Control Strategy of Unmanned Aerial Vehicle (UAV) By Using Sliding Mode Control Method

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ABSTRACT
Unmanned Aerial Vehicle (UAV) is a machine that can be controlled remotely by using remote, or it is able to control itself. UAVs have many missions, one of which is to oversee the dispute area. In its development required a control method that can be applied to the uncertainty model. Sliding Mode Control (SMC) is a control method that can be applied to the uncertainty model. Therefore, the Sliding Mode Control method is designed to control UAV movements. From the simulation result it is known that by applying the SMC method, the UAV motion is able to follow the given set point. In other words, the Sliding Mode Control method can be applied to control UAV motion.

Keywords: *Sliding mode control (SMC), robust control, uav.*

I. INTRODUCTION

Aerospace technology in Indonesia is increasingly developing which is characterized by the many uses of aerospace technology in several fields. One of them is in the field of developing unmanned aircraft vehicle or better known as UAV. A UAV is a flying machine that is controlled by a remote control by a pilot or capable of controlling itself. In the development of UAVs it takes many disciplines related to the implementation of research and development, including the instruments in it [1]. In Indonesia, UAVs are researched and developed by several agencies, one of which is BPPT (Agency for the Assessment and Application of Technology). One of the UAVs developed by BPPT is PUNA Wulung. PUNA Wulung is designed as a surveillance aircraft for the Indonesian border region with neighboring countries and is operated at an altitude of 10000 feet. In addition, PUNA Wulung is also used to supervise illegal activities in the archipelago, namely fishing theft, illegal logging, and is used to conduct surveillance for transportation, search and rescue, research, atmosphere, disaster control, artificial rain, etc. PUNA Wulung is able to fly for four hours with a distance of more than 150 km and capable of carrying a 120 kg payload [1][2].

In the air, the UAV cannot be fully controlled using remote control. So, the UAV is designed to be able to control itself after being in predetermined position. In the design required a method of control that is able to stabilize the motion of the UAV when experiencing interference from the system (atmosphere) or interference that occurs in the system. The purpose of this control design is to control the rolling and pitching motion of the UAV. pitching motion is the motion of the UAV that occurs when the UAV will move forward. This motion is influenced by the pitch angle. while the rolling motion is the motion needed by the UAV to make a turn. In the rolling motion required roll angle. There are several subjects that can inhibit the motion of UAVs in the air, so that the UAV is not able to work optimally, this disturbance can affect the pitch angle and roll angle produced by the input, so that the plane runs not in accordance with the given path. So we need a control method that is able to overcome the interference that occurs in the UAV due to interference from outside or from within the system itself. So, the sliding mode control was chosen.

The Sliding Mode Control (SMC) is a system control method that uses a high frequency switching method application. This method has a control concept for the uncertainty model, but rather on a limited estimate. In addition, the SMC method itself was developed for localization system of the UAV motion which can overcome non-Gaussian processes and observational noise that are appropriate for UAV navigation in unknown dynamics. So, this method is considered able to maintain the stability of the motion the UAV in the air[3][4][5].

II. MATHEMATICAL MODELS OF THE UAV MOTION EQUATION

UAV equation motion are formed from equations of force and moments aerodynamics. In addition, input control is given to the system with the aim of controlling the motion of the UAV. The input controls are controls on the aileron, elevator, rudder, and throttle with their respective goals being to rolling, pitching, and yawing. The UAV motion equation is divide into two motion equations, namely the longitudinal motion equation and the lateral-directional motion equation.

The UAV parameter used in this paper is a case study BPPT parameters on Wulung UAV platforms. The values is given in table I as follow [1][2]:

Table I. Parameter Values of UAV

Parameter	Notation	Value
MTOW	m	$120\ kg$
Center of gravity		$28\%\ MAC$
MAC	$\bar{\bar{c}}$	$0.6\ m$
Wing area	S	$3.717\ m^2$
Horixontal tail wing area	S_T	$0.883\ m^2$
Pitch moment inertia	I_{yy}	$105.3\ kg.m^3$
Wing span	b_W	$6.355\ m$
Wing rigging angle	η_W	$6°$
Roll moment inertia	I_{xx}	$79.045\ kg.m^2$
Yaw moment inertia	I_{zz}	$159.541\ kg.m^2$

A. Longitudinal Equation Motion

Longitudinal motion is the plane motion caused by the forces acting on the XZ symmetrical plane. This motion involves linear velocity forward, upward, the speed of the angular angle and the angular angle. So, the longitudinal equation of motion is given as follows[6][7]:

$$\dot{u} = X_u u + X_\alpha \alpha - g\cos\Theta_0\,\theta + X_{\delta_e}\delta_e + X_{\delta_T}\delta_T \quad (1)$$

$$\dot{\alpha} = Z_u^* u + Z_w \alpha + U_0 q - g\sin\Theta_0\,\theta + Z_{\delta_e}^*\delta_e + Z_{\delta_T}^*\delta_T \quad (2)$$

$$\dot{q} = M_u u + M_\alpha \alpha + M_q q + M_{\delta_e}\delta_e + M_{\delta_T}\delta_T \quad (3)$$

$$\dot{\theta} = q \quad (4)$$

Equations (1) - (4) can be written in the form of a state equation as follows:

$$\dot{x} = Ax + Bu$$

$$\begin{bmatrix}\dot{u}\\ \dot{\alpha}\\ \dot{q}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix} X_u & X_\alpha & 0 & -g\cos\Theta_0\\ Z_u^* & Z_w & U_0 & -g\sin\Theta_0\\ M_u & M_\alpha & M_q & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}u\\ \alpha\\ q\\ \theta\end{bmatrix} + \begin{bmatrix} X_{\delta_e} & X_{\delta_T}\\ Z_{\delta_e}^* & Z_{\delta_T}^*\\ M_{\delta_e} & M_{\delta_T}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\delta_e\\ \delta_T\end{bmatrix} \quad (5)$$

Then the control and observatory test in equation (5) is performed, and it is known that the system is controlled and observed.

B. Lateral-directional Equation Motion

Lateral-directional motion is the plane motion caused by the forces acting on the XY symmetrical plane. This motion involves linear velocity to side, the speed of the roll angle and the speed of the yaw angle. So, the lateral-directional equation of motion is given as follows[6][7][8]:

$$\dot{\beta} = Y_v\beta - r + \frac{g\cos\Theta_0}{U_0}\phi + \frac{Y_{\delta_r}}{U_0}\delta_r \quad (6)$$

$$\dot{p} = L_\beta\,\beta + L_p\,p + L_r\,r + L_{\delta_a}\delta_a + L_{\delta_r}\delta_r \quad (7)$$

$$\dot{r} = N_\beta\beta + N_p p + N_r r + N_{\delta_a}\delta_a + N_{\delta_r}\delta_r \quad (8)$$

$$\dot{\phi} = p + r\tan\Theta_0 \quad (9)$$

Equations (6) - (9) can be written in the form of a state equation as follows:

$$\dot{x} = Ax + Bu$$

$$\begin{bmatrix}\dot{\beta}\\ \dot{p}\\ \dot{r}\\ \dot{\phi}\end{bmatrix} = \begin{bmatrix} Y_v & 0 & -1 & \frac{g\cos\Theta_0}{U_0}\\ L_\beta & L_p & L_r & 0\\ N_\beta & N_p & N_r & 0\\ 0 & 1 & \tan\Theta_0 & 0\end{bmatrix}\begin{bmatrix}\beta\\ p\\ r\\ \phi\end{bmatrix} + \begin{bmatrix} 0 & \frac{Y_{\delta_r}}{U_0}\\ L_{\delta_a} & L_{\delta_r}\\ N_{\delta_a} & N_{\delta_r}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\delta_a\\ \delta_r\end{bmatrix} \quad (10)$$

Then the control and observatory test in equation (10) is performed, and it is known that the system is controlled and observed.

III. SLIDING MODE CONTROL DESIGN

Sliding Mode Control (SMC) is a high-speed switching feedback control system that can be applied to linear and nonlinear systems. The working principle of sliding mode control is to force the trajectory state of a system to a particular sliding surface and maintain it on the sliding surface [3][4][5]. SMC has several advantages, namely its very robust nature, being able to work well on nonlinear systems that have model or parameter uncertainties. The SMC design is related to the following functions and conditions:

A. Switching Function

The switching function, which is the surface of $S(x,t)$ in a R^n state space, satisfies the equation:

$$S(x,t) = S\left(\frac{d}{dt} + \lambda\right)^{n-1} e \quad (11)$$

S is an matrix with dimension $m \times n$ and has constan elements. It is the parameters for the sliding surface equation constant.

B. Sliding Surface

Sliding surface is a condition when the switching function is fulfilled:

$$S(x,t) = 0 \tag{12}$$

Sliding surface in the form of a line which is an important component of SMC as a trajectory where the state slides from the initial conditions to the desired state.

C. Sliding Condition

The design of the control law in SMC is done, so that $\tilde{x}(t)$ moves towards the sliding surface and glides on that surface for all $t \geq 0$. To obtain control law, a function similar to Lyapunov function is used where the function constructed is a positive definitive function [3][4][5].

$$V = \frac{1}{2}s^2 \tag{13}$$

Where $V(0) = 0$ and $V > 0$. The condition of stability system is defined as the first derivative of the above equation, so that it is obtained:

$$\dot{V} = s\dot{s} \leq -\eta|s| \tag{14}$$

Inequality (14) is referred to as a sliding condition that can be expressed as:

$$\dot{s}sgn(s) \leq -\eta \tag{15}$$

Where η is a positive constant and the sgn function is defined as:

$$sgn(x) = \begin{cases} -1, & x < 0 \\ 1, & x \geq 1 \end{cases} \tag{16}$$

D. SMC with Boundary Layer

The emergence of chattering is one of the shortcomings of the SMC method [3][4][5]. Chattering is on oscillation of the controller output with high frequency caused by very fast switching to form sliding mod. This can cause instability in the system. To prevent instability due to chattering, the SMC applies a boundary layer on a sliding surface that makes it smooth and convincing that the system is inside the layer. The width of Boundary layer is expressed as 2θ. Take $|s|$ as the distance between $\tilde{x}$ and the sliding line $S = 0$. Then the $\tilde{x}$ state vector is inside boundary layer if $|S| \leq \theta$, and outside if $|S| > \theta$. Using boundary layer in the control law of $a = \hat{a} - K.sgn(S)$ is done by replacing the sgn function with $sat(S\theta)$ and K is positive constant. Where the saturation function sat is defined as follows[3][4][5][9]:

$$sat(x) = \begin{cases} x \quad , & \text{if } |x| < 1 \\ sgn(x), & \text{if } |x| \geq 1 \end{cases} \tag{17}$$

After the SMC control plan is obtained, it is then implemented in the block diagram that has been made in Fig. 1.

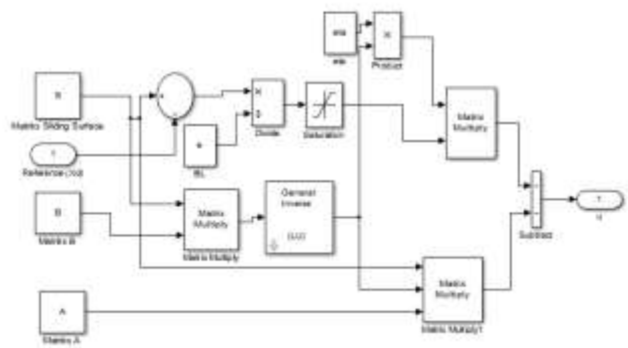

Figure 1. Block Diagram SMC

IV. SIMULATION

In this section, the SMC system is designed using the following state equation:

$$\dot{x} = Ax + Bu \tag{18}$$

$$y = Cx + Du \tag{19}$$

In this paper, the control design of the longitudinal and lateral-directional system is done separately. The Purpose of the control design is to stabilize the motion of the UAV while in the air. So that the UAV will be able to work properly. Control is done on the rolling and pitching motion.

A. Longitudinal Motion

Control design in longitudinal motion consists of θ (pitch roll) reference, the SMC controller subsystem and longitunial state space subsystem and output in the form of pitch angle. At this stage, a simulation is performed to look up, that is, when the aircraft will move upward. The simulation is carried out within 50 seconds by giving an order so that the plane is able to form an angle of $0.2\ rad$ or equal to 11.459^{o}. The goal is the plane can move forward with the upward leaning. The simulation results on longitudinal motion are shown in Fig.2.

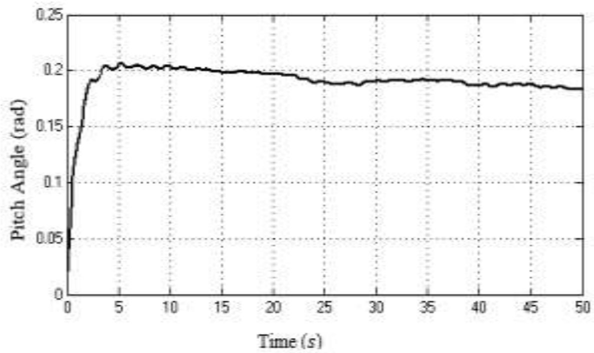

Figure 2. Simulation result of Pitch Angle with SMC

Fig. 2. is the result of output system using SMC method with applying set point of $0{,}2$ rad or $11{,}46^{\circ}$. From the simulation result can be observed that the roll angle stable in the angle as big as 0,2 rad in the time 3,35 second with the value of the maximum overshoot (M_p) of $0{,}22$ rad or 10%. On the Fig. 2 we know that the graph is right at angle of $0{,}2$ rad for 7 seconds. At 11 seconds into the chart further down, but still within the tolerance limits overshoot so that the system can be said to be stable. The parameters values obtained from these simulations are delay time (t_d) for $0{,}1$ second, rise time (t_r) system occurs during $1{,}9$ seconds. Settling time (t_s) is needed for a system for $3{,}9$ seconds. The time it takes the system to achieve throughput the first during $3{,}63$ seconds.

Simulation results show that there is still an error in the system, but the value of the error that occurs is not large. The error value that occurs in the system is shown in Fig. 3. The error value given is the error value that occurred in the system when the system is working for 50 seconds.

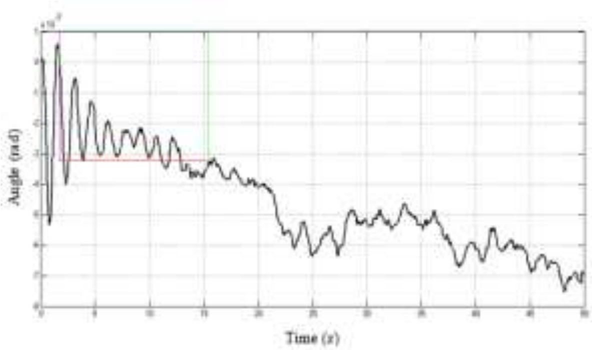

Figure 3. The Error Value That Occurs at Pitch Angle

Fig. 3. Indicates that the system is able to follow a given set point, the system is able to move forward using an angle of $0.2\ rad$ for 50 seconds. In the Fig. 3. Shows that the scale of values that occur at interval of $-5 \times 10^{-3}\ rad$ to $0.02 \times 10^{-3}\ rad$, it show that the average error that occurs is $2{,}5\%$ from the set point of the system. So this error can be tolerated.

B. Lateral-Directional Motion

Control design in lateral-directional motion consists of β (roll angle) reference, the SMC controller subsystem and lateral-directional state space subsystem and output in the form of roll angle. At this stage, a simulation is performed to turns, that is, when the aircraft will move to side. The simulation is carried out within 100 seconds by giving an order so that the plane is able to form an angle of $0.2\ rad$ or equal to 11.459^{o}. The goal is the plane can move to side with turn sideways. The simulation results on lateral-directional motion are shown in Fig.4.

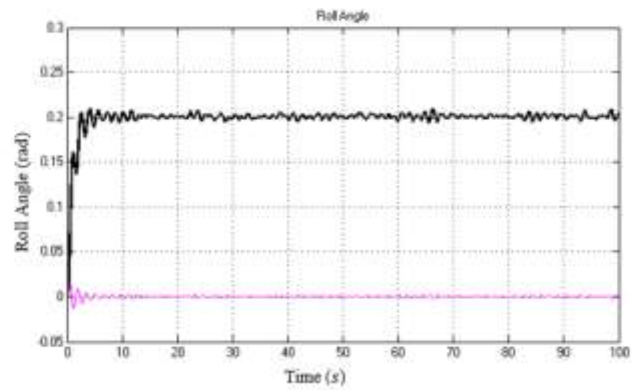

Figure 4. Simulation result of roll angle with SMC

The simulation on the Fig. 4 is doing with $t_o = 0$ to $t_f = 100$ seconds with the simulation result in the Fig. 4. In the Fig. 4, the vertical axis shows the angle formed, and the horizontal axis shows the travel time of the angle formed. The simulation result on the Fig. 4 is the result of system output by using SMC control system to the lateral-directional motion by applying a set point of 0,2 rad or $11{,}46^{\circ}$. From the simulation result can be observed that the roll angle stable in 0,2 rad in the time 3,35 seconds with the value of the maximum overshoot of $0{,}0135$ rad or $6{,}75\%$. At 22 seconds into the chart further down, but still within the tolerance limits overshoot so that the system can be said to be stable. The parameter values obtained from these simulations are delay time (t_d) for $0{,}1s$, *rise time* (t_r) system occurs during $1{,}8s$. *Settling time* (t_s) is needed for a system for $3{,}35s$. The time it takes the system to achieve throughput the first during $3{,}7s$.

Simulation results show that there is still an error in the system, but the value of the error on the roll angle that occurs is not large. The error value that occurs in the system is shown in Fig. 5. The error value of roll angle given is the error value that occurred in the system when the system is working for 50 seconds.

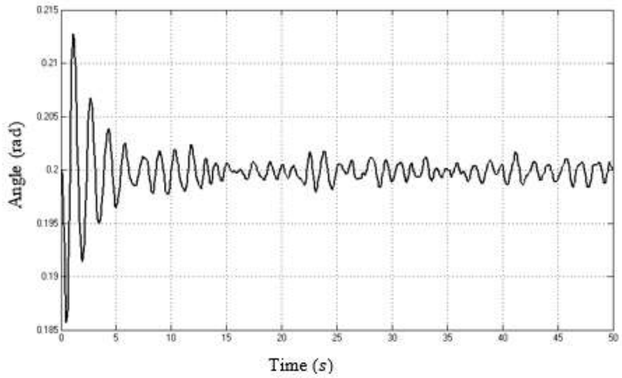

Figure 5. The Error Value That Occurs at Roll Angle

Fig. 5. Indicates that the system is able to follow a given set point, the system is able to move side way using an roll angle of $0.2\ rad$ for 50 seconds. In the Fig. 5 Shows that the scale of values that occur at interval of $-0.185\ rad$ to $0.215\ rad$, it show that the average error that occurs is $7{,}5\%$ from the set point of the system. So this error can be tolerated.

V. CONCLUSION

From the analysis and discussion presented in the previous chapter, it can conclude some of the following:

1. The application of the SMC method to the UAV control system can help to find out and improve the response time of pitch and roll output.

2. SMC is quite strong is responding to disturbances both in the form of internal noise or external interference that is momentary or continuous.

Based on the result of simulation with the SMC method obtained parameter values to rolling is the value of maximum overshoot as $0{,}0135$ rad or $6{,}75\%$. The time needed to delay time (t_d) is $0{,}1$ seconds, rise time (t_r) occurs during $1{,}8$ seconds. Settling time (t_s) occurs during $3{,}35$ seconds. The time needed to reach the first throughput is $3{,}7$ seconds. As for the response of the pitch angle output is known that the value of maximum overshoot as $0{,}22$ rad or 10%. The time needed to delay time (t_d) is $0{,}1$ seconds, rise time (t_r) occurs during $1{,}8$ seconds. Settling time (t_s) occurs during $3{,}9$ seconds

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