Trajectory planning of quadrotor using sliding mode control with extended state observer

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Abstract
This paper presents the trajectory planning of an under-actuated quadcopter unmanned aerial vehicle. To control the complete structure of the rotorcraft, the main model is divided into two sub-models, namely inner model and external model. The inner model is for the attitude control model controlled by the sliding mode controller and the outer model is altitude control model governed by the extended state observer. The quadrotor unmanned aerial vehicle is a type of multivariable, multi-degree-of-freedom and nonlinear in nature. Planning the trajectory of the unmanned aerial vehicle and stabilizing its flight are complex tasks because of its ability to maneuver quickly. Due to these stated issues, the tuning of this type of dynamic system is a difficult task. This paper deals with these issues by designing the aforementioned dual controller scheme. In addition, the effectiveness of the proposed controller is apparent in simulations performed in MATLAB, Simulink 2016. The designed controller shows better results and robustness than traditional controllers do.

Keywords
Controlling of unmanned aerial vehicle, quadrotor unmanned aerial vehicle, sliding mode controller, trajectory planning

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Introduction
In the last few years, the trajectory tracking and planning of quadrotors have developed considerably and have generated widespread interest in the study of quadcopter unmanned aerial vehicles (UAVs). This is because UAVs have the capability of taking off and landing vertically and can hover and maneuver at low velocities. It can also reach places like mountainous regions, which are difficult for humans to reach. The demand of reliable and stable hardware of the quadrotor type aircrafts for precision remote sensing has increased manifold. These aerial vehicles are widely used for civilian as well as for military purpose. The UAVs are classified into two types, multi-rotor aircraft and fixed-wing aircraft. Rotorcraft UAVs have many advantages over typical aircrafts like, low weight, advance and unique design and simplicity in the structure of vehicle. The important features of rotorcraft UAV are greater mobility, low cost, ability to perform vertical takeoff and landing. In the current era, according to the demand of advance precision remote sensing the rotorcrafts are programmed for surveying and mapping.

In recent times, quadrotor UAV is emerging to be a well-known topic among scientists and academics for its ability to take off and land vertically, to hover and maneuver in difficult environments. In addition, it has major usages in many fields; for example, reconnaissance, product deliveries, trajectory tracking and infrastructure inspections. However, trajectory tracking of a quadrotor UAV is quite difficult in a dynamic environment while considering dangerously high altitudes and other limitations. Therefore, this paper tries to design a flight control algorithm that is robust and efficient even in a dynamic environment. It makes sure that the quadrotor UAV works fine despite the limitations of the environment.

This research chooses a quadrotor type model of rotorcraft just because of its precise altitude and attitude control. To simulate the model of UAV, the time response of the system is much longer when combined with control method of six degrees-of-freedom (6-DOF) model of UAV, the performance is not so efficient and the learning time is too longer. This research paper mainly focuses on trajectory planning using sliding mode control.
mode observer and proposes a new attitude control architecture.\textsuperscript{6-8}

The dynamic modeling of the quadrotor aircraft is studied by Chen et al.\textsuperscript{9} The rigid body dynamic equations are used for the modeling of the quadrotor aircraft. However, a small literature is needed to provide practical methods for testing the model parameters. As the relationship between the aerodynamics and the propellers is quite complex, there is a demand for more precise equipment for testing.

Learning-based control methods are presented in Mod and Farid\textsuperscript{10} and in Benosman et al.,\textsuperscript{11} it is based on fuzzy control, neural network adaptive algorithm and robust neural network control to design the quadrotor flight controller, although this type of controller does not require the motion model of the UAV but requires massive experiments and flight data to stabilize the system. This system has huge hardware requirements and there is little practical implementation of the system.

Different linear control methods as given in the literature works\textsuperscript{12-14} based on proportional–integral–derivative (PID) designed for the quadrotor attitude controller such as linear controllers which are relatively simple. Still, the controller performance will significantly decrease when the aircraft faces adverse conditions. Meanwhile, the researchers began to apply the control techniques to design the attitude controller for the UAV in Madni et al.\textsuperscript{15} The core system is able to estimate the total disturbance of the real-time system, but not implemented in hardware. In Ali and Li,\textsuperscript{16} a quadrotor-based model of an aerial vehicle along with a gripper attached to grab the wanted object for remote areas, hybrid adaptive controller is used to tackle the nonlinear behavior of the rotor craft.

Nonlinear control methods present in Razmi and Afshinfar\textsuperscript{17} are based on feedback linearization and sliding mode control (SMC) design of the UAV controller. Such control techniques depend on accurate model parameters. On the basis of model parameter, the quadrotor performance and flight range can be enhanced because the SMC has better robustness. This type of controller does not interface with the system for real-time observation and the control effect is not ideal when the interference is large.

This paper presents a quadrotor trajectory-planning algorithm based on sliding mode and extended state observer (ESO) design for the control characteristics of UAV aircraft. To implement the designed algorithm, sequence of experiments is designed to obtain the modeling parameters then the control of three attitude angles of the quadrotor is analyzed by SMC and ESO, the flutter phenomenon which exists in SMC is improved. Finally, ESO is used to achieve real-time estimation of the total disturbance of system, which is combined with the SMC and the real-time interference compensation of the control output is carried out. Hence, the simulation result shows that the controller has good strong anti-jamming capability, better trajectory tracking performance for the attitude angle command while achieving stable attitude of the UAV compared with ordinary SMC.

The important accomplishments of this paper are given below:

1. The gains of sliding mode observer and ESO are responsible for the trajectory planning of the controller.
2. The sensitivity function is the basis of both the ESO and sliding mode observer for the whole system.
3. For the precise controlling of the multivariable system, state of the art control strategy is designed.
4. The features of the proposed model of the UAV considered practical for the experimental aspects.

The whole research paper is comprised of six sections. Introduction is defined in section “Introduction.” The mathematical modeling of the quadrotor is discussed in section “Modeling of quadrotor UAV.” Section “Internal and external control structure” discusses the internal and external control structure in depth. Section “Architecture improvement in the ESO-based sliding mode controller” details architecture improvement in the ESO-based sliding mode controller. In addition, simulations and its results are discussed in section “Simulation results.” Finally, the whole research paper is concluded in section “Conclusion.”

\textbf{State of the art}

This section deals with the latest trends in the field of quadrotors and their trajectory planning. The state of the art in quadrotor research has considerably changed over the last few years. The number of studies undertaking this problem has significantly increased. Many of these studies comprise of commercially available UAVs altered subsequently to have more sensors and capabilities. This section discovers some of the most important quadrotor projects for the last 5 years. Ali and Li\textsuperscript{18} design an innovative technique to control the non-linear dynamics of an under-actuated quadrotor UAV. The researchers in a laboratory of Massachusetts Institute of Technology (MIT) have designed a kind of a hybrid drone. A quadcopter that can hover like helicopters and fly like planes. RoboBee X-Wing, a solar-powered quadcopter with wings has turned out to be the smallest device that can fly with no power supply.\textsuperscript{19} Having weight of only 259 mg, it is inspired from flying insects. It carries four wings that moves 170 times/s. The length from one wing to another is 3.5 cm and it is 6.5-cm tall. The researchers at Harvard University designed this insect-inspired UAV. Neuroflight, another promising project, is the world’s first neural-network-enabled drone. Its controller is designed by a researcher from Boston University.
Modeling of quadrotor UAV

The body or structure of quadrotor UAV is shown in Figure 1. It shows that arm 1 to arm 4 of the UAV distributed equally from the center of the body. The rotors placed at the end of arms 1 and 3 rotate counterclockwise and the remaining two rotors 2 and 4 rotate clockwise. The two co-ordinate systems applied on the body of UAV are inertial co-ordinates $Oxyz$ and body co-ordinate system $Ox_{i}y_{i}z_{i}$. The rotation speed of overall actuators is defined as $\omega_{i}(i = 1, 2, 3, 4)$. The lift generated along the $z_{i}$ axis in the positive direction, which is rewritten as $F_{i} = b_{0}\omega_{i}(i = 1, 2, 3, 4)$ where $b_{0}$ is the lift coefficient.20

Supposition. The nose of quadrotor UAV is along the $x_{b}$ axis in the positive direction.

The angle $\phi$ produced and the body of UAV rotates along $x_{b}$ axis when the actuators on arms 1 and 3 have different speeds and the actuators on arms 2 and 4 have same speed. The angle $\theta$ produced and the body of UAV rotates along $y_{b}$ axis when actuator on arms 1 and 3 have same speed while not considering the actuators on the arms 2 and 4. The angle $\psi$ produced and the body of UAV rotates along $z_{b}$ axis when the actuators on the arms 1 and 3 have different speeds from the actuator of arm 2 and arm 4.

Remark 1. During the motion, the state of quadrotor UAV attained by the position angles, that is, $[x\;y\;z]^{T}$ and the attitude angles, that is, $[\phi\;\theta\;\psi]^{T}$.

When the quadrotor UAV is on the long flight, the external disturbances, for example, noise, air resistance and so on will disturb the stability of the system. By considering the Newton's second law and Euler's dynamic equation, the quadrotor UAV model defined as

$$
\begin{align*}
\dot{x} &= u_{1,x} + \xi_{1} \\
\dot{y} &= u_{1,y} + \xi_{2} \\
\dot{z} &= u_{1,z} - g + \xi_{3} \\
\dot{\phi} &= \frac{I_{y}}{I_{x}}\cdot \dot{\theta} + \frac{1}{I_{x}}u_{2} + \xi_{4} \\
\dot{\theta} &= \frac{I_{z}}{I_{x}}\cdot \dot{\phi}\theta + \frac{1}{I_{x}}u_{3} + \xi_{5} \\
\dot{\psi} &= \frac{I_{y}}{I_{x}}\cdot \dot{\phi}\theta + \frac{1}{I_{x}}u_{4} + \xi_{6}
\end{align*}
$$

Equation (1)

In the above-mentioned equation (1) $u_{1,x}, u_{1,y}, u_{1,z}$ are the position of control inputs

$$
\begin{align*}
u_{1,x} &= \frac{m}{I_{z}}(\cos\theta \cdot \sin\phi \cdot \sin\theta + \sinh \cdot \sin\phi) \\
u_{1,y} &= \frac{m}{I_{z}}(\cos\theta \cdot \sin\phi \cdot \sin\theta - \sinh \cdot \sin\phi) \\
u_{1,z} &= \frac{m}{I_{z}}(\cos\theta \cdot \cos\phi)
\end{align*}
$$

where $u_{1}$ is the position control, $m$ is the class of quadrotor UAV, $g$ is the gravity acceleration, $I_{z}, I_{x}, I_{z}$ are the moments of inertia of the body, $l$ is the distance among the center of quadrotor UAV and rotors, $c$ is the torque force proportional coefficient, and $u_{1}, u_{2}, u_{3}$ are the control impacts of attitude.

Lemma 1. During the flight, the system is disturbed by the external disturbances and thus the interference function $\xi_{i}(i = 1, 2, 3, 4, 5, 6)$ is added to the model of the system.

Internal and external control structures

Figure 2 shows the external and internal control structures of the system. Equation (1) shows the mathematical model of position and attitude object of UAV. The input position signal that passes by the sliding mode observer is given as $X_{1} = [x\;\dot{x}; y\;\dot{y}; z\;\dot{z}]^{T}$, the input attitude signal is $X_{2} = [\phi\;\dot{\phi}; \theta\;\dot{\theta}; \psi\;\dot{\psi}]^{T}$. The received disturbance signals are given as $a_{1} = [\xi_{1}\;\xi_{2}\;\xi_{3}]^{T}$ and $a_{2} = [\xi_{4}\;\xi_{5}\;\xi_{6}]^{T}$. The reconfigurable system states are given as $X_{1} = [x\;\dot{x}; y\;\dot{y}; z\;\dot{z}]^{T}$ and $X_{2} = [\phi\;\dot{\phi}; \theta\;\dot{\theta}; \psi\;\dot{\psi}]^{T}$. The external interference is from $\xi_{1}$ to $\xi_{6}$. The position control input results in desired roll, pitch and yaw angles. For the stable tracking, the drone could position at the required trajectory $x_{d}, y_{d}, z_{d}$ and attitude at the desired state $\phi_{d}, \theta_{d}, \psi_{d}$.

SMC method

The control system of the UAV can track the ideal attitude instruction with the help of sliding mode method.21 In reference, the derivation and discussion of the sliding mode are discussed as

$$
\begin{align*}
u_{1} &= \tau_{\phi} = (I_{z} - I_{y})y_{2}v_{0} - I_{z}(e_{1}z_{1} - a_{1}\text{sign}(s_{2})) \\
u_{2} &= \tau_{\theta} = (I_{x} - I_{z})y_{2}v_{0} - I_{z}(e_{2}z_{2} - a_{3}
\end{align*}
$$

Here, $y_{1d}, y_{2d}, y_{3d}$ for the command value of first derivative and $y_{1d}, y_{2d}, y_{3d}$ for the command value of second derivative. $\beta_{1} - \beta_{3}$ are greater than zero constant; $a_{1} - a_{6}$
are greater than zero constant; \( s_2 - s_4 \) are the structures of the sliding mode surface.

The traditional sliding mode controller has a very distinct feature that is to contain a symbolic function. The resulting control instruction will be non-continuous, therefore the sliding surface will produce vibration phenomenon in sliding mode. To avoid chattering phenomenon, sat(\( s \)) used to replace the symbol function with the approximate continuous saturation function. The function expression is expressed below

\[
\text{sat}(s) = \begin{cases} 
\frac{s}{|s| + e} & \text{if } e \in [0, 1]
\end{cases}
\]  

(3)

In this research, given \( e = 0.25 \), it can improve the sliding mode controller and will slow down the chattering phenomenon. In addition to this, the structure of sliding mode controller needs to know the ideal value command of first derivative (e.g. \( \dot{y}_{1d} \)) and second derivative (e.g. \( \ddot{y}_{1d} \)). It is also necessary to develop a second-order filter to get these values. Before the command enters the attitude controller, first it will do to the second-order filter then to the controller. This paper has adopted a second-order low pass filter, and its transfer function is as follows.

Remark 2. A second-order low-pass filter adopted, and its transfer function is as follows

\[
\frac{X_c(s)}{X_0(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}
\]  

(4)

where \( X_0 \) is the input value and \( X_c \) is the output value. The expression in the time domain given as

\[
\ddot{y} = -2\xi\omega_n \dot{y} + \omega_n^2 (X_0 - X_a)
\]  

(5)

The specific structure of the filter design in this research paper, damping ratio \( \xi = 0.788 \), natural frequency \( \omega_n = 4.735 \), according to second-order link response time formula, the step response time is about 1 s.

**ESO configuration of a quadrotor UAV**

The ESO is part of the self-immunity controller discussed in Zhao et al. The core use of ESO is that it can be a good dynamic estimation system (real-time acceleration of the system). The process only needs to use the original object input–output information. ESO can estimate the amount of acceleration in real time. The fundamental reason is that as long as the system satisfies observability conditions, it is possible to extract information from the output.

The observed real-time effect is equivalent to the effect of various disturbances (model, un-modeled dynamics and external disturbances). To achieve system linearization this estimation of real-time dynamic compensation is required. The ESO structure is illustrated by an example of the quadrotor roll angle implementation. To combine with the state space equation, the roll angle \( \varphi \) equations are written as

\[
\begin{align*}
\dot{y}_1 &= y_2 \\
\dot{y}_2 &= f_1(\varphi, \dot{\varphi}, \theta, \dot{\theta}, \psi, \dot{\psi}) + \dot{\omega}_2(t) + b_0 U_1 \\
x &= y_1
\end{align*}
\]  

(6)

Lemma 2. Here, \( b_0 \) is the control factor, \( \dot{\omega}_2(t) \) is the amount of external interference and \( f_1(\cdots) + \dot{\omega}_2(t) \) is the sum of various disturbances including (model, unmodeled dynamics and external disturbances). The expansion of state variables, that is, \( y_3 = f_1(\varphi, \dot{\varphi}, \theta, \dot{\theta}, \psi, \dot{\psi}) + \dot{\omega}_2(t) \), then the linear system is defined in equation (6)
Then, the system to establish the nonlinear expansion state observer is

\[
\begin{aligned}
\dot{y}_1 &= y_2 \\
\dot{y}_2 &= y_3 + b_0 U_1 \\
\dot{y}_3 &= \hat{\omega}_0 \\
x &= y_1
\end{aligned}
\] (7)

Then, the system to establish the nonlinear expansion state observer is

\[
\begin{aligned}
e &= z_1 - y \\
\dot{z}_1 &= z_2 - \beta_{01} e \\
\dot{z}_2 &= z_3 - \beta_{02} \text{fail}(e, c_1, h) + b_0 U_1 \\
\dot{z}_3 &= - \beta_{03} \text{fail}(e, c_2, h)
\end{aligned}
\] (8)

Among them

\[
\text{fail}(e, c, \gamma) = \begin{cases} 
|e|^\gamma \text{sign}(e), & |e| > \gamma \\
\frac{e}{\gamma}, & |e| \leq \gamma
\end{cases}
\] (9)

Set the parameters \(\beta_{01}, \beta_{02}, \beta_{03}\) and \(c_i = (1, 2)\) normally considers \(c_1 = 0.455, c_2 = 0.245\), then the expanded state observer output \(z_1\) can well estimate the original system of each state quantity \(y_i\), where \(z_3 \rightarrow y_3 = f_1(\cdots) + \hat{\omega}_2(t)\), although \(f(\cdots)\) and \(\hat{\omega}(t)\) of the specific function expression are unknown, but the expansion state \(z_3\) can still be good estimates for total state disturbance \(c\). Similarly, the pitch angle \(\theta\) and the yaw angle \(\psi\) are processed by the same algorithm, so that the dynamic compensation linearization of each channel can be achieved.

**Architecture improvement in the ESO-based sliding mode controller**

Sliding mode controller used to achieve the non-linear method of robust control effectively solves the problem of control stability and performance consistency in case of any inaccuracy in the model. Nevertheless, it did not interface with the system to estimate the real-time observation, when the interference is large, the control effect is not ideal.

However, the ESO is for real-time interference estimation and dynamic compensation. The input is the system input and output, output is the sum of estimated state quantity and expanded state quantity (total disturbance), and its structure is easy to combine with other control methods. Thereby increasing the anti-jamming capability of the controller. Therefore, the combination of ESO and sliding mode controller can improve the robustness, anti-interference ability and the attitude control of the quadrotor UAV (Figure 3).

The resulting algorithm based on sliding mode and ESO controller and the inputs rewritten as

\[
\begin{aligned}
e &= z_{1\theta} - y_1 \\
\dot{z}_{1\theta} &= z_{2\theta} - \beta_{01} e \\
\dot{z}_{2\theta} &= z_{3\theta} - \beta_{02} \text{fail}(e, 0.5, h) + \left(\frac{1}{I_x}\right) U_1 \\
\dot{z}_{3\theta} &= - \beta_{03} \text{fail}(e, 0.5, h) \\
U_1 &= (I_x - I_y) y_4 y_6 - I_x (\beta_1^2 z_1 + a_1 \text{sat}(s_2) + a_2 s_2 - \ddot{y}_{1d}) \\
&- I_x z_{3\theta}
\end{aligned}
\] (10)

Similarly, to obtain the remaining two attitude angles, that is, pitch and yaw, to control the output

\[
\begin{aligned}
U_2 &= (I_x - I_y) y_2 y_6 - I_x (\beta_2^2 z_3 + a_3 \text{sat}(s_3) + a_4 s_3 - \ddot{y}_{3d}) \\
&- I_x z_{3\theta}
\end{aligned}
\] (11)
Table 1. Parameters of quadrotor UAV.

| Constants | Value | Unit |
|-----------|-------|------|
| $M$       | 3.2   | kg   |
| $I_x$     | 0.38997 | m$^2$ kg |
| $I_y$     | 0.974 | m$^2$ kg |
| $I_z$     | 0.7887 | m$^2$ kg |
| $l$       | 0.267 | m   |

Table 2. Supposition states of quadrotor UAV.

| $y_1$ | $y_2$ | $y_3$ | $y_4$ | $y_5$ | $y_6$ |
|-------|-------|-------|-------|-------|-------|
| $\phi$ | $\dot{\phi}$ | $\theta$ | $\dot{\theta}$ | $\psi$ | $\dot{\psi}$ |

where $z_{3\phi}$, $z_{3\theta}$, $z_{3\psi}$ are the roll angle loop, pitch angle and yaw angle.

Simulation results

This section determines the efficiency of the proposed method. Table 1 defines the parameters of quadrotor UAV. The overall model of the aircraft is divided into altitude and attitude control sub-models. The arrangement of both the altitude and attitude control loops will make the effective flight as per the referred direction and position as well. The primary errors in the model are controlled and stabilized by the angular sub-system. Moreover, the angular rates converge nearly equal to zero, at the time when the aircraft is at hovering state. The steady state and transient characteristics of the input lie in the range of 0–4 s, along with minimum oscillations. The preferred altitude for hovering scenario is about 2 s. Remaining simulations in Figures 5 to 7 demonstrate the Euler angle responses, angular velocity and the flight trajectory tracking of the quadrotor UAV (Table 2).

The sampling time of overall simulation is about 0.212 s for every simulated result that is done for about 50 s. The proposed method that is able to control the maneuvering to the desired path effectively is shown in Figures 4 to 7 correspondingly. The strength of the

Figure 4. Linear velocity of UAV.
Figure 5. Angular rates of quadrotor UAV.

Figure 6. Angular velocity during the flight.
designed method is demonstrated on MATLAB, Simulink.

Figure 4(a) to (c) describes the linear velocity of UAV along with the global (x, y, z) axes. Figure 4(a) represents the x-component of the linear velocity. It starts at around 25 m/s then dips below for a while to finally go back to 25 m/s. Figure 4(b) represents the y-component of the linear velocity. It starts at 0 and then peaks at 0.75 m/s. Then it goes as low as −0.75 m/s before converging back to zero. Figure 4(c) represents the z-component of the linear velocity. It starts at around 0.5 m/s and then remains steady for a while. Then, it keeps oscillating between 0.5 and 3 m/s.

All the above actions go to zero in finite interval of time after completing the given task. The given task starts from the originated state (takeoff), UAV reaches to desired state and remain in hovering position (lock the altitude) as per given command, and return back to the originated position asymptotically.

The above figure shows the angular rates or Euler angle responses of quadrotor UAV during the whole mission. In Figure 5(a), the angular rate phi starts with zero, go as high as 0.25 rad/s, then starts to decrease and go as low as −0.25 rad/s. Then, after almost 35 s, it converges to zero. In Figure 5(b), the angular rate theta starts with 0.1 rad/s, then reaches its peak at 0.25 rad/s and then oscillates between 0.1 and 0.25 rad/s. In Figure 5(c), the angular rate psi starts at −0.5 rad/s, and then converges to zero before dropping to −1.5 rad/s. In addition, Figure 5(a) to (c) ensures that angular rates track the desired angular rates within an applicable scope.

Figure 6(a) to (c) defines the angular or rotational velocity of UAV along the global coordinate system. Figure 6(a) presents p or roll rate. The roll rate of a UAV is the angular velocity of the rotation of the UAV along x-axis. It starts at zero and then oscillates between −0.3 and 0.3 rad/s. Figure 6(b) presents q or pitch rate. The pitch rate of a UAV is the angular velocity of the rotation of the UAV along y-axis. It starts at zero and remains steady for a while before it starts oscillating between −0.25 and 0.25 rad/s. Figure 6(c) presents r or yaw rate. The yaw rate of a UAV is the angular velocity of the rotation of the UAV along z-axis. It starts at zero and reaches its peak at 0.1 rad/s then drops to −0.1 rad/s. It then converges back to zero. The angular velocity of the rotors of the UAV directly reflects the change in the height of UAV. Decreasing or increasing the angular velocity of the rotors will decrease or increase the altitude of UAV.

Finally, Figure 7 shows the flight trajectory with the reference signal, SMC, and the proposed approach SMC–ESO. It shows that our proposed method has better responses as compared to SMC. It is evident that the SMC–ESO trajectory is closer to the reference signal compared to SMC. In addition, the projected tracking trajectory of the proposed method is able to build the path of quadrotor UAV despite external disturbances and the imprecision of the reference path. It tracks the reference trajectory in an efficient way, as shown in Figure 7. Therefore, it is clear that our proposed method has better robustness with disturbance and noisy surroundings under typical uncertainties.

Conclusion

To summarize the overall paper, it is observed that the proposed flight control method plans the trajectory of the quadrotor UAV in an effective and robust way. In addition, the outer loop (altitude control) and the inner loop (attitude control and UAV dynamics) were modeled to attain the preferred altitude and keep the UAV in hovering mode using SMC. To demonstrate the proficiency of the proposed method, this paper ran simulations on MATLAB, Simulink. The simulation results prove that the trajectory tracking of the proposed method is closer to the reference signal than the classic approach. Finally, the proposed model of quadrotor UAV completes the task despite external disturbances and noise.

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References

1. Michailidis MG. Nonlinear controller design for UAVs with time-varying aerodynamic uncertainties. PhD thesis, University of Denver, Denver, CO, 2019.
2. Saeed AS, Younes AB, Cai C, et al. A survey of hybrid unmanned aerial vehicles. *Prog Aerospace Sci* 98 2018: 91–105.

3. Ren He Zhao Y, Xiao W and Hu Z. A review of UAV monitoring in mining areas: current status and future perspectives. *Int J Coal Sci Technol* 2019; 6: 320–333.

4. Erceg A and Kilic Z. The use of unmanned aerial vehicles: a comparison of Turkey and Croatia. In: Erceg A and Kilic Z (eds) *Unmanned aerial vehicles in civilian logistics and supply chain management*. Pennsylvania, PA: IGI Global, 2019, pp. 64–85.

5. Xiang TZ, Xia GS and Zhang L. Mini-unmanned aerial vehicle-based remote sensing: techniques, applications, and prospects. *IEEE Geosci Remote Sens Mag* 2019; 7(3): 29–63.

6. Bøhn E, Coates EM, Moe S, et al. Deep reinforcement learning attitude control of fixed-wing UAVs using proximal policy optimization. In: *2019 international conference on unmanned aircraft systems (ICUAS)*, Atlanta, GA, 11–14 June 2019, pp. 523–533. New York: IEEE.

7. Bowkett M, Thanapalan K and Constant E. Failure detection of composites with control system corrective response in drone system applications. *Computers* 2018; 7(2): 23.

8. Emran BJ and Najjaran H. A review of quadrotor: an underactuated mechanical system. *Ann Rev Control* 2018; 46: 165–180.

9. Chen K, Shi Z, Tong S, et al. Aerodynamic interference test of quad tilt rotor aircraft in wind tunnel. *Proc IMechE, Part G: J Aerospace Engineering* 2019; 233: 5553–5566.

10. Mo H and Farid G. Nonlinear and adaptive intelligent control techniques for quadrotor UAV: a survey. *Asian J Control* 2019; 21(2): 989–1008.

11. Benosman M, Lewis FL, Guay M, et al. Editorial for the special issue on learning-based adaptive control: theory and applications. *Int J Adapt Control Signal Pr* 2019; 33(2): 225–227.

12. Rossetti G. Development of a flight control architecture for rotary wing UAVs with model based design approach. PhD Dissertation, University di Bolonga.

13. Gonzalez-de-Santos P, Ribeiro A, Fernandez-Quintanilla C, et al. Fleets of robots for environmentally-safe pest control in agriculture. *Precis Agr* 2017; 18(4): 574–614.

14. Qayyum U. *Real-time visual-inertial slam for multirotor platform*. PhD thesis, 2015, https://openresearch-repository.anu.edu.au/handle/1885/150106

15. Madni AM, Sievers MW, Humann J, et al. Formal methods in resilient systems design: application to multi-UAV system-of-systems control. In: Madni AM, Boehm B and Ghanem R (eds) *Disciplinary convergence in systems engineering research*. Cham: Springer, 2018, pp. 407–418.

16. Ali ZA and Li X. Modeling and controlling of quadrotor aerial vehicle equipped with a gripper. *Meas Control* 2019; 52(5–6): 577–587.

17. Razmi H and Afshinifar S. Neural network-based adaptive sliding mode control design for position and attitude control of a quadrotor UAV. *Aerosp Sci Technol* 2019; 91: 12–27.

18. Ali ZA and Li X. Controlling of an under-actuated quadrotor UAV equipped with a manipulator. *IEEE Access* 2020; 8: 34664–34674.

19. Jafferis NT, Farrell Helbling E, Karpelson M, et al. Untethered flight of an insect-sized flapping-wing microscale aerial vehicle. *Nature* 2019; 570(776): 491–495.

20. Qiao J, Liu Z and Zhang Y. Gain scheduling based PID control approaches for path tracking and fault tolerant control of a Quad-rotor UAV. *Int J Mech Eng Robot Res* 2018; 7: 401–408.

21. Jia Z, Yu J, Mei Y, et al. Integral backstepping sliding mode control for quadrotor helicopter under external uncertain disturbances. *Aerosp Sci Technol* 2017; 68: 299–307.

22. Rong Y, Jiao R, Kang S, et al. Sigmoid super-twisting extended state observer and sliding mode controller for quadrotor UAV attitude system with unknown disturbance. In: *2019 IEEE international conference on robotics and biomimetics (ROBIO)*, Dali, China, 6–8 December 2019. New York: IEEE, pp. 26–47.

23. Zhao S, Xiong H, Chang J, et al. The ADRC and simulation of pitching angle for unmanned aerial vehicles. In: *2015 Chinese automation congress (CAC)*, Wuhan, China, 27–29 November 2015, pp. 427–430. New York: IEEE.

24. Ren T, Dong Y, Wu D, et al. Collision detection and identification for robot manipulators based on extended state observer. *Control Eng Pract* 2018; 79: 144–153.