Lateral and Longitudinal Dynamics Control of a Fixed Wing UAV by using PID Controller

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ICENS 4TH INTERNATIONAL CONFERENCE ON ENGINEERING AND NATURAL SCIENCE
2 - 6 May 2018 KIEV UKRAINE

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Abstract

Unmanned aerial vehicles (UAV) are taking more attention in both civilian and army applications in the world. One of the most important thing in UAV applications is to make an autonomous, fast and stable control of a UAV. In this study, one of the fixed wing UAV model (Ultrastick -25e) is analyzed and aerodynamic parameter coefficients of the UAV model which needed for dynamic equations are acquired from literature. For that reason, firstly, as a classical control techniques of a fixed wing UAV, PID controller is applied and transfer functions of different state variables are derived by using state-space model. PID gains of state variables according to different control inputs are obtained by using Matlab tuning and Ziegler-Nichols methods. Optimum PID gains, rise time, settling time, peak overshoots of the roll, pitch and yaw dynamics are obtained. Future studies will give a chance to compare classical PID controller results and modern control techniques in terms of altitude, roll and heading angle controller of the UAV model.

Keywords: Fixed wing, PID controller, unmanned aerial vehicle, Ziegler-Nichols.

1. INTRODUCTION

UAVs are commonly known as drone or remote-control aircraft and they have been very popular for both academic and practical applications during past few decades because of their mobility, cost and application areas. UAVs are especially used in army applications such as reconnaissance and surveillance and armed UAV applications and also they have a safe and low cost operation in terms of pilot needs [1], [2]. In addition to that, UAVs have different types and sizes according to their subtask such as mapping, crop monitoring and spraying pesticide in agriculture, photography, cargo transport etc.

According to their mission and capacity, different types of UAVs can be used, and UAVs are classified in to two groups like fixed-wing and multi-rotor applications. They have different advantages and some disadvantages according to their subtask. Fixed-wing UAVs are mostly chosen for high speed and heavy payload applications but not capable to stay in a position while rotary wings have capability to stay in a stationary position. Multi-rotor aircrafts are not suited to lift heavy payload. Many studies are investigated in this part to understand UAV types and missions [3], [4], [5].

The main objective of this research is to design an optimum PID controller and compare PID parameter setting techniques for UAV which will be used in real time applications. The UAV is a fixed-wing aircraft and it will be used in agricultural areas such as crop monitoring, spraying etc. To achieve an effective flight, it is needed to develop an autonomous system to process multiple functions at the same time, in an effective and stable manner [6], [7], [8]. In addition, it is necessary to develop stable and fast system under different conditions and even when there is no connection between UAV and ground station [9]. In UAV applications, autopilots need PID controller by implementing proportional, integral and derivative (P, I, D) terms. To have a stability of the flight, PID parameters must be chosen well suited to the system dynamics. [10].

In this study, it is chosen a UAV model which is called “Ultra-stick 25e” from the previous studies in Minnesota University UAV research group. All system parameters and sizes are obtained according to chosen UAV model. The UAV model has a rudder, aileron, elevator control surfaces and an electric motor to drive propeller.

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2. SPECIFICATONS OF THE UAV MODEL

The Ultrastick-25e UAV model is chosen to design a PID controller and its' aerodynamic characteristics and specifications are used in this study. The UAV model has fixed wing and its wingspan is 1.2 m and its weight is 1.9 kg. Table 1 represents some properties of the given UAV model and Figure 1 shows the aircraft axis and control surfaces [11].

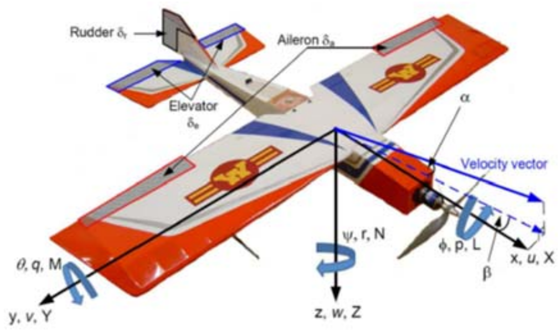

Figure 1. Ultrastick 25e UAV platform [11]

Table 1. Specifications of the given UAV model

Parameter	Definition	Value
S	Wing reference area	0.32 m^2
b	Wing span	1.27 m
$\bar{c}$	Wing Chord	0.25 m
m	Gross weight	1.9 kg
I_x	Roll moment of inertia	0.0894 kg.m^2
I_y	Pitch moment of inertia	0.144 kg.m^2
I_z	Yaw moment of inertia	0.162 kg.m^2
I_{xz}	Product of inertia	0.014 kg.m^2

- ***Longitudinal and Lateral Aircraft Equations of Motions***

The main purpose of obtaining aircraft equations of motion is to define and model system dynamics which reflect the real time applications. Aircraft equations are based on Newton laws and obtained from Nelson [12]. Equations in (1) determine the aircraft equations of motion. The subscripts a, g, c, p, d in eq. (1) mean as aerodynamics, gravitational, control surfaces, thrust and atmospheric disturbance effects respectively.

$$
\begin{aligned}
& m.(\dot{u}+qw-rv) = X_a + X_g + X_c + X_p + X_d \\
& m.(\dot{v}+ru-pw) = Y_a + Y_g + Y_c + Y_p + Y_d \\
& m.(\dot{w}-qu+pv) = Z_a + Z_g + Z_c + Z_p + Z_d \\
& L = I_x.\dot{p}-(I_y - I_z)qr - I_{xz}(pq+\dot{r}) = L_a + L_g + L_c + L_p + L_d \\
& M = I_y.\dot{q}+(I_x - I_z)pr + I_{xz}(p^2 - r^2) = M_a + M_g + M_c + M_p + M_d \\
& N = I_z.\dot{r}+(I_x - I_z)pq + I_{xz}(qr - \dot{p}) = N_a + N_g + N_c + N_p + N_d
\end{aligned} \tag{1}
$$

X, Y, Z indicate force equations and L, M, N define the roll, pitch and yaw moments respectively. I is the inertial moment in the x, y, z axis and m is the gross weight of the UAV. Velocity components are u, a, v in the x, y, z axis.

- ***State Space Representations of the UAV Model***

In this part, longitudinal and lateral state space (ss) models are obtained according to given aircraft equations of motion in 1 and UAV motion is analyzed by separating equations of motion in to two parts as longitudinal and lateral state space model. State space models are needed to develop transfer functions of each state variables and control inputs. By using state space models all transfer functions are obtained under different conditions such as different velocities (40 km/h, 60km/h etc.). In this study, 40 km/h airspeed is investigated. In equation (2), longitudinal state space model equation is given. Gust disturbance is not considered for state space model in this study.

$$
\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{q} \\ \Delta\dot{\theta} \\ \Delta\dot{h} \end{bmatrix}
=
\begin{bmatrix}
X_u & X_w & 0 & -g & 0 \\
Z_u & Z_w & u_0 & 0 & 0 \\
M_u + M_{\dot{w}} Z_u & M_w + M_{\dot{w}} Z_w & M_q + M_{\dot{w}} u_0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
-\sin(\Theta_0) & -\cos(\Theta_0) & 0 & -u0^{*}\cos(\Theta_0) & 0
\end{bmatrix}
\begin{bmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta\theta \\ \Delta h \end{bmatrix}
+
\begin{bmatrix}
X_\delta & X_{\delta_T} \\
Z_\delta & Z_{\delta_T} \\
M_\delta + M_{\dot{w}} Z_\delta & M_{\delta_T} + M_{\dot{w}} Z_{\delta_T} \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix} \Delta\delta_e \\ \Delta\delta_T \end{bmatrix} \tag{2}
$$

Equation (3) defines the lateral state space model of a UAV. The variables in the matrix frames can be derived from different resources and detailed formulas are obtained from Nelson [13].

$$
\begin{bmatrix} \Delta\dot{v} \\ \Delta\dot{p} \\ \Delta\dot{r} \\ \Delta\dot{\phi} \\ \Delta\dot{\psi} \end{bmatrix}
=
\begin{bmatrix}
Y_v & Y_p & -(u_0 - Y_r) & -g.\cos\theta_0 & 0 \\
L_v & L_p & L_r & 0 & 0 \\
N_v & N_p & N_r & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & \sec(\Theta_0) & 0 & 0
\end{bmatrix}
\begin{bmatrix} \Delta v \\ \Delta p \\ \Delta r \\ \Delta\phi \\ \Delta\psi \end{bmatrix}
+
\begin{bmatrix}
0 & Y_{\delta_r} \\
L_{\delta_a} & L_{\delta_r} \\
N_{\delta_a} & N_{\delta_r} \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix} \Delta\delta_a \\ \Delta\delta_r \end{bmatrix} \tag{3}
$$

According to given eqs. above, for 40 km/h flight speed, calculated state space models for both longitudinal and lateral dynamics are obtained and shown in Fig. 2. A_long indicates longitudinal state variables while A_lat indicates lateral state variables. B matrix defines control input matrix in Fig. 2.

$$A\_long = \begin{bmatrix} -0.1492 & 0.1490 & 0 & -9.81 & 0 \\ -0.5272 & -5.2988 & 11.1100 & 0 & 0 \\ 2.6669 & -3.3818 & -32.9054 & 0 & 0 \\ 0 & 0 & 1.0 & 0 & 0 \\ -0.0523 & -0.9986 & 0 & -11.0948 & 0 \end{bmatrix} \quad B\_long = \begin{bmatrix} 8.4872 & 0 \\ 0 & -1.6553 \\ 0.2546 & -49.7923 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$A\_lat = \begin{bmatrix} -0.9512 & 0 & -1.0000 & 0.8830 & 0 \\ -12.0240 & -7.4665 & 5.8687 & 0 & 0 \\ 5.0421 & -1.9428 & -6.6032 & 0 & 0 \\ 0 & 1.0 & 0 & 0 & 0 \\ 0 & 0 & 1.0 & 0 & 0 \end{bmatrix} \quad B\_lat = \begin{bmatrix} 0 & 0.2189 \\ 21.6477 & 4.4873 \\ -0.2506 & -5.7111 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Figure 2. Longitudinal and Lateral State Space Values

All the transfer functions are extracted by using MATLAB toolbox from given ss models. Some of the transfer functions are listed below according to different control inputs such as throttle, elevator, aileron and rudder. It is obtained totally 20 transfer functions from each state variables and control inputs for longitudinal and lateral motion but just a few of the transfer functions are presented below. Subscripts t, e, a, r indicates throttle, elevator, aileron and rudder respectively.

3.PID CONTROLLER DESIGN

PID controller structure consists of proportional, integral, derivative (P, I, D) respectively. PID structure has a general use in UAV applications to achieve autonomous and stable flight by using feedback control algorithm. To achieve a stable and fast response at the flight conditions, PID parameters must be set very well and appropriate to system dynamics conditions. For that reason, in this study, MATLAB tune algorithm and Ziegler-Nichols (ZN) methods are applied to set up the optimum PID parameters. Both methods are compared and analyzed.

3.1.PID Controller Structure

The general PID feedback controller structure of the UAV is shown in Fig. 3. In this study, PI, PD, PID algorithms are evaluated to compare results and it is checked which control algorithm was more suitable for each transfer functions.

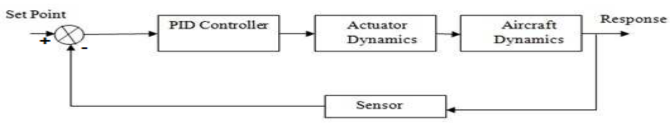

Figure 3. PID feedback controller structure of the UAV

Optimum PID results are investigated according to ZN setting and MATLAB tune methods. Ideal MATLAB tuning structure is depicted in Fig. 4. ZN method can also be called as continuous cycling method or ultimate gain tuning method. The gain is gradually reduced or increased until the system response oscillates continuously. A main design criteria is the decay of oscillation to 1/4 of its initial value.

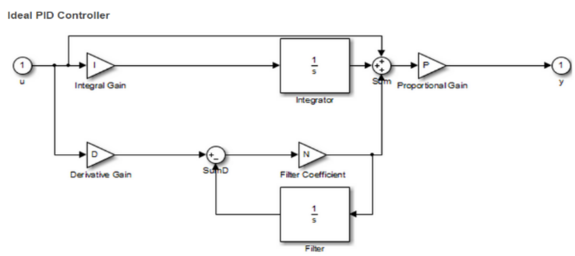

Figure 4. Ideal PID controller structure for Matlab Tuning

4.RESULTS

In this section, MATLAB Tuning and ZN setting results for PID controller structure are presented. First, all transfer functions are evaluated in terms of MATLAB tuning algorithm. Step input is applied to each control inputs of throttle, elevator, aileron and rudder. After obtaining tuning results, ZN method is applied to PI, PD, PID controller structure to compare and choose best results for transfer functions. Results are presented in figures below and PID responses of the two methods are given in Table 2 and 3. Some of the longitudinal PID results for elevator deflection is given in Fig. 5-6-7-8.

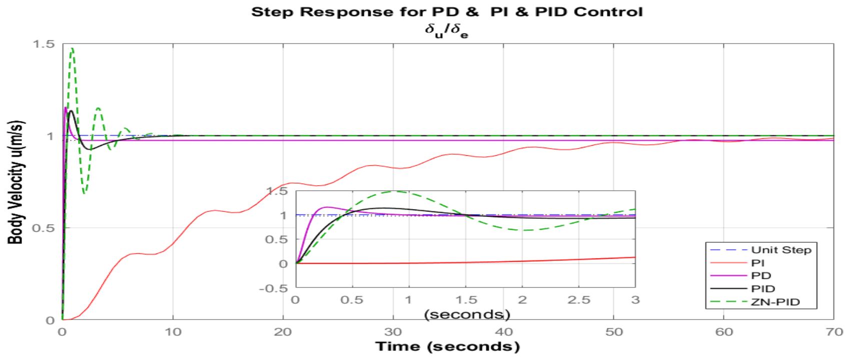

Figure 5. “Matlab Tune – ZN PID” step response for elevator control input and airspeed output

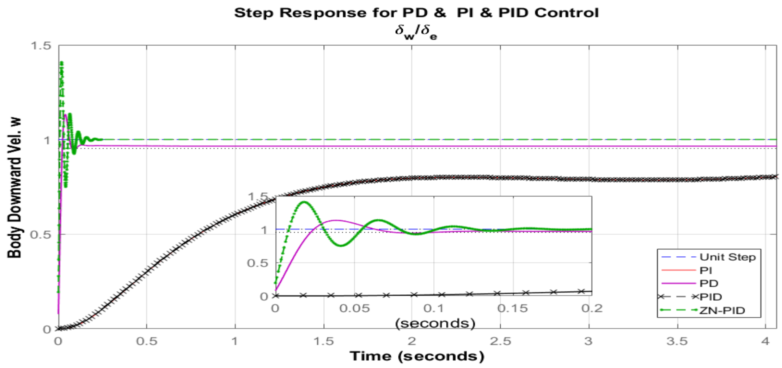

Figure 6. “Matlab Tune – ZN PID” step response for elevator control input and downward speed output

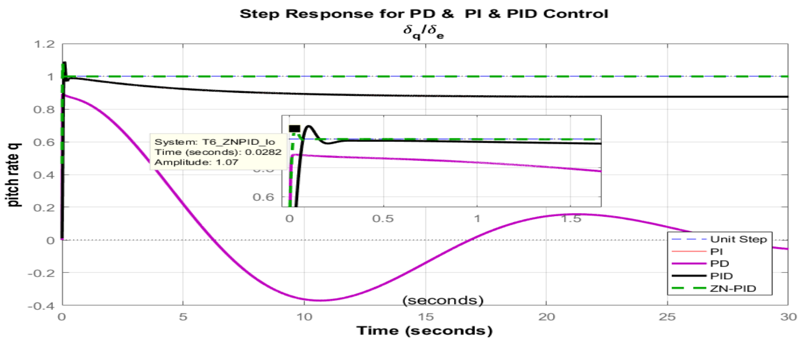

Figure 7. “Matlab Tune – ZN PID” step response for elevator control input and pitch rate output

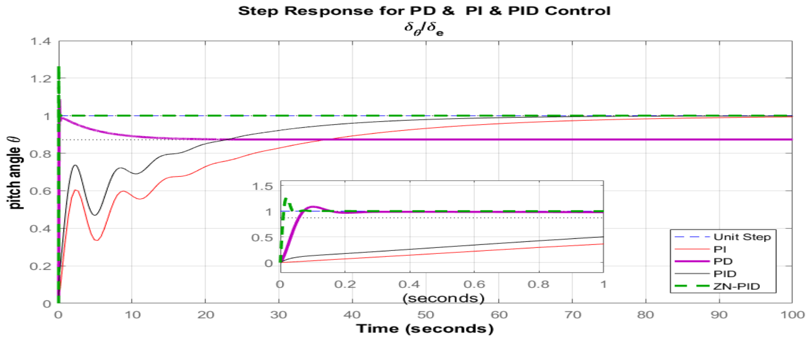

Figure 8. “Matlab Tune – ZN PID” step response for elevator control input and pitch angle output

Figures between 9-12, show some of the lateral PID controller results for both Matlab tuning and ZN setting results.

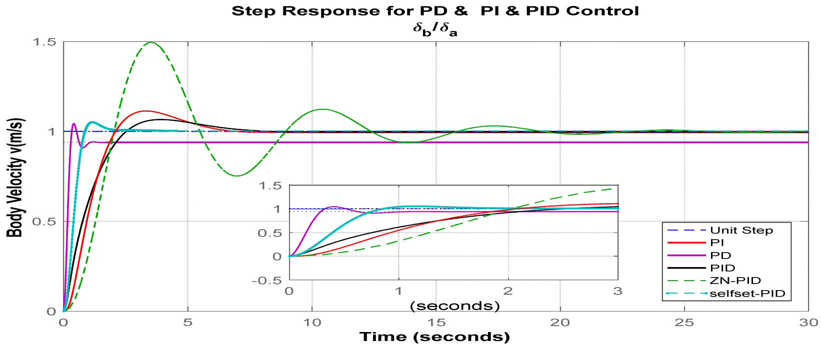

Figure 9. “Matlab Tune – ZN PID” step response for aileron control input and body velocity output

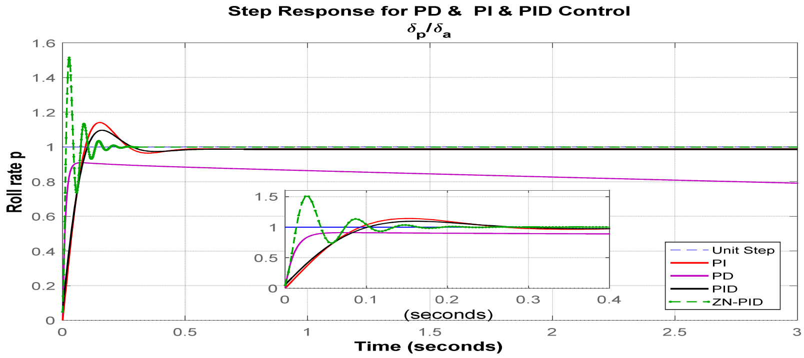

Figure 10. “Matlab Tune – ZN PID” step response for aileron control input and roll rate output

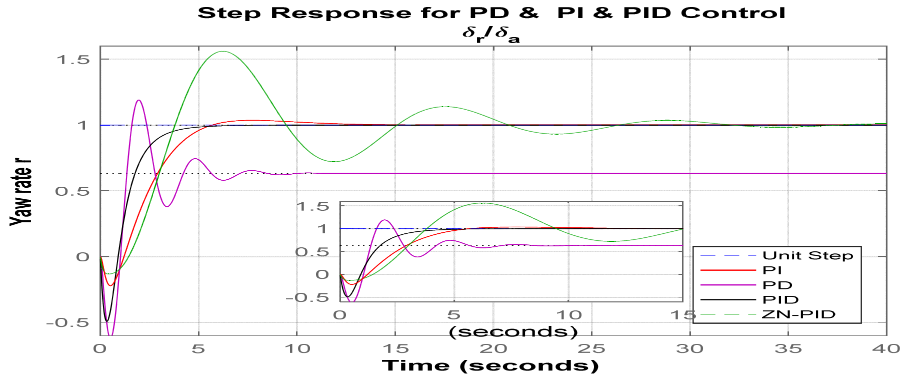

Figure 11. "Matlab Tune – ZN PID" step response for aileron control input and yaw rate output

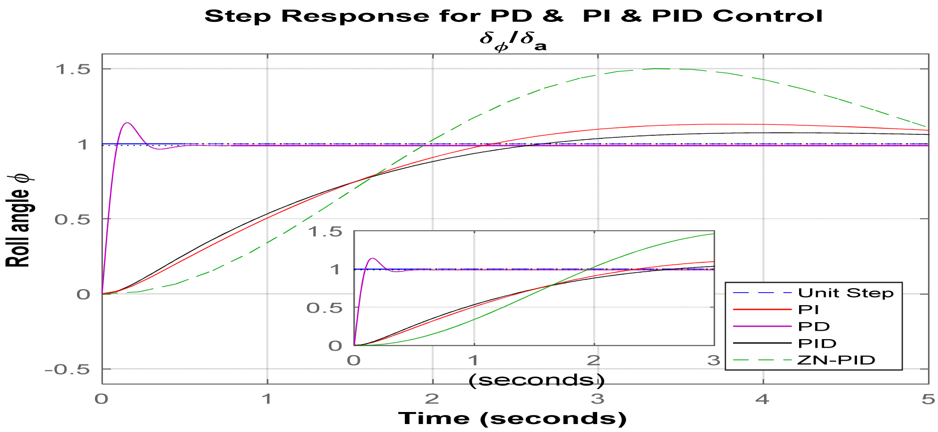

Figure 12. "Matlab Tune – ZN PID" step response for aileron control input and roll angle output

In Table 2, step responses of the longitudinal transfer functions for both Matlab tuning and ZN methods are given. Only elevator (de) control surface is shown as a control input in Table 2.

Table 2. Step Response Results of the Matlab Tune and ZN Settings for Longitudinal Motion

Matlab TUNE	**Rise Time**	**Peak Time (s)**	**Peak Value**	**Overshoot (%)**	**Settling Time**	**Ziegler Nichols**	**Rise Time**	**Peak Time**	**Peak Value**	**Overshoot (%)**	**Settling Time (s)**
du/de	0,106	0,285	1,155	18,742	0,748	**du/de PD**	0,298	0,825	1,260	38,014	2,348
du/de	0,304	0,756	1,135	13,541	3,684	**du/de PID**	0,310	0,875	1,475	47,500	4,794
dw/de	5,009	7,969	1,081	8,052	9,208	**dw/de PI**	0,006	0,017	1,770	77,039	0,342
dw/de	0,017	0,038	1,134	19,006	0,064	**dw/de PD**	0,008	0,019	1,147	16,329	0,034
dw/de	5,020	7,987	1,080	8,037	9,211	**dw/de PID**	0,007	0,018	1,409	40,894	0,114
dq/de PI	0,042	0,100	1,088	24,753	5,734	**dq/de PI**	0,008	0,020	1,092	10,603	0,035
dq/de	0,000	0,026	0,892	inf	34,805	**dq/de PD**	1,678	0,052	0,834	inf	36,292

dq/de	0,042	0,101	1,090	24,851	5,764	**dq/de PID**	0,013	0,032	1,075	8,808	0,055
dΘ/de	41,418	123,745	0,998	0,000	56,580	**dΘ/de PI**	0,008	0,023	1,758	75,834	0,230
dΘ/de	0,042	0,100	1,088	24,753	5,734	**dΘ/de PD**	0,008	0,019	1,235	24,613	0,033
dΘ/de	26,215	86,445	0,998	0,000	36,756	**dΘ/de PID**	0,008	0,020	1,266	26,570	0,034

Table 3 represents step responses of the lateral transfer functions. Aileron input (da) is given in Table 3 for both Matlab Tuning and ZN methods.

Table 3. Step Response Results of the Matlab Tune and ZN Settings for Lateral Motion

Matlab TUNE	Rise Time	Peak Time (s)	Peak Value	Overshoot (%)	Settling Time (s)	Ziegler Nichols	Rise Time	Peak Time	Peak Value	Overshoot (%)	Settling Time (s)
db/da PI	1,375	3,313	1,114	11,401	5,070	**db/da PI**	1,302	3,417	1,503	50,284	14,505
db/da PD	0,195	0,408	1,044	11,072	0,535	**db/da PD**	0,000	0,000	0,000	0,000	0,000
db/da PID	1,730	3,912	1,066	6,629	5,031	**db/da PID**	1,336	3,438	1,496	49,621	14,579
dp/da PI	0,069	0,153	1,141	15,414	0,238	**dp/da PI**	0,045	0,104	1,174	18,114	0,172
dp/da PD	0,000	0,074	0,909	inf	68,463	**dp/da PD**	0,000	0,000	0,000	0,000	0,000
dp/da PID	0,074	0,161	1,096	10,992	0,242	**dp/da PID**	0,054	0,121	1,154	16,057	0,199
dr/da PI	2,965	7,725	1,035	3,515	4,767	**dr/da PI**	1,697	6,158	1,591	59,067	24,172
dr/da PD	0,257	1,950	1,190	88,652	5,300	**dr/da PD**	3,118	9,582	0,234	0,000	4,533
dr/da PID	1,958	8,939	0,998	0,000	3,252	**dr/da PID**	1,824	6,235	1,560	56,038	24,331
dϕ/da PI	1,695	3,769	1,131	13,087	5,782	**dϕ/da PI**	1,278	3,339	1,501	50,074	14,168
dϕ/da PD	0,069	0,153	1,141	15,414	0,238	**dϕ/da PD**	0,000	0,000	0,000	0,000	0,000
dϕ/da PID	1,834	4,108	1,074	7,367	5,485	**dϕ/da PID**	1,279	3,341	1,501	50,059	14,170

4.CONCLUSIONS

In this study, “Ultra-stick 25e” fixed-wing UAV model is chosen to design PID controller structure. The UAV model and its aerodynamic parameters obtained from previous studies to build state space model. 40 km/h airspeed is analyzed for a cruise flight condition and all transfer functions are obtained according to 40 km/h airspeed.

Two different PID parameter setting algorithms like Matlab Tuning and ZN methods are applied to compare results and chose optimum ones. Results show that Matlab Tuning was not capable to reach step response very quickly at some transfer functions. ZN results have less settling time in general even if it has more overshoot.

PID structure has less steady state error even if, PD has a quick response in some cases. It is obvious that both methods have some advantages and disadvantages. ZN methods need more time to catch optimum P, I, D parameters while Matlab Tuning choose parameters automatically. It is seen that for some transfer functions, parameters can be set by using ZN methods even if MATLAB tuning was not successful.

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