Adaptive-PID with Sliding Mode Control for Longitudinal Flight of an UAV

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Abstract: *Aircraft control has been evolving since its beginning. With advancements in technology more and more control methods are being applied to this area. This paper presents the design of an adaptive PID sliding mode control (A-SMC). The developed adaptive law computes suitable PID gains on-line. The A-SMC is able to follow the desired path in presence of uncertainties present in the system. Simulations prove that A-SMC methodology gives satisfactory trajectory tracking.*

Keywords: *PID Controller, Adaptive Control, Sliding Mode Control, Robust Control*

I. INTRODUCTION

Unmanned Aerial Vehicle (UAV) is an aerial vehicle capable of sustained flight without the need of human operator onboard. UAV are mostly used in military application such as border security, power cable surveillance, combat missions, etc., UAV can perform scientific, public and commercial service such as data and image acquisition of areas, traffic monitoring, building maps, forest fire surveillance etc. [1]. On the course of these missions an UAV is remotely controlled and is expected to withstand uncertainties and to work in high precision. In order to achieve these goals, an effective control scheme is needed to ensure accurate position tracking.

The PID controller is most widely used controller because of its simple design. Gain parameters of a PID, KI, KP, KD, are usually fixed. An automatic control system design for longitudinal flight dynamics based on Integral Squared Error (ISE) parameter optimization technique was proposed [6]. A genetic algorithm was used to find the optimum tuning parameters of the PID taking integral absolute error as fitness function [14]. However, the disadvantage of fixed gains PID controller is its poor capability of dealing with system uncertainties. Sliding mode control (SMC) is one of the popular methodologies used to deal with uncertainties present in the system [2], [12]. By altering control law structure, SMC makes a system robust towards external disturbances and lower sensitive to parameter variations [3].

In this paper, an Adaptive-PID SMC is applied to a UAV model in the presence uncertainties. Adaptive law obtains suitable value of PID gains (KP, KI, and KD) on-line. To eliminate chattering caused by SMC, boundary layer technique is applied. Simulations results demonstrate satisfactory trajectory tracking without chattering. This paper is organized as follows: A brief introduction to Adaptive-PID with SMC is given in Section II. Section III deals with problem formulation. Longitudinal dynamics of an UAV are explained in Section IV. Simulation and results are presented in Section V. Section VI concludes the paper.

II. ADAPTIVE-PID WITH SMC

SMC is used because of its insensitivity to uncertain parameters and its ability to reject external disturbances. It is a control method that switches between two distinctly different control laws depending on the state of the system. The system is forced to slide along a prescribed surface by the discontinuous control signal. This results in a robust control system [3].

First, the structure of the system is dictated by the sign of the function s(x), the switching function. The line on the phase plane described by s(x) = 0 is called the switching surface. There are two phases for the response of an SMC system. The first is the reaching mode. During the reaching condition, the initial state of the system is driven toward the sliding surface. Next, the sliding phase occurs. The state slides along the sliding surface toward the equilibrium point as shown in Fig 1.

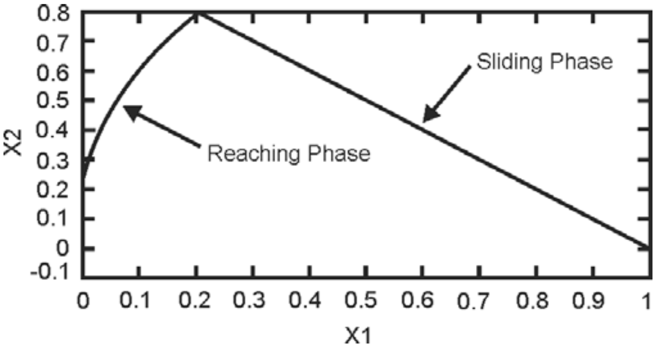

Fig 1. Reaching Phase followed by Sliding Phase

There are two main steps to designing an SMC. First, the switching surface, $s(x) = 0$, must be designed so that the desired system dynamics are achieved. Next, a control law $u(x)$ must be designed to drive any initial state to the sliding surface in a finite amount of time.

Sliding surface is a line in the phase plane containing the point

$$\mathbf{y_d = [y_d\, y_d]^T}$$

where is the desired trajectory. Starting from any initial condition, the state trajectory reaches the time-varying surface in a finite time & then slides along the surface towards exponentially. Since the implementation of the associated control switching is necessarily imperfect, because practical switching is not instantaneous, this leads to high-frequency oscillations in the output known as chattering as shown in Fig. 2.

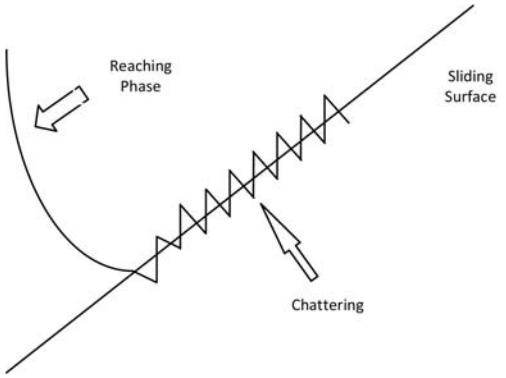

Fig 2. Chattering in output

Chattering is an undesirable characteristic of sliding mode control systems. It can cause wear and tear of mechanical parts and high heat in power circuits. Further, it may excite high frequency dynamics neglected in the course of modeling [3]. Thus, discontinuous control law u needs to be suitably smoothed to achieve an optimal tracking precision.

Addition of SMC to the PID control scheme will enable the controller to adapt itself over time thereby rejecting external disturbances and protecting against parameter variations. *A*daptive control is made up of two parts: an on-line parameter estimator and a control law. The on-line parameter estimator, also called the adaptive law, estimates the unknown parameters at every instant. The control law is based on the known parameters of the system. The adaptive PID is able to update the three parameters, KI, KP and KD online during the control procedure.

III. PROBLEM FORMULATION

Consider a second order uncertain system which can be described by

$$\dot{x}_1\,(t) = x_2\,(t) \qquad \ldots(1)$$

$$\dot{x}_2\,(t) = f\,(x_1)\,(t),\, x_2\,(t),\, (t)$$

$$+\ \Delta f\,(x_1\,(t),\, x_2\,(t),\, t) \qquad \ldots(2)$$

$$+\ d\,(t) + bu$$

$$y\,(t) = x_1\,(t) \qquad \ldots(3)$$

where x_1 (t) and x_2 (t) are measurable states, u is control input, y is the output, b is the input gain, f (.) is parameter of plant, df (.) is the plant uncertainty and d (t) denotes external disturbance. It is assumed that $|\Delta f.\,() \leq g|$ and $|< \phi$.

Let e be the error between the desired trajectory and the output y, i.e.

$$e = y_d - y \qquad \ldots(4)$$

In order to have a second-order error dynamics, we define a signal xr as

$$\dot{x}_r = \ddot{y}_d + K_{1\dot{e}} + K_{oe} \qquad \ldots(5)$$

where K_1 and K_0 are chosen by designers such that roots of $s^2 + K_1\, s + K_0 = 0$ are in the open left-half complex plane. Generally, K_1 and K_0 are chosen as $K_1 = 2\zeta\omega_n$ and $K_0 = W_n^2$, where ζ is the damping ratio and W_n is the natural frequency of oscillations.

Sliding Surface is defined as

$$s = x_2 - x_r \qquad \ldots(6)$$

If sliding mode occurs, i.e. if s=0, then

$$x_r = x_2 \qquad ...(7)$$

Substituting (7) in (5)

$$\ddot{e} + K_1\,\dot{e} + K_{oe} = 0 \qquad ...(8)$$

Control Input u be

$$u = u_{PID} + u_s \qquad ...(9)$$

where

$$U_{PID} = \frac{1}{b}\left[\,K_P e + K_1 \int e.\,dt + K_D\dot{e}\,\right] \qquad ...(10)$$

$$U_s = -\;\frac{1}{b}\;[|f| + g + \alpha + |\dot{x}_r| + b|u_{PID}| + K_2]\ \text{sign}(s) \qquad ...(11)$$

Gain K_2 is a positive scalar and sign is signum function defined as

$$\text{sign}\ (s) = \begin{cases} -1, & s < 0 \\ +\ 1, & S > 0 \end{cases}$$

The three PID controller gains computed on-line by adaptive laws are defined as:

$$\dot{K}_p = -\eta_1\ \sigma e \qquad ...(12)$$

$$\dot{K}_1 = -\eta_2\ \sigma \int e.dt \qquad ...(13)$$

$$\dot{K}_p = -\eta_3\ \sigma\dot{e} \qquad ...(14)$$

where 9< > 0 is defined as the learning rates, i=1, 2, 3.

In order to eliminate chattering, boundary layer technique is used where a smooth approximation of *sign*(*s*) with a boundary layer approach is applied. The *sign*(*s*) function is replaced with the saturation function, *sat* $\frac{s}{\varnothing}$ defined as

$$\text{sat}\left(\frac{s}{\varnothing}\right) = \begin{cases} 1, & \frac{s}{\varnothing} \geq 1 \\ \frac{s}{\varnothing}, & -\ 1 < \frac{s}{\varnothing} < 1 \\ -1, & \frac{s}{\varnothing} \leq -1 \end{cases} \qquad ...\ (16)$$

where $\varnothing$ is the width of the boundary layer. It enables the sliding function s to reach and stay within the boundary layer $|s| \leq \varnothing$.

IV. LONGITUDINAL DYNAMICS OF AN UAV

Equations of motion which govern the longitudinal flight are well defined in literature [7]. The change of pitch angle (θ) to a given elevator deflection (δ_e) in longitudinal flight is given as [6]:

$$\frac{\theta\ (s)}{\delta_e\ (s)} = \left\{ \frac{1.423s^2 + 0.134s + 1.834}{0.02424s^4 + 0.06836s^3 + 0.1s^2 + 0.0859s + 0.0836} \right\} \quad ...(16)$$

Controllability investigation of eq. (13) proves that the system is controllable. So, A-SMC can be applied to it.

V. SIMULATION AND RESULT

The Adaptive PID controller was applied to longitudinal dynamic transfer function of a UAV $\frac{\theta(s)}{\delta_e(s)}$, described in Eq. (13).

The desired trajectory is

$$y_d = 2\ \sin \qquad ...(17)$$

The control input was implemented using eq. (10)-(11). For a damping ratio $\zeta = 1$ and natural frequency ω_n=7, $K_1 = 2\zeta\omega_n = 14$ and $K_o = \omega_n{}^2 = 49$. The PID controller gains, K_1, K_p & K_D are initially set to zero. By, hit and trail method, the learning rates are set to be $\eta_1 = 5$, $\eta_2 = 5$, $\eta_3 = 20$. The boundry layer is set to be ϕ =0.1.

With these parameters, performance of UAV has been analyzed on Simulink whose blockset is given in Fig. 4 with sampling time taken as 10^{-5} sec.

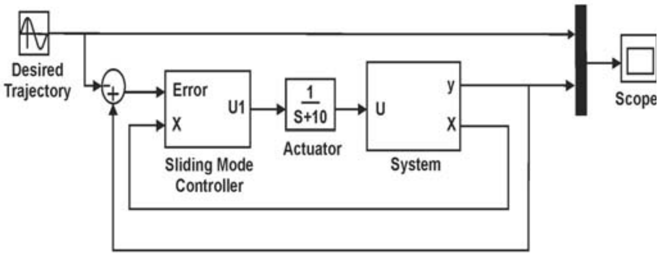

Fig 3. Block diagram of Adaptive PID control with SMC

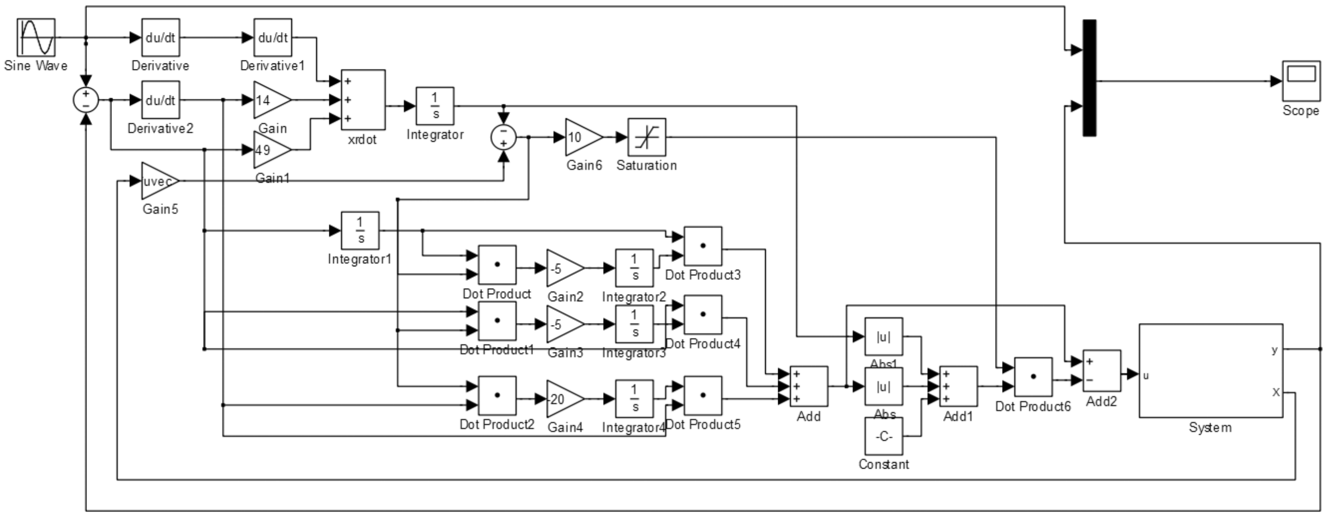

Fig 4. Simulink Implementation of Adaptive-PID with SMC

As it can be observed from Fig. 5, system output y_d tracks the desired trajectory yd after a few initial small overshoots and completely converges to y_d in less than 1 sec.

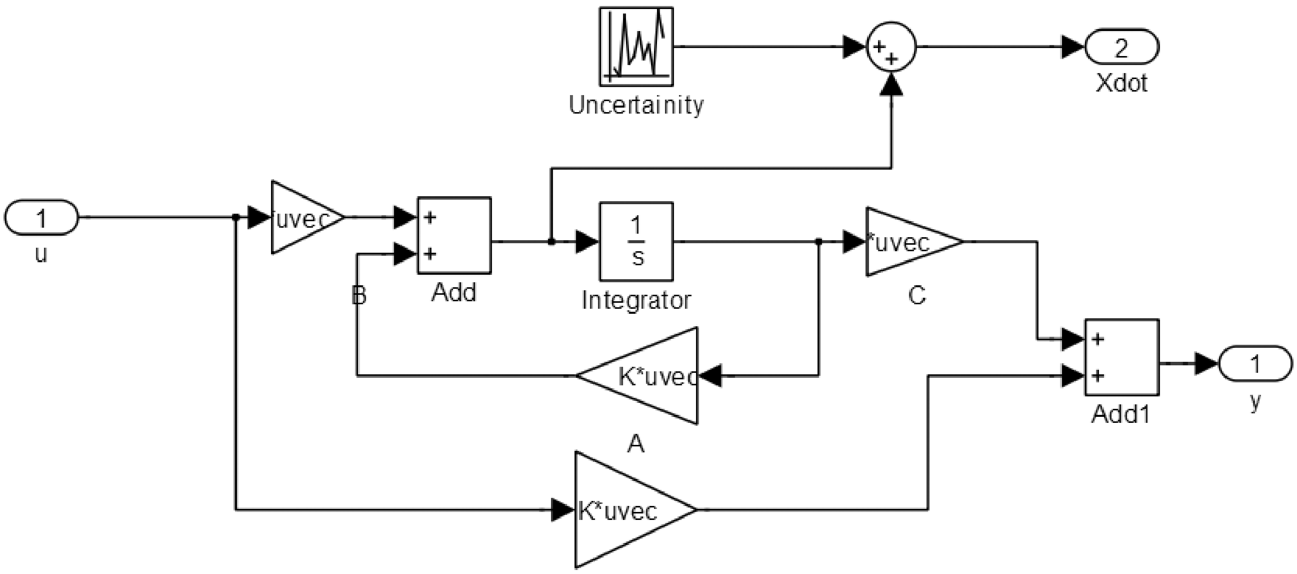

Fig 5. Exploded view of System

Table 1 : Results

Average error between desired and actual trajectory	-1.2829×10^{-4}
Standard Deviation of error	1.6206×10^{-2}
Variance	2.6266×10^{-4}

It can be inferred from Figs. 6, 7, 8 and 9 that KD and KP are smooth, bounded and reach optimum values. KI is varying in nature. Control input u is bounded and becomes smooth after 1.5 sec.

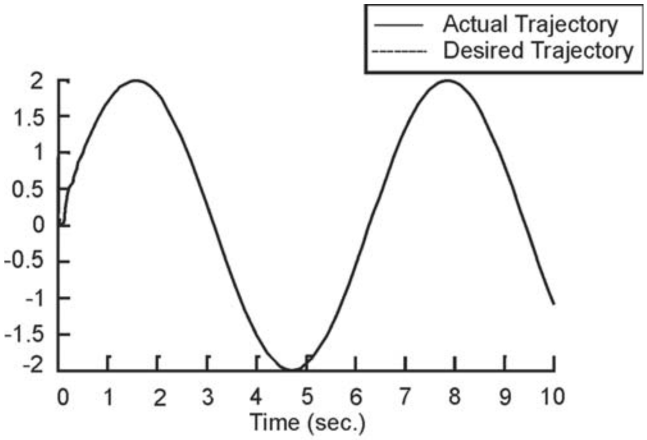

Fig 6. Actual trajectory and desired trajectory

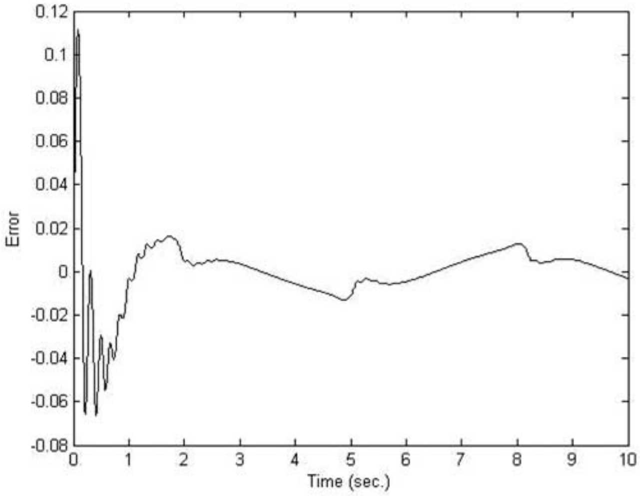

Fig 7. Error between Actual and desired trajectory

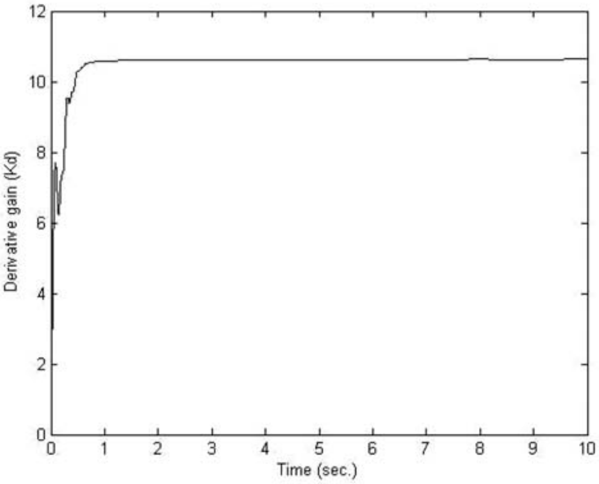

Fig 8. Controller gain, K_d

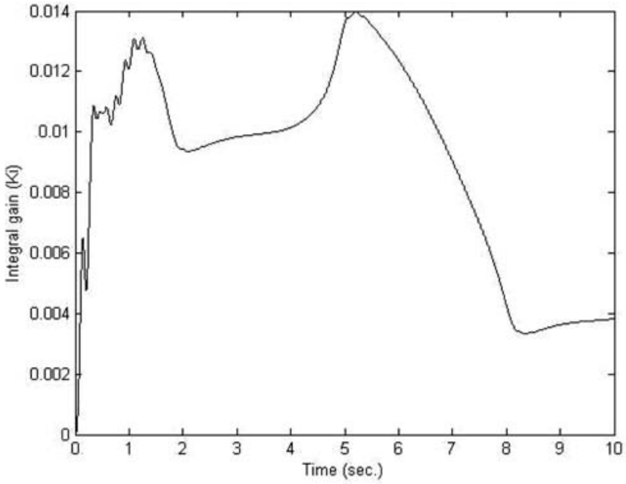

Fig 9. Controller gain K_i

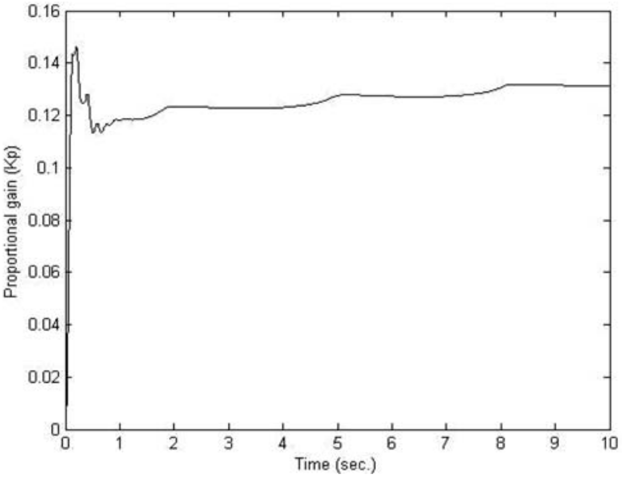

Fig 10. Controller gain K_P

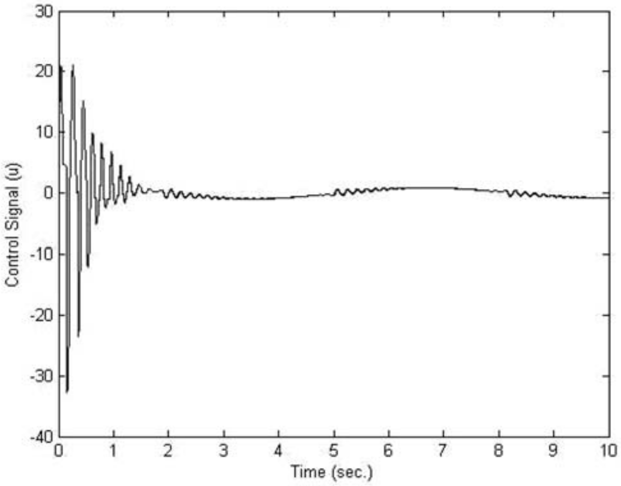

Fig 11. Control input u

VI. CONCLUSION

In this paper, adaptive-PID with SMC was applied to pitch control of an UAV model. Simulation results show that it effectively tracks the desired trajectory even in presence of uncertainties. PID controller gains were computed online by means of an adaptive law. Gains vary according to varying uncertainties. Chattering in the control input was removed using boundary layer technique.

VII. FUTURE WORK

The learning rates 9, 9 and 9; chosen here were based on hit and trail method, but they can be tuned as well.

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