Modified Non-linear PID Controller Design for Small UAV

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Abstract– Fixed-wing unmanned aerial vehicles (UAVs) have become increasingly important in military, civil, and scientific sectors. Because of the existing nonlinearities, effective control this type of UAV remains a challenge. This paper proposes a modified proportional-integral derivative (PI-D) control system for fixed-wing UAVs where a family of PID cascade control systems is designed for several operating conditions of airspeed. The proposed modification of the PID controller based on adopting the angular rates measured by the angular gyroscopes as negative feedback instead of differentiating the desired step reference. The practical enhancement ensured from this modification due to the validity of the IMU sensor to provide the required feedback. Moreover, the anti-windup mitigation introduced by preventing background integration while saturation. The numerical simulation results confirm the reduction of the control effort using the proposed modifications.

Keywords—PI-D, UAV, Set-point Kick, anti-windup.

I. INTRODUCTION

Recently, fixed-wing unmanned aerial vehicles (UAVs) have become a feasible solution for many applications in military, civil, including surveillance, localization, and mapping. UAVs will routinely operate in urban environments for a range of applications and around large infrastructure for data gathering or sapling extending range and endurance [1]. Due to the nature of fixed-wing aircraft's nonlinear dynamics, a robust control system is required in order to achieve stable flights in most outdoor conditions. Although there are many advances in control algorithms, such as model predictive control, adaptive control, and sliding mode control, they are computationally demanding and unsuitable for small scale embedded processors in UAV avionics [2].

It is fascinating to note that more than half of the industrial controllers in the different applications are Proportional, Integral, Derivative (PID) controllers or modified PID controllers. A feedback controller is designed to generate a control command that exerts some corrective effort to be applied to the underlying system to steer feedback measured system state towards the desired reference value. Virtually, the control command generated by detecting the error between the desired set-point and the measurement of the system variable. The difference errors created as soon as an operator changes the reference intentionally or when an external disturbance changes the process variable accidentally [3]. The PID controller is widely employed because it is very understandable, easy for implementation, and quite effective. Consequently, it attracts many researchers not only for numerical simulation but also for the implementation of the control system even without a deep understanding of control theory [5]. Moreover, the simplicity of adjusting the controller parameter on-site results in suggesting diverse types of tuning rules to achieve the delicate and fine-tuning of the controllers. Also, the automatic tuning method has been upgraded to possess an on-line automatic tuning capability.

Many practical methods for bumpless switching (from manual operation to automatic operation) and gain scheduling are commercially available. The usefulness of PID controls lies in their general applicability to most control systems. In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the most useful controller [4]. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. In the field of aerospace control system design, it is well known that the basic and modified PID control schemes have proved their usefulness in providing satisfactory control, although in many given situations they may not provide optimal control [5].

The flight guidance and control system used to autonomously guide the UAV without the assistance of a pilot during diverse phases of flight (take-off, landing, ascend, descend, level flight). PID controller is adopted as the main core of the majority of the industrial applications including aerospace applications due to the potential ability to gather between accepted tracking performance associated with guaranteed system robustness [6]'[7].

This paper presents the practical aspect of modifying the classical PID controller and improve the tracking performance by using a feed-forward controller. The comparative analysis between the designed nonlinear controller and the well-known classical controller is established to evaluate the modification and enhancement of the designed controller. The central premise of the PID is the decoupled dynamics between the lateral and the longitudinal states lead to the best tracking response.

The paper's structure is as follows: Section I I presents the nonlinear modeling of the UAV. Section III discusses the proposed modifications of the conventional PID control law. The designed flight control law in pitch and roll channel is introduced in section IV. Finally, the conclusions of this paper are given in Section V.

II. AIRPLANE MATHEMATICAL MODELING

The first step to develop a 6-DoF nonlinear flight simulation model for a UAV is to develop the mathematical model that describes its dynamics and its surroundings. It includes the development of the airplane Equations of Motion (dynamic model), development of the mathematical representation for the aerodynamic forces and moments, and development of the equations describing the variations in air temperature, pressure and density with altitude (atmospheric model).

A. Dynamic Model

The dynamic model contains the nonlinear differential equations describing the motion of the airplane. The Equations of Motion (EoM) of the airplane are developed assuming the airplane as a rigid body, the earth is flat, non-rotating, the airplane mass is constant during any particular dynamic analysis, and the X-Z plane is a plane of symmetry. The force and moment equations are derived from Newton’s second law and then represented in airplane body axes. For the trajectory equations, since airplane position updates usually occur in earth axes, then airplane linear velocities must be converted into linear position rates in the earth axes. This is achieved by applying a transformation from body axes to earth axes. The standard six degrees of freedom nonlinear differential equations for a conventional fixed-wing airplane can be summarized in the state space vector form as follows:

$$\dot{\vec{V}}_b = \vec{\omega}_b X \vec{V}_b + B\vec{g}_o + \vec{F}_b / m \tag{1}$$

$$\dot{\vec{\omega}}_b = I_B^{-1}\left[\vec{\omega}_b \otimes I_B \vec{\omega}_b + \vec{M}_b\right] \tag{2}$$

$$\dot{\vec{\phi}}_b = \varepsilon \vec{\omega}_b \tag{3}$$

$$\dot{\vec{r}}_e = B^T \vec{V}_b \tag{4}$$

where ε is the transformation matrix of angular velocity to Euler angle rates, B is the transformation matrix form local horizon to body axes, $\vec{\omega}_b = \left[p,q,r\right]^T$, $\vec{V}_b = \left[u,v,w\right]^T$ $\vec{\varphi}_b = \left[\varphi,\theta,\psi\right]^T$, $\vec{r}_e = \left[x,y,h\right]^T$, $I_b = \left[I_x, I_y, I_z, I_{xz}\right]^T$. These equations represent the core of the airplane mathematical model [11]. They are in the state space form which $\dot{X} = f\left(x,\mathrm{u}\right)$ where, $u = \left[\delta_a, \delta_e, \delta_r, \delta_t\right]$ is the airplane control input vector and is the airplane states vector $x = \left[u,v,w,p,q,r,\varphi,\theta,\psi,x,y,h\right]^T$.

B. Aerodynamic Forces and Moments

Aerodynamic loads are classified into longitudinal and lateral loads. For the longitudinal aerodynamics, the longitudinal forces and moment are affected by the angle of attack AoA, elevator deflection δ_e , pitch rate q ,the derivative of the AoA $\dot{\alpha}$. The effects of the $q, \dot{\alpha}$ are generally appear in lift and pitching moment [12], while they are assumed equal zero for the drag. So, the lift L drag D , and pitching moment m may be written as:

$$L = 0.5\rho V_T^2 S C_L\left(\alpha, q, \delta_e, \dot{\alpha}\right) \tag{5}$$

$$Y = 0.5\rho V_T^2 S C_Y\left(\beta, p, r, \delta_a, \delta_r\right) \tag{6}$$

$$D = 0.5\rho V_T^2 S C_D\left(\alpha, \delta_e\right) \tag{7}$$

$$l = 0.5\rho V_T^2 S c C_l\left(\beta, p, r, \delta_a, \delta_r\right) \tag{8}$$

$$m = 0.5\rho V_T^2 S b C_l\left(\alpha, q, \delta_e, \dot{\alpha}\right) \tag{9}$$

$$n = 0.5\rho V_T^2 S c C_n\left(\beta, p, r, \delta_a, \delta_r\right) \tag{10}$$

where ρ is the air density, V_T is the total velocity, S is the wing plan form area, c is the wing mean aerodynamic chord, C_L, C_D, C_m are the lift, drag and pitching moment coefficients respectively, C_l, C_m, C_n are roll, pitching, yaw moment coefficients respectively. A summary of the measured geometric data is shown in Table I.

TABLE I
GEOMETRIC CHARACTERISTICS OF THE UTILIZED UAV

Geometric characteristics	**Wing**	**H. Tail**	**V. Tail**
Span [m]	1.554	0.54	1.554
Root Chord [m]	0.28	0.202	0.28
Tip Chord [m]	0.28	0.10	0.28
Quarter chord sweep angle	0^o	16^o	42^o
Leading edge sweep angle	0^o	20^o	45^o
Root chord incidence angle	2.0^o	0^o	0^o
Twist angle	0^o	0^o	0^o
Dihedral angle	2.0^o	0^o	0^o

III. MODIFIED PID CONTROLLER

The PID controller algorithm includes three distinct constant gains for the proportional, the integral, and the derivative values of the error, therefore, it is called the three term controller. The combination of the three terms interprets the current error value represented by P, the accumulation of the past error I, and the prediction of the future of the error D. The weighted sum of these three values is the control law given in (11) that used to track the desired reference, overcome the model mismatch, attenuate the associated noise, and reject the external and internal disturbances.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{7}$$

where e(t) represents the tracking error between the output y and the desired input r, kp is the proportional gain, Ki is the integral gain, and Kd is the derivative gain. The process of generating the control law u to guide the system state to a new value that will be feedback to generate a new error and continuously till accurately tracks the desired reference with high efficiency. Although the optimality of using the PID in flight control is not missing it remains the core for any commercial autopilot that used to autonomously guide the flying vehicle to follow a certain path or track a predetermined trajectory. Consequently, most of the researcher introduces the conventional classical control in their research either for increasing the closed-loop system robustness through augmentation with any flight controller or validate the designed flight controller with the high confidence and physically tested PID flight controller. In this research, the PID introduced to be used for the validation of the designed different flight controllers as a first step for building a generic autopilot to be used for any UAV airframe. The PID is used to generate the guidance law in the outer guidance loop as well as generating the flight control law in the inner control loop. In the aerospace field, the PID can be improved by adjusting the following concepts.

A. Consecutive Loop Termination

The central premise of this concept is controlling the most inner loop then sequentially close the successive loops till controlling the most outer guidance loop. In other words, for the pitch channel, it is required to track the desired altitude which is considered the input for the guidance loop; the output of the guidance loop is the desired angle of attack which is considered the input for the subsequent loop; the output of the angle of attack loop is the desired body pitch rate which is conceded the input to the most inner control loop, finally, the elevator control command is designed to achieve the required pitch rate. The roll channel is also following this concept by responding to the desired guidance command by tracking the desired roll angle followed by achieving the desired body roll rate by generating the aileron control surface command. The side-slip angle is also regulated using this concept by generating the required body angular yaw rate which performed through commanding the rudder fins. The basic idea behind this concept is assuming the decoupled dynamics i.e. the longitudinal dynamics like UAV airspeed, pitch rate, and the angle of attack are decoupled from the lateral dynamics like roll angle, sideslip angle, roll rate, and yaw rate. Moreover, for the satisfaction of this concept, it is important to ensure the execution of the inner loop must be faster than the outer sequential loop i.e. the inner loop has the highest bandwidth than the next outer loop by a factor (5: 10) times smaller in frequency.

B. Derivative Kick Avoidance

In the conventional classical control law given in (11), if the desired input is including any step variation, then due to the existence of the derivative term in the control action, the generated control surface command contains an impulse command. The most prominent solution for avoiding this pure derivative is to include a low path filter for the input to the derivative term, therefore, the generated control surface command is including a sharp pulse with duration depending on the utilized filter gain rather than involving impulse command. However, building the control law without taking into consideration the pre-filter will leads to degrading the tracking performance which is not considered an optimal solution. The enhancement of the classical control law to avoid this phenomenon, the derivative action is negatively taken only in the feedback path, consequently, the derivative is performed only for the measured feedback signal which significantly pure from the sharp step response. The classical PID controller is modified without changing the closed-loop system tracking response introduced by the designed conventional controller. In other words, for pitch channel tracking loop, the attitude error difference between the desired angle of attack and the actual one is applied to the modified PID controller to generate the elevator control surface command given in (12), in which the derivative term is not applied to the error but taken from the angular body pitch rate. The modified PID providing the same performance of the classical PID but with avoiding the set-point kick phenomenon. The roll channel tracking loop is designed by analogy to the pitch channel through introducing the angular roll rate as a derivative term instead of differentiating the attitude rolls angle error.

$$\begin{aligned}\delta_e(t) &= K_{p\alpha}(\alpha(t)-\alpha_c(t)) + \\ &K_{i\alpha}\int(\alpha(t)-\alpha_c(t))dt - K_{dq}q\end{aligned} \tag{12}$$

C. Reset Windup Mitigation

The PID control law normally applied to the saturation limits to constrain the control command based on the physical allowable fin deflection. In other words, if the control command is either increased beyond the maximum saturation limit or decreased under the minimum saturation limits, the control command will be either the maximum or the minimum saturation limit respectively. Consequently, when the control law output is the saturation limit, the integrator is continuously accumulating the error which leads to increasing the PID output, therefore, increasing the discharging time when returning to the boundary i.e. it reveals itself in the form of weird lags because as soon as the reference point is dropped the output has to wind down before getting below that final desired value. As a result, the anti-wind mechanism will be used when the control law is beyond the saturation margin i.e. it has no effect when the PID output is within the margins. For instant, the pitch channel elevator control surface command is given in (13). The difference error $(sat(\delta_e)-\delta_e)$ reduces the signal to be integrated while the control law exceeding the saturation limits which gradually prevent the accumulation at the integrator.

$$\delta_e(t) = K_{p\alpha}(\alpha(t) - \alpha_c(t)) + \\ (K_{i\alpha} + K_b(sat(\delta_e) - \delta_e))\int \Delta\alpha dt \quad (13) \\ -K_{dq}q$$

D. Bumpless Control

Changing flight controller mode from manual to autonomous is considered one of the most significant features of the autopilot design. However, switching suddenly from manual to auto (on/off) control will cause terrible chock to the actuators as the PID keeps computing the output in the background without applying it to the actuator, in other meaning the integrator is continuously accumulating the past error hence increasing the control law [164]. Once returning to the auto mode which means the use of the PID controller, that control command is a massive immediate value due to the background integration of the past error. Consequently, a tracking mechanism must be designed to be used in the manual mode to prevent the PID from background integration. The solution based on allowing the PID to track the applied input to the system in manual mode through a feedback tracking reference signal to the controller. The difference between the tracking signal and the PID controller applied to an integral part to be accumulated to assist the controller to track the command input to the system even it is not controlling it. For an instant, the pitch channel elevator control surface command is modified in (14) to avoid the background accumulation of an integral part of the PID controller, where **TR** is the tracking reference signal is equal to the PID output elevator control surface command in case of auto mode i.e. the tracking reference feedback has no effect in the designed PID control law and it is equal to the system input in manual mode.

$$\delta_e(t) = K_{p\alpha}(\alpha - \alpha_c) + \\ (K_{i\alpha} + K_b(TR - \delta_e))\int \Delta\alpha dt - K_{dq}q \quad (14)$$

E. On-The-Fly Tuning Changes

To improve the tracking performance of the designed flight control law, the PID gains must be auto-tuned i.e. it must be able to tune the parameters while the system is running. However, the drastic changes of the control law mainly due to the integral gain Ki as it is multiplied by the integration error which can be represented in (15).

$$K_{i\alpha}\int \Delta\alpha(t)dt \approx \\ K_{i\alpha t}\left[\Delta\alpha(t1) + \Delta\alpha(t2) + ...\right] \quad (15)$$

Where $\Delta\alpha(t)$ is the instantaneous difference error. The problems come when changing Ki as it involves the whole accumulated error. It is assumed to rescale the error sum to ensure the Ki tuning has the effect of the last error, not all previous error history i.e having the gain Ki inside the integral. Consequently, the smooth transfer of the new gain will have occurred without any complexity while achieving the required response. For instant, the integral part of the pitch channel elevator control surface command is given in (16), if the gain Ki is changed it will contribute the old error only rather than the total accumulated error.

$$K_{i\alpha}\int \Delta\alpha(t)dt \approx \\ K_{i\alpha t1}\Delta\alpha(t1) + K_{i\alpha t2}\Delta\alpha(t2) + ... \quad (16)$$

IV. ATTITUDE CONTROLLER DESIGN

Practically, it is common to start the design of the flight control system with controlling the UAV airspeed through using the throttle command, followed by controlling the longitudinal plane states using the elevator control surface command, finally tracking the desired reference of the lateral directional plane through generating aileron control surface command while using the rudder control surface command to decrease the coupling associated with the roll and yaw states especially for conventional UAV airframe.

The outer guidance loop is concerned with tracking the desired waypoint which translated to tracking the desired altitude with the pitch channel attitude loop and also tracking the desired latitude and longitude with the roll channel attitude control loop. Consequently, the fully autonomous integrated guidance and control system is designed to guide the UAV to the desired waypoint by generating both guidance law responding to the desired reference followed by generating the desired control law to achieve the desired guidance law. In Most commercial open source autopilot, the abovementioned sequence of design the flight control system has been followed, while the method of achieving either the guidance law or the control law is varying from autopilot to another based on the desired robustness, tracking performance, and finally the commercial cost of the designed autopilot. PID control technique is considered the central core of the autopilot design as it is well-known reliable flight control techniques. However, adopting PID in generating either the guidance law or the control law is introduced in a diverse structure that allows the UAV to track the desired reference signal in an accepted manner.

A. Altitude Tracking Loop

The desired altitude h_c is generated from the outer guidance loop is applied to the subsequent loop with the UAV actual altitude is the feedback which derived by the GPS while the output is the desired angle of attack α_c. The altitude control loop is designed using a PI controller designed based on the improvement concepts described above, the altitude saturation limit is employed to constrain the altitude error according to the flight envelope specification of the Tiger – Trainer UAV model. The altitude tracking loop is consisting of two PI cascaded control loop; the first PI loop responds to the desired altitude guidance command with the feedback is the UAV altitude and the output is the desired vertical speed $\dot{h}_c$, while the second loop is tracking the desired vertical airspeed with the actual UAV vertical speed is the feedback provided by the GPS and the output is the desired angle of attack. In some PID structures, vertical airspeed is omitted for simplicity, but in this research, it is applied to control the climbing or descending rate of the UAV speed. The altitude control loop equation is given in (17) shows that the UAV altitude is controlled by executing a certain angle of attack.

$$\dot{h}_c = (h_c - h)(K_{ph} + K_{ih}/s)$$

$$\alpha_c = (\dot{h}_c - \dot{h})(K_{p\dot{h}} + K_{i\dot{h}}/s) \qquad (17)$$

The two cascaded PI controller is used to increase the robustness and also tracks the rate of change of climbing and descending as shown in Fig.1

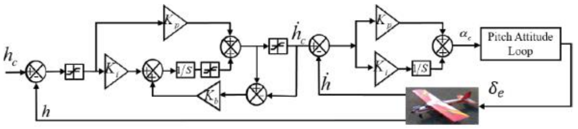

Fig. 1 Altitude control loop.

The common standard reference input is applied as a desired reference angle of attack given in Fig. 2, while the associated coupled attitude angles roll and side-slip angle remains zero. The transient tracking response of the designed flight control system based on the PID controller ensures the capability of the classical modified PI-D controller to be employed with a nonlinear complex UAV system. It is also known with the optimal tuning of the defined PID controller gains, the tracking performance improved to be efficient. No matter the model uncertainty or the existing external disturbances, the PID controller is considered one of the most prominent robust controllers for complex industrial systems. The PID is proved for the industrial application to optimally solve the problem of obtaining a robust response associated with the accepted tracking performance. The internal stability of the flight control system introduced by the response of the most inner loop body angular pitch rate of P as presented in Fig. 3. The executed roll and yaw rates are zero which strengthens the concept of the potential ability of the PID controller to decouple the UAV longitudinal states from the lateral states. The body angular pitch rate is applied within the allowable standard limit of the small UAV angular rates.

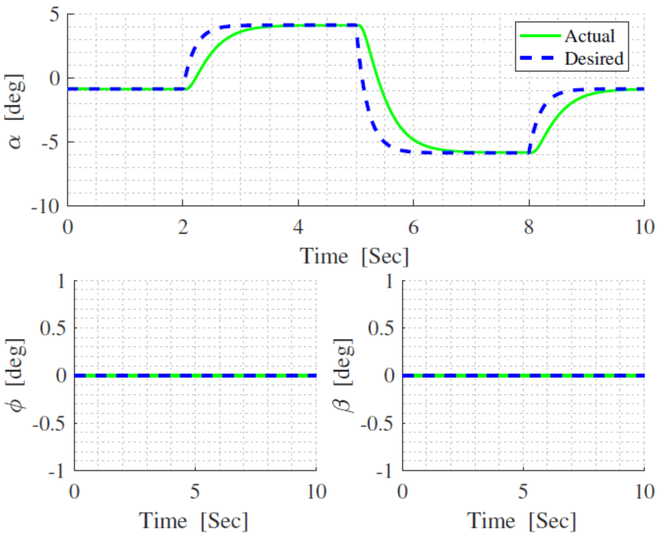

Fig. 2 Altitude angle tracking response.

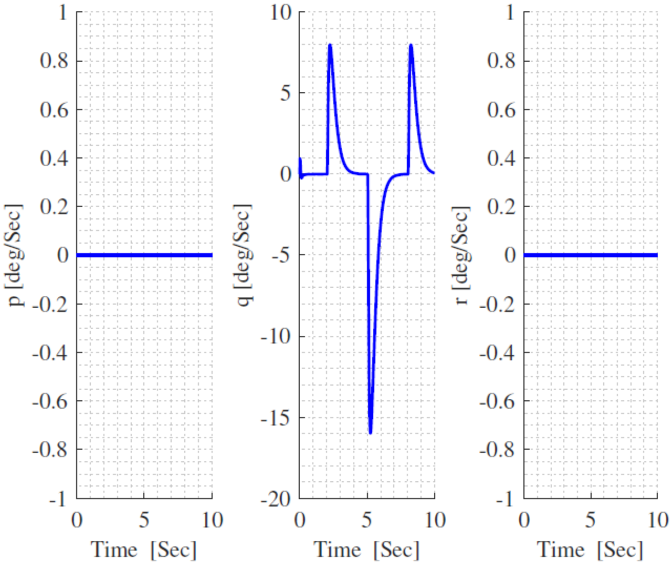

Fig. 3 Altitude rate response.

B. Roll Channel Tracking Loop

The significant responsibility of the roll channel control loop is to respond to the outer guidance command φ_c by varying the UAV heading to ride the desired predetermined path. Additionally, it overcomes the model mismatch, rejects the disturbances, reduces the coupling effect with yaw states, and attenuate the associated measurement noise. The roll angle tracking control loop is divided into two sets, the first one is the feedback control loop concerning tracking the desired roll angle and also regulating the side-slip angle to zero, while the second control law is the feedforward control law that introduced to reduce the coupling effect between the roll and yaw angles. The roll channel control loop is designed in responding to the outer loop guidance command ψ_c by performing a stable roll attitude through deflecting the aileron control surface command as illustrated in Fig. 4. The bank to turn concept is exploited while guiding the UAV to the new attitude by executing bank angle while keeping the side normal acceleration zero to avoid generating the opposite force. The two cascaded loops represent the roll tracking channel, the first loop is with the desired yaw angle is the input and the output is the desired roll angle meanwhile, the PI control technique is adopted, while the second tracking loop is with the input is the desired roll angle and the output is the required aileron control surface command meanwhile, the modified PI-D is designed to be the inner loop controller.

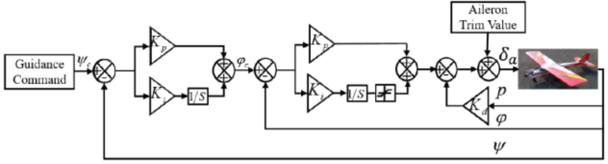

Fig. 4 Roll channel tracking loop.

The roll channel tracking loop equation is given in (18), starting with the outer guidance loop to generate the desired roll angle based on the classical PI controller then the cascaded second loop to track the desired roll angle by introducing the required aileron command based on the PI-D.

$$\begin{aligned}\varphi_c &= (\psi_c - \psi)(\mathrm{K}_{p\psi} + \mathrm{K}_{i\psi}/s)\\ \delta_a &= (\varphi_c - \varphi)(\mathrm{K}_{p\varphi} + \mathrm{K}_{i\varphi}/s) - \\ &\mathrm{K}_{d\varphi}\, p + \delta_{atrim}\end{aligned} \tag{17}$$

The performance of the modified PI-D of following the required roll angle is shown in Fig. 5. The designed feed-forward controller improves the response of the controller by reducing the associated coupling effect in the yaw channel, hence improving the tracking response. The initial starting trim value of the angle of attack pointing out to the response of the pitch channel with the only α_{trim} is the reference input.

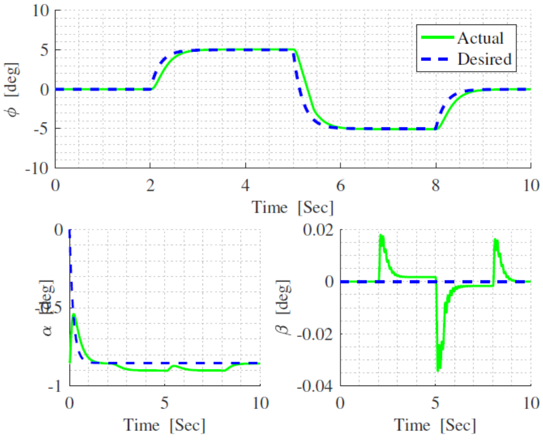

Fig. 5 Roll angle tracking loop.

The most inner tracking loop is ensuring the prospective ability of the designed modified PI-D controller for tracking the sharp roll maneuver with neglected associated coupling as shown in Fig. 6. The allowable body angular roll rate constrains the rate of turning to keep the safety of the UAV from falling while turning.

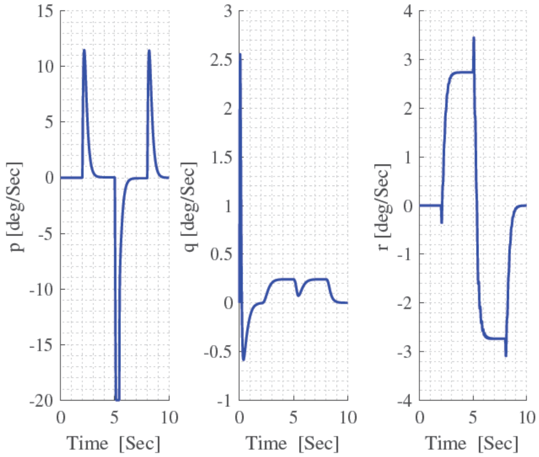

Fig. 4 Angular rate response.

V. CONCLUSION

The modification of the PID controller is introduced to avoid the differentiation of the step reference that generates an impulse chock to the actuators, the wind-up associated with the integrator during the saturation values also avoided to improve the PID performance. The common successive loop closure concept is employed for controlling the pitch channel and also roll channel taking into consideration the allowable limits of the UAV body angular rates. The mode-switching from manual to auto with the PID controller leads to the terrible change of the control command due to background integration, therefore, a feedback controller is added to the integral term. Finally, the problem accompanied by the on-fly-tuning is easily solved through neglecting the past accumulated error while tuning the integral term gain.

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