UAV's Pitch Angle Control Scheme based on Terminal Sliding Mode Control

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Abstract. As their application scenarios become more diverse, the demand for control methods that can resist interference is also growing. This is particularly important for UAVs operating in some scene happened in complex environments, where they may be susceptible to various external interference factors, such as wind, which can affect their stability and performance. To address this issue, this paper aims to provide a novel control method based on Terminal Sliding Mode (TSM) control. TSM control is a type of robust control strategy that has been successfully applied to a wide range of systems, including UAVs. By using various stimulations,the aim is set to create a tailor-made TSM method that can effectively weaken the influence of interference, such as wind, on fixed-wing UAVs. The verification of the effectiveness of the proposed TSM control method will be conducted through simulations and experiments. This research not only contributes to the development of UAV control technology but also has practical significance for the application of UAVs in fields such as disaster relief, environmental monitoring, and military operations, where stable and reliable flight performance is of paramount importance.Furthermore, the proposed TSM control method can be potentially applied to other types of UAVs and even other types of robotic systems, providing a more general solution for the interference problem in robotic control.

Keywords: Fixed-wing UAV, Terminal Sliding Mode (TSM), Control

1 Introduction

In some competition of air plane model, the player is asked to design an airplane to throw the projectile to a target. It is probably a difficult problem to the controller, so a plan that the UVA can throw the projectile by itself is be raised.

In this scene, projectiles will be threw from the UVA when the UVA is on its route. In this case, the route can be considered as a line, but it need maintain the speed, which means the drone does not allow the speed changing too fast. If the speed changes too fast, the UVA will face the risk of stalling speed. On the other hand, the UVA need a pitch angle to make sure the position of the projectile.

The technology of UAV has became more and more significant. The development of drones brings some convenience in some areas such as surveillance, search and

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rescue missions [1]. By controlling the attitude and trajectory of the unmanned aerial vehicle, it can complete various modes so that it can fit different kinds of situations. Although rotary-wing drones can solve some kinds of situations, it still have some shortcomings. So fixed-wing unmanned aerial vehicle has more and more chance especially in military science. However, this kind of UVA need a kind of control system which can resist the influence such as wind. However, it is well known that a UAV platform research is difficult multidisciplinary process, which includes mechanical design, aerodynamics, modeling, controller design and the development of hardware and software. The modeling of UAVs plays a key role in the development of a UAV platform, especially in hybrid UAVs [2].

In this area, many learned men have came up with many ways of controlling the UVA, such as PID method with genetic algorithm [3], Robust cooperative tracking control [4]. To some degree, the TSM can be a good method.

With the continuous development of industrial system, the linear sliding mode function used in traditional sliding mode control can not guarantee the finite time convergence of system error, so it can not be applied to high precision control system [5]. To solve this problem, a non-singular fast terminal sliding mode sliding control method has been proposed, which has good finite-time convergence, stability of trajectory tracking and robustness to lumped uncertainties. However, the reason why the sliding mode control is robust is that it uses sufficiently large and fixed sliding gain to deal with lumped unknown disturbance in the design process [6], but the buffeting phenomenon caused by it will seriously damage the system and reduce the practical applicability of the sliding mode control. In addition, when the UAV is operating in the external environment [7], the disturbance will directly act on the UAV, which is also a reason for the buffeting of sliding mode control. So how to deal with the disturbance becomes the key problem in the research.The paper also introduces a category of second-order sliding mode Lyapunov function [8], which provides a design and analysis tool for the study of higher-order sliding mode control theory [9]. In this paper, we propose an output feedback regulator using a reliable control design which can control the pitch angle together with an appropriate high gain observer.

2 Model Construction

2.1 Terminal Sliding Mode (TSM) control

Sliding mode control is a kind of special nonlinear control in essence, and the nonlinearity is the discontinuity of the control. The difference between this control strategy and other controls is that the "structure" of the system is not fixed, but can be purposefully changed according to the current state of the system in the dynamic process, forcing the system to move according to the predetermined "sliding mode" state trajectory. Because the sliding mode can be designed and is independent of the object parameters and perturbations, the sliding mode control has the advantages of fast response, insensitive to the change of corresponding parameters and perturbations, no need to identify the system online, and simple physical implementation. Later, in order to make the sliding mode control have better performance, it is thought to design the sliding mode surface as a nonlinear function and construct the Terminal sliding mode surface, so that the error on the sliding mode surface can converge to 0 in the specified time T, so that the terminal sliding mode is generated.

Based on the function above, sliding mode surface can be constructed. Based on the traditional sliding mode control, terminal sliding mode control introduces nonlinear terms to accelerate the state convergence of the system [8].Terminal Sliding Mode Control (TSMC) is an extension of Sliding Mode Control (SMC), which mainly solves the problem of steady-state error when traditional sliding mode control tracks the desired trajectory. In sliding mode control [10], the dynamics of the system are limited to a predetermined sliding surface, which is determined by the design of the control law. However, the traditional sliding mode control law does not guarantee that the system state can accurately track the desired trajectory after reaching the sliding surface, especially when the expected trajectory is an integral of the time function, such as the expected trajectory of position and velocity.

By introducing a nonlinear term into the sliding surface design, the terminal sliding mode control enables the system to reach and finally stabilize on the desired trajectory in a finite time, thus eliminating the steady-state error. Such nonlinear sliding surfaces usually contain higher-order terms for the derivatives of the system states, allowing the system to converge to a zero-error state in a finite time, maintaining robustness even in the presence of uncertainties and external disturbances in the system model. Terminal sliding mode control is widely used in robot control, spacecraft attitude control and motor control, because it can provide fast response and good robustness.

2.2 UVA Model Construction

First and foremost, it is essential to introduce the UVA model, a cutting-edge aircraft design made from wood with a maximum take-off weight of 3.3 kilograms. The primary structure of this aircraft utilizes a truss system, providing a sturdy yet lightweight framework. To maintain strength while minimizing weight, the skin of the aircraft is composed of heat shrinkable film, resulting in a total self-weight of only 1.8 kilograms.

In order to establish the specific parameters for the aircraft, an extensive selection process was undertaken. Initially, the optimal length for the fuselage was determined based on mission objectives and estimated time and route requirements for task completion. This decision was followed by thorough calculations and testing to refine the design.

Upon further analysis, it was determined that a Reynolds number of 300,000 would ensure optimal aerodynamic performance. The airfoil type selected was NACA4412 due to its superior lift-to-drag ratio which enhances efficiency. The chord length measured at 200 millimeters with a spread length extending to 1500 millimeters providing ample surface area for stable flight.

Regarding weight distribution, precise calculations positioned the center of gravity at the top 30% of the chord length ensuring well-balanced and stable flight even under challenging conditions. Overall, the UVA model represents an innovative approach to aircraft design by combining wood-based materials with advanced engineering techniques resulting in a lightweight, efficient and durable aircraft. The UVA was shown in Figure 1, and the UVA is constructed by partha wood and carbon fiber, which carries Jeston Nano as the flight controller.

Fig. 1. The UVA described above

Then, the relationship between velocity and pitch angle is complex. The pitch motion of an aircraft can be described by the following differential equations:

$$\theta' = q \tag{1}$$

$$q' = \frac{M}{I_{yy}} \tag{2}$$

In the equations above, θ symbolizes pitch the angle and q symbolizes the pitch angle velocity. The M means the pitching moment acting on an aircraft and Iyy means the moment of inertia of the aircraft around the pitch axis. The pitch moment M can be calculated from the aerodynamic characteristics of the aircraft:

$$M = C_m \frac{1}{2} \rho V^2 Sc \tag{3}$$

In the equations above, Cm represents the pitch moment coefficient, which is a function of the pitch angle θ and the angle of attack α.ρ is the density of air. V is the speed of the plane. S is the reference area of the wing.c is the average chord length of the wing. During flight, the aircraft's lift force L must be balanced with its gravitational force W. The equation is:

$$L = W \tag{4}$$

$$L = C_L \frac{1}{2} \rho V^2 S \tag{5}$$

$$W = \text{mg} \tag{6}$$

In the equations above, CL is the lift coefficient, which is a function of the Angle of attack α.m is the mass of the plane.g is the acceleration of gravity. From the equation above , the relation between V and θ can be concluded like the equation followed:

Sliding mode surface can be designed as:

$$\text{s} = V_{design} - V_{current} \tag{7}$$

In the equation,V_{design} means the speed ideal designed speed, V_{current} means actual speed. The general form of the terminal sliding mode control law can be expressed as:

$$\text{u} = k \cdot \text{sgn}(s) \cdot sat(\alpha \cdot |s|) \tag{8}$$

In the equation, u is the control input. k is the controller gain. s is the sliding mode surface. sgn() is a symbolic function used to produce a switch control effect. sat() is a saturation function used to smooth control inputs and reduce buffeting. α is a sliding mode control factor used to adjust the dynamic characteristics of the controller. In this case, the controlled mass is the pitch angle and quality control is speed. So the control law can be expressed as:

$$\text{theta} = \text{k} \cdot \text{sign(s)} \cdot \text{atan(alpha} \cdot |\text{s}|) \tag{9}$$

In the equation, controller gain is k and sliding mode control coefficient is alpha. By adjusting controller gain and sliding mode control coefficient, the control system can show different effects.When the disturb is zero and k equal to 1 with the number of alpha at 0.5, the system can be stable. The pitch angle does not change rapidly. And, Figure 2 showed the control system’s diagram.

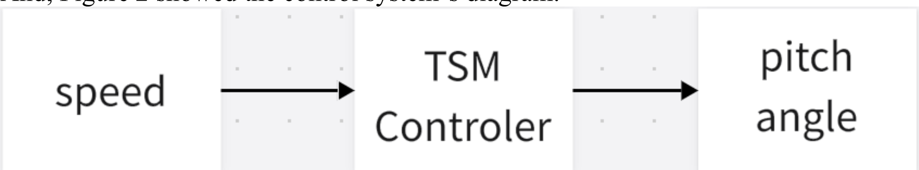

Fig. 2 The control system’s diagram

The control system’s diagram can be constructed just like above. The numerical value of speed is sent to the controler in order to control the pitch angle

3 Results

3.1 Modeling Method

Based on the Simulinks, the model is constructed , which contain the controler and the UVA model. By adjusting the numerical value of argument, the model becomes stable.

3.2 Results and analysis

The output signal, in this case, represents a change in pitch angle. The controller calculates this change based on the speed input and other factors such as the aircraft's weight, altitude, and flight path. The change in pitch angle is then transmitted to the actuator, which is responsible for physically adjusting the aircraft's nose up or down to achieve the desired pitch. As the curve shown in Figure 3, the system shows that a change happened when the input was given.

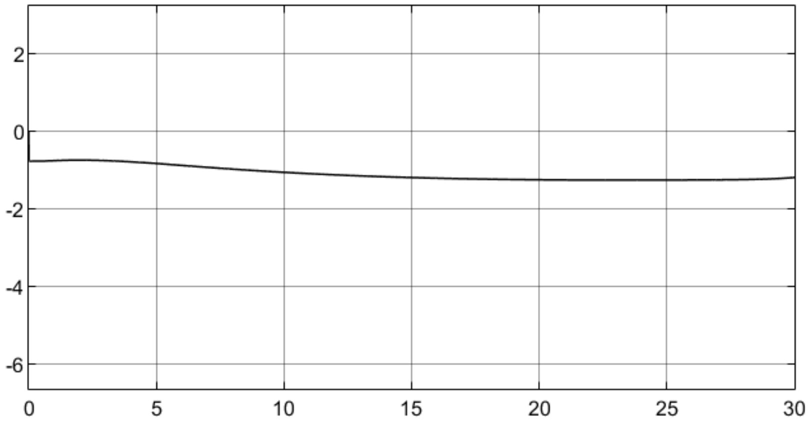

Fig. 3. The pitch angle’s change without interference

As the level of disturbance within the system escalates, it is essential to assess the manner in which the system's performance is affected. In this case, the observation that the system's performance remains stable in the face of increased disturbance suggests that the system is relatively robust and resistant to the interference caused by these disturbances. This stability indicates that the system is capable of maintaining its essential functions and operations despite the presence of external disruptions. The minimal impact of interference on the system can be attributed to several factors. Firstly, the system may have been designed with built-in redundancies and fail-safes, which enable it to continue functioning even when faced with certain levels of interference. Secondly, the system may be operated by a skilled and experienced team who are able to identify and mitigate the effects of disturbances before they can have a significant impact on the system's performance. Lastly, the system may be regularly maintained and upgraded, ensuring that it remains up-to-date with the latest technological advancements and capable of adapting to changing conditions. Overall, the observation that the system's performance remains stable in the face of increased disturbance is a testament to the system's resilience and adaptability, as well as the effectiveness of the measures taken to mitigate the impact of interference. As the curve shown in Figure 4 and Figure 5, the system shows stability when it faces the interference.

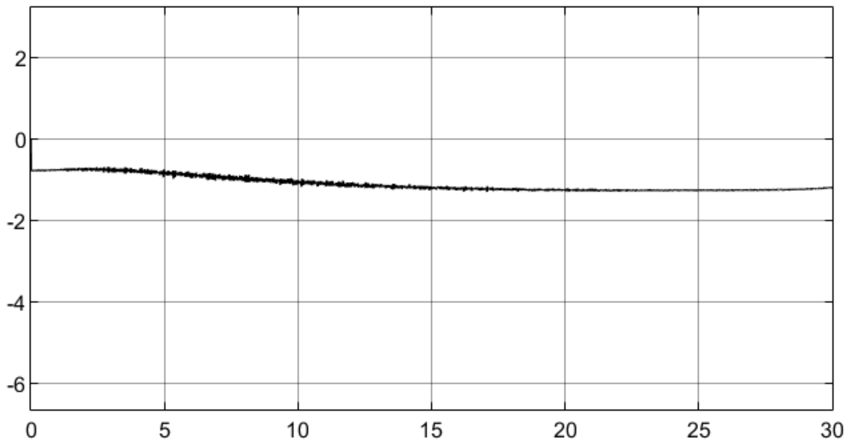

Fig. 4.The pitch angle's change with little interference

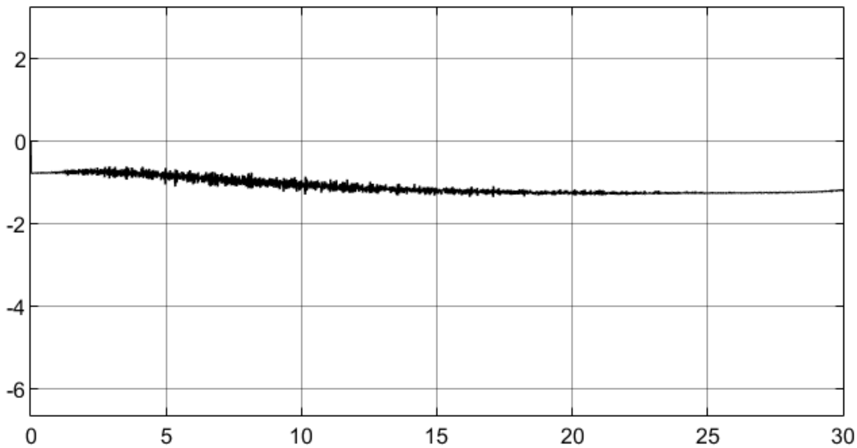

Fig. 5.The pitch angle's change with certain amount of interference

4 Discussion

This project comes from a competition. The rules of competition is that it needs a portable fixed-wing aircraft that can carry simulated missiles, reconnaissance and identification of multiple targets in unknown areas through autonomous flight, and carry out simulated strike missions against specific targets. With accurate reconnaissance, high strike accuracy and short mission time to win. This race needs the UVA can be boxed into a box which has a sum length containing length, wide and height no more than 1600mm.This means the UVA is ask to be designed as small as possible and as flexible as possible. On the other hand, the UVA can carry many kinds of senors, such as IMU, GPS, camera and so on.The process is limited to 6 minutes. As a result, the control system must be designed to be accurate and fast which put forward higher requirements for the controller. Other participating teams also provided some interesting control method, for instance, they tried PID combined with neural network and robust control based on some research [10].

The paper offers an exhaustive and meticulous analysis of the challenges associated with controlling the pitch angle of a UAV, particularly when the target follows a predetermined trajectory. It introduces an innovative control scheme based on terminal sliding mode control, which has demonstrated remarkable effectiveness in addressing this issue. To validate the precision and effectiveness of this pioneering design, the study conducts simulations involving maneuvering targets for a specific UAV. The results suggest that under certain interference conditions, it may not be immediately apparent how the system is influencing outcomes, underscoring the need for a more resilient and adaptable control strategy. To tackle this challenge, adjustments are proposed within various parameters of the control scheme to ensure that alterations in pitch angle occur gradually. This approach serves to mitigate potential risks associated with sudden variations, thereby reducing the likelihood of mission failure or accidents involving UAVs. While suitable for straightforward scenarios at specific task, its applicability is constrained by its inherent simplicity.

Looking forward, future research efforts will focus on enhancing more sophisticated modeling techniques and refining control strategies aimed at addressing complex situations across diverse operational environments. Additionally, practical factors such as resource constraints, environmental uncertainties, and operational requirements will be taken into account in developing a comprehensive and pragmatic solution for managing UAV pitch angles. With the improvement of technology, it will be widely used in other occasions and it will become a mature scheme applied in future competitions .

5 Conclusion

The study has demonstrated the efficacy of utilizing terminal synovial control to effectively manage the pitch angle of a fixed-wing UAV during bomb dropping missions. The research findings indicate that this control method offers superior performance, even under challenging conditions such as wind interference, mechanical failures, or electronic malfunctions. By making adjustments to the controller gain and synovial membrane control coefficient, it is feasible to achieve a model with smoother variation in pitch angle without necessitating significant changes to the overall aircraft design. This not only enhances the UAV's maneuverability but also improves its overall efficiency and safety.

It's crucial to note that this study specifically focused on predetermined parameters of a fixed-wing UAV model, including aspect ratio, airfoil, and fuselage weight, which remained constant throughout the research process. As such, there are inherent limitations when applying these findings to other types of fixed-wing UAVs with differing specifications, as well as to UAVs with variable-geometry wings or those utilizing different control systems.

Looking ahead, potential future applications could involve implementing a terminal synovial control system for regulating various aspects beyond just pitch angle, such as yaw angle, flight speed, and even hover stability. This may encompass controlling multiple actuators and sensors to optimize the performance of the UAV in a variety of environments and scenarios. These advancements have the potential to enhance the operational capabilities of diverse fixed-wing UAV models by optimizing their internal structures without requiring extensive modifications to their overall designs, thereby improving their adaptability and versatility.

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