy some terminal constraints. Nonlinear simulation results using a fixed-wing and rotary-wing UAV models are presented.

**Key Word** : Guidance law, Vision-based, Automatic landing, Fixed-wing, Rotary-wing, $t_{go}-$ polynomial, Terminal constraints, Nonlinear simulation.

## Introduction

Two main capabilities are required for an automatic landing of UAVs. The first one is decision of where to land, and the second one is generating the guidance command to guide UAVs for a safe landing. A typical automatic landing system[1,2] of manned aircraft uses a radio beam directed upward from the ground. The onboard equipment of an aircraft measures the angular deviation from the beam and compute the perpendicular displacement of the aircraft from a given flight path angle in vertical channel. Also, additional equipment is used to provide azimuth information, so that the aircraft can be aligned with the runaway. Unfortunately, it is impossible to equip these instruments in UAV system which should have the ability to launch and recover in various uncontrolled environments for the flexibility in operations. Thus, recently vision-based approaches to the problem of automatic landing have been widely studied[3-5]. Most of these approaches involve using image processing technique[6,7]. However, it is hard to find the research on guidance and control problem effectively applicable to UAV systems[8,9].

The object of this paper is to design a guidance law successfully applicable to automatic landing problem of UAVs with vision sensors. The proposed guidance law was derived by using the concept of missile-target intercept. We can observe that the control inputs derived from optimal guidance problems[10-14] can be represented as a function of time-to-go $t_{go}$. Based on this result, we initially

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assume the guidance command as a polynomial form of $t_{go}$ and determine the coefficient of $t_{go}-$ polynomial function to satisfy the terminal constraints. Also, to obtain the robustness against $t_{go}$ estimation error, two additional constraint on acceleration and time-derivative of acceleration are considered. The proposed $t_{go}-$ polynomial guidance law was applied to automatic landing problem of a fixed-wing UAV and a rotary-wing UAV. From the nonlinear simulation results, we conclude that the proposed guidance law shows a satisfactory performance in automatic landing problem of these two different type UAVs.

## Guidance Law Design

Now, consider the homing guidance geometry for a stationary target as shown in Fig. 1. In Fig. 1, $V_m(t)$, $\theta(t)$, and $\theta_f$ denote, respectively, the missile velocity, the flight path angle, and the predetermined impact angle at the final time. Also, $a(t)$ is the acceleration applied normal to the velocity vector to change the flight path angle $\theta(t)$.

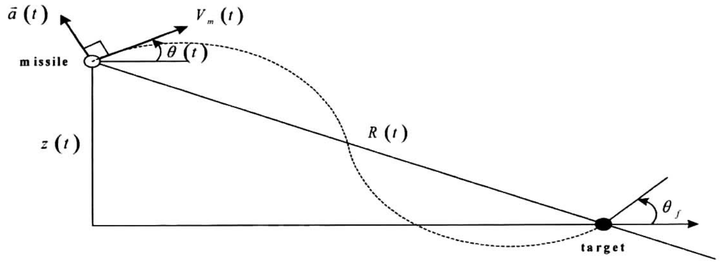


**Fig. 1. Homing guidance geometry**

The equation of motion in this homing problem can be represented as

$$\begin{aligned} \dot{z}(t) &= V_m(t)\sin\theta(t) \\ V_m(t)\dot{\theta}(t) &= a(t) + \bar{g} \end{aligned} \tag{1}$$

where $\bar{g}$ means a gravitational acceleration components in lateral direction. If the autopilot lag of the system is neglected, then the control input is $u(t) = a(t)$. Under the assumption that missile velocity $V_m(t)$ is constant and the flight path angle $\theta(t)$ is small, Eq. (1) can be linearized as

$$\begin{aligned} \dot{z}(t) &= V_m\theta(t) = v(t) \\ \dot{v}(t) &= a(t) + \bar{g} \end{aligned} \tag{2}$$

Generally, the control inputs of optimal guidance laws are obtained to minimize the quadratic cost function subjected to some terminal constraints by using the linearized dynamics shown in Eq. (2). These optimal guidance commands are represented as a function of time-to-go $t_{go}$[10-13]. The main obstacle to implement these optimal guidance law is how to precisely obtain $t_{go}$. Estimation error on $t_{go}$ might induce severe terminal miss distance and impact angle error.

### $t_{go}-$ polynomial guidance law

In this paper, we initially assume the guidance command as a polynomial form of $t_{go}$, and select the coefficients of this polynomial function to satisfy the predetermined terminal constraints by integrating the dynamics. The proposed guidance law called a $t_{go}-$ polynomial guidance law which can easily determine the lateral acceleration and its time-derivative having the desired values. We can consider two constraints on the lateral acceleration as follows:

constraint I : lateral acceleration should be zero at the final time

$$a_y(t_f) = 0$$

constraint II : time-derivative of lateral acceleration should be zero at the final time

$$\frac{da_y}{dt}(t_f) = 0$$

Consideration of the second constraint is further desirable to obtain a robust guidance law against $t_{go}$ estimation error since, in real application, it is so hard to precisely satisfy the first constraint caused by $t_{go}$ estimation error. In the proposed $t_{go}-$ polynomial guidance law, we choose an acceleration command as

$$a(t) = c_0 + c_1(t_f - t) + c_2(t_f - t)^2 + \cdots \tag{3}$$

In Eq. (3), the coefficient $c_0$ and $c_1$ of $t_{go}-$ polynomial should be zero ( $c_0 = c_1 = 0$ ) to satisfy the constraints I and II, simultaneously. Since the required number of coefficients to determine a unique solution satisfying the terminal constraints $z(t_f) = 0$ and $v(t_f) = 0$ is two, the acceleration command in Eq. (3) can be selected as follows:

$$a(t) = c_m(t_f - t)^m + c_n(t_f - t)^n \quad , \quad m \neq n \tag{4}$$

If $m > 1$ and $n > 1$, then the constraints I and II are simultaneously satisfied. Substituting Eq. (4) into Eq. (2) and then integral, the position and velocity at the terminal time are written as

$$v(t_f) = v(t_0) + \bar{g}\, t_{go} + \left(\frac{t_{go}^{m+1}}{m+1}\right) c_m + \left(\frac{t_{go}^{n+1}}{n+1}\right) c_n \tag{5}$$

$$z(t_f) = z(t_0) + v(t_0)\, t_{go} + \frac{1}{2}\bar{g}\, t_{go}^2 + \left(\frac{t_{go}^{m+2}}{m+2}\right) c_m + \left(\frac{t_{go}^{n+2}}{n+2}\right) c_n \tag{6}$$

where $t_{go} = t_f - t_0$. From Eqs. (5) and (6), the coefficients $c_m$ and $c_n$ satisfying the terminal constraints $z(t_f) = 0$ and $v(t_f) = 0$ can be determined as

$$c_m = p_1\left[-(n+1)\, t_{go}^{-1}\, v_b + (n+2)\, t_{go}^{-2}\, z_b\right] t_{go}^{-m} \tag{7}$$

$$c_n = p_2\left[-(m+1)\, t_{go}^{-1}\, v_b + (m+2)\, t_{go}^{-2}\, z_b\right] t_{go}^{-n} \tag{8}$$

where $p_1 = \frac{(m+1)(m+2)}{n-m}$ and $p_2 = \frac{(n+1)(n+2)}{n-m}$. Also, $z_b$ and $v_b$ denote the lateral position and velocity from initial time $t_0$ to terminal time $t_f$ without lateral acceleration command, i.e. free flight only under the gravity, and can be expressed

$$\begin{aligned} v_b &= v(t_0) + \bar{g}\, t_{go} \\ z_b &= z(t_0) + v(t_0)\, t_{go} + \frac{1}{2}\bar{g}\, t_{go}^2 \end{aligned} \tag{9}$$

Substituting Eq. (9) into Eqs. (7) and (8), the coefficient $c_m$ and $c_n$ are

$$c_m = p_1\left[(n+2)\, t_{go}^{-2}\, z(t_0) + t_{go}^{-1}\, v(t_0) - \frac{n}{2}\bar{g}\right] t_{go}^{-m} \tag{10}$$

$$c_n = p_2\left[-(m+2)\, t_{go}^{-2}\, z(t_0) - t_{go}^{-1}\, v(t_0) + \frac{m}{2}\bar{g}\right] t_{go}^{-n} \tag{11}$$

To obtain the guidance law in a feedback form, firstly, we calculate the acceleration command at initial time $t = t_0$ using Eqs. (10), (11), and (4).

$$a(t_0) = -(m+2)(n+2)\,t_{go}^{-2}\,z(t_0) - (m+n+3)\,t_{go}^{-1}\,v(t_0) + \left(\frac{mn-2}{2}\right)\bar{g} \tag{12}$$

If the coefficient $c_m$ and $c_n$ initialize and recalculate at each step, Eq. (12) can be written as a feedback form guidance law

$$a(t) = -(m+2)(n+2)\,t_{go}^{-2}\,z(t) - (m+n+3)\,t_{go}^{-1}\,v(t) + \left(\frac{mn-2}{2}\right)\bar{g} \tag{13}$$

where $t_{go}$ means $t_{go} = t_f - t$ .

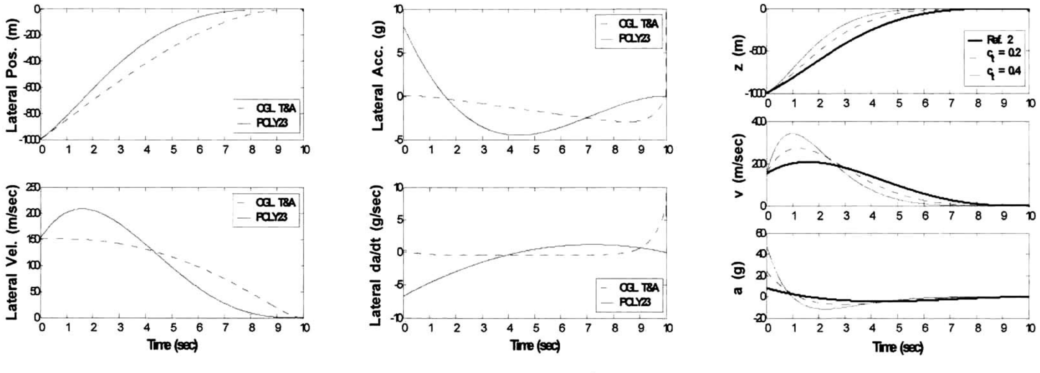
As shown in Eq. (13), $t_{go}-$ polynomial guidance law presents a simple form. The proposed $t_{go}-$ polynomial guidance laws according to several combination of design parameters $m$ and $n$ are summarized in Table 1.

Table 1. Examples of the $t_{go}-$ polynomial guidance law

| Nomenclature | Polynomial type | Guidance law | Satisfaction of constraints |
|---|---|---|---|
| POLY-01 | $m=0,\ n=1$ | $a = -6\,t_{go}^{-2}z - 4\,t_{go}^{-1}v - \bar{g}$ | None |
| POLY-12 | $m=1,\ n=2$ | $a = -12\,t_{go}^{-2}z - 6\,t_{go}^{-1}v$ | Only I |
| POLY-13 | $m=1,\ n=3$ | $a = -15\,t_{go}^{-2}z - 7\,t_{go}^{-1}v + \frac{1}{2}\bar{g}$ | Only I |
| POLY-23 | $m=2,\ n=3$ | $a = -20\,t_{go}^{-2}z - 8\,t_{go}^{-1}v + 2\bar{g}$ | Simultaneously I and II |

## Properties of $t_{go}-$ polynomial guidance law

We can observe some interesting properties on the proposed $t_{go}-$ polynomial guidance law as shown in Table 1. First, POLY-01 is identical to the optimal guidance law considering zero miss distance and impact angle. In the case of $n = m+1$ such as POLY-01, POLY-12, and POLY-23, $t_{go}-$ polynomial guidance law is the same as that of optimal guidance law studied in Ref. [10], but



(a) $z(t)$ & $v(t)$ (b) $a(t)$ & $\frac{d}{dt}a(t)$ (c) time varying $m$ & $n$

Fig. 2. Linear simulation results of $t_{go}-$ polynomial guidance law

it is more general form than that of Ref. [10]. In other word, the proposed $t_{go}-$ polynomial guidance law should not be required for $n = m+1$ and integer values of $m$ and $n$ . Moreover, in the proposed guidance law, it is possible to shape the trajectory using $m$ and $n$ as time-varying parameters. Fig. 2 depicts some simulation results of the $t_{go}-$ polynomial guidance law applied to linear model. In Fig. 2, OGL T&A[14] means the optimal guidance law considering impact time and angle. From the simulation results shown in Fig. 2, the $t_{go}-$ polynomial guidance law initially generates a large command compared with OTL T&A and aggressively maneuvers to satisfy the given constraints I and II. However, this drawback can be remedied by using the design parameters $m$ and $n$ varied with $t_{go}$ . Fig. 2 (c) shows the simulation result with time-varying design parameters $m$ and $n$ . Here, the design parameters $m$ and $n$ are chosen as $m = 2 + c_t t_{go}$ and $n = m + 1$, respectively. From this simulation result, $t_{go}-$ polynomial guidance law can be achieved the specified guidance objective with a similar level of guidance command.

## Application Results in Automatic Landing Problem

The final objective of automatic landing of UAV is to safely recover for the purpose of re-use. Also, it is required that the UAV has the ability to launch and recover in various uncontrolled environments for its usefulness. In fact, these two requirements are contrary to each other. For example, it is very difficult for fixed-wing UAVs to automatically land in shipboard operations or field operations without an appropriate runaway. For this reason, net recovery system for an automatic landing of fixed-wing UAV is widely used in realistic operation condition. On the other hand, the rotary-wing UAV sufficiently accomplish these two different requirements without any contradiction, since its hovering and vertical take-off and landing capability.

The proposed guidance law can be applied to net recovery scheme with automatic landing of fixed-wing UAVs and vertical landing of rotary wing UAVs. In this paper, we applied the proposed $t_{go}-$ polynomial guidance law to automatic landing problems of fixed-wing and rotary-wing UAVs.

### Fixed-wing UAV

In the automatic landing of fixed-wing UAV using net recovery system, UAV could automatically fly into a net for recovery as shown in Fig. 3. Recently, optical sensing payloads such as Day Light TV (DLTV), mini panoramic camera, Forward Looking Infra Red(FLIR), and Infra Red Line Scan (IRLS) are added to UAV systems to search an arbitrary target. These optical sensors might be used to detect a net for recovery. In realistic application of net recovery system, it is very critical requirements that the lateral deviation error from the center of a net location and the lateral acceleration of the vehicle should be perfectly eliminated to minimize the damage of the vehicle. Since the $t_{go}-$ polynomial guidance law generates a lateral guidance command to satisfy the given constraints I and II as well as the lateral position and velocity at the terminal time are zero, the proposed guidance law can be directly applied to the automatic landing problem of a fixed-wing UAV using net recovery system. Fig. 4 shows the control system of a fixed-wing UAV[15]. Figs. 5 ~ 8 show the nonlinear simulation results in the automatic landing scenario of a fixed-wing UAV. We assume that the UAV is initially 500m deviated in lateral direction and above 90m from the center of a net location. And initial heading angle of a UAV is assumed, respectively, 0 deg and 40 deg. In this simulation scenario, we also assume a UAV can exactly detect the net location with image sensor. Here, the speed of UAV is linearly decreased from 20m/sec to 10m/sec and the altitude is exponentially from 100m to 10m during landing procedure. Only the lateral guidance command is generated by the proposed $t_{go}-$ polynomial guidance law. From the results shown in Figs. 5 and 6, we observe that the fixed-wing UAV precisely flies into the center of a net location reducing the speed of vehicle. Moreover, the lateral velocity and acceleration are zero at the terminal time of $t_f = 100\,\mathrm{sec}$.

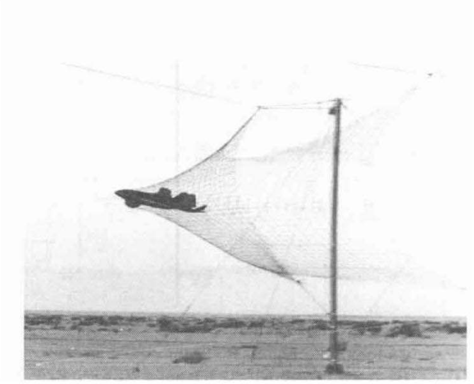


Fig. 3. Net recovery system

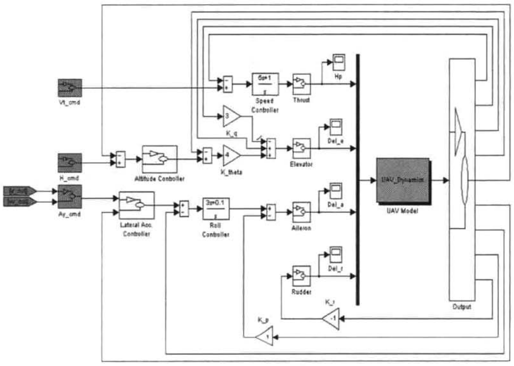


Fig. 4. Control system of fixed-wing UAV

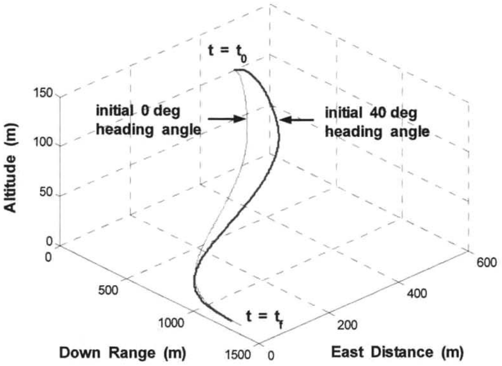


Fig. 5. Three dimensional trajectories

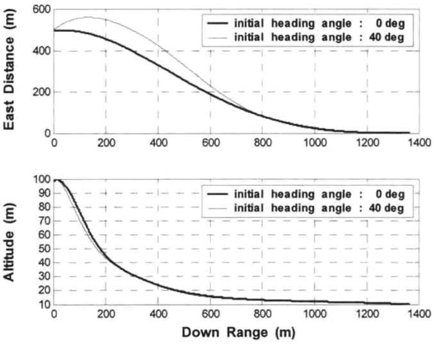


Fig. 6. Two dimensional trajectories

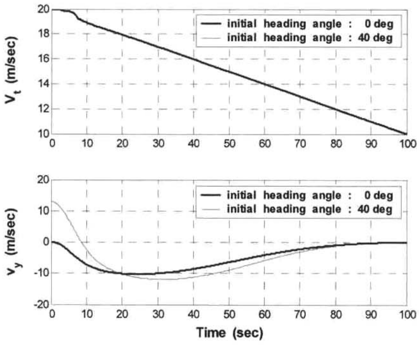
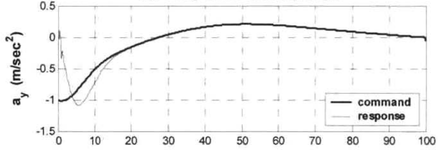


Fig. 7. Total velocities & lateral velocities

(a) 0 deg initial heading angle



(b) 40 deg initial heading angle

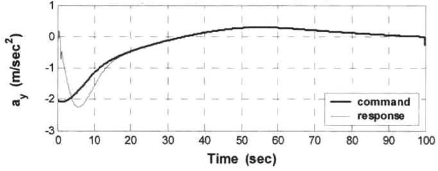


Fig. 8. Acceleration commands & responses

## Rotary-wing UAV

Rotary-wing UAV is a versatile flight machine because of its hovering capability, vertical take-off and landing, and aggressive maneuverability. In the automatic landing problem of rotary-wing UAV, firstly, it is required to autonomously recognize a landing pad. After recognition, the rotary-wing UAV is initially commanded to fly toward on the landing pad, and is oriented with it. Finally, the rotary-wing UAV descends only altitude until it contact the landing pad maintaining the position and attitudes. So, to successfully complete the automatic landing of rotary-wing UAV, the height

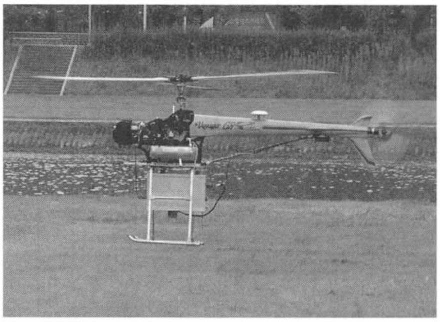


Fig. 9. Configuration of rotary-wing UAV

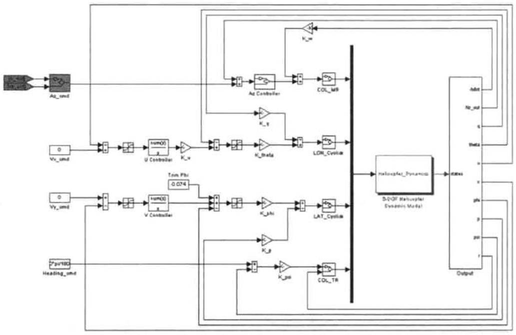


Fig. 10. Control system of rotary-wing UAV

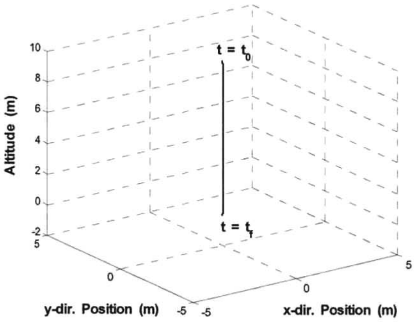


Fig. 11. Three dimensional trajectory

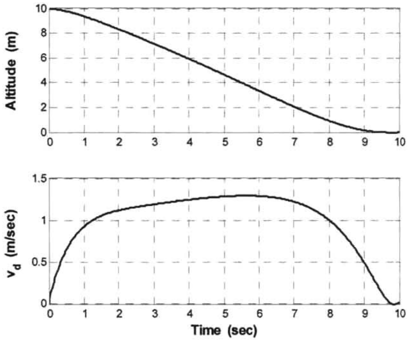


Fig. 12. Altitude & down velocity

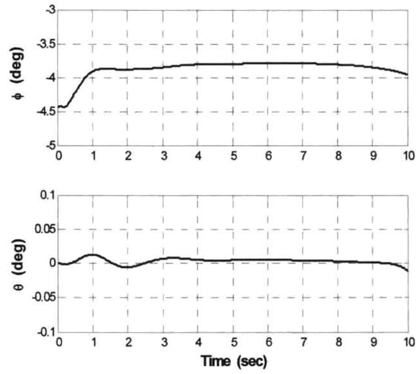


Fig. 13. Roll & pitch attitude angles

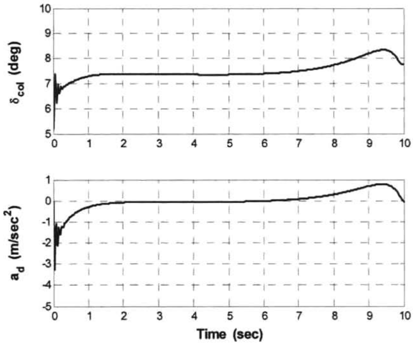


Fig. 14. Collective angle & down acceleration

and the vertical acceleration should be precisely controlled during landing procedure. To achieve this control objective, we applied the proposed $t_{go}-$ polynomial guidance law to the vertical channel of a rotary-wing UAV system. Figs. 9 and 10 illustrate the configuration of our rotary-wing UAV and its control system [16], of which performance was proven through flight test. Where the autopilot of vertical channel was redesigned to applied the proposed guidance law. In this simulation scenario, we assume that the rotary-wing UAV is oriented with landing pad above 10m height. Figs. 11 ~ 14 show the nonlinear simulation results. From the results depicted in Figs. 11 and 12, the control objective for automatic landing of a rotary-wing UAV is perfectly completed by applying the proposed guidance law. Also, we can find out the attitude of a vehicle is maintained and there is no vertical acceleration at the terminal time of $t_f = 10\,\mathrm{sec}$. The small amount of variation in roll attitude angle is caused by the coupling effect among collective, longitudinal, and lateral cyclic angles.

## Conclusions

In this paper, we proposed a $t_{go}-$ polynomial guidance law to apply to the automatic landing problem of UAVs. According to the combination of design parameter in the newly introduced guidance law, the guidance command shows an identical result in optimal guidance law, but the proposed guidance law is a further generalized form. The main advantage of $t_{go}-$ polynomial guidance law is robust against $t_{go}$ estimation error, since the guidance law might be more effective than optimal guidance law in the realistic application. Alto, the trajectory shaping of a vehicle is possible by using the time-varying design parameter without any violation of the given constraints. In the application results for the automatic landing problem of a fixed-wing UAV and a rotary-wing UAV, the proposed $t_{go}-$ polynomial guidance law shows a satisfactory performance.

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