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ATTITUDE CONTROL FOR A STATION KEEPING AIRSHIP USING FEEDBACK LINEARIZATION AND FUZZY SLIDING MODE CONTROL

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Abstract. *A novel attitude control scheme for a station-keeping airship using feedback linearization and fuzzy sliding mode control is proposed. First, the ZY-1 airship is introduced, and the nonlinear attitude control system of the airship is derived. Second, the nonlinear attitude control system is decoupled into three single-input single-output linear subsystems through the differential geometry theory. The attitude control law is then designed for each subsystem using sliding mode control. To improve control performance, a fuzzy sliding mode control approach is proposed in which the control gains are tuned according to fuzzy rules, with switching sliding surface function and its derivative as fuzzy control inputs and control gain as fuzzy control output. The stability of the closed-loop control system is proven using the Lyapunov theorem. Finally, simulation results illustrate the effectiveness of the proposed control scheme.*
Keywords: Flight control, Feedback linearization, Sliding mode, Fuzzy system, Airship, Station-keeping

1. **Introduction.** As a typical lighter-than-air (LTA) vehicle, the autonomous airship represents a unique and promising platform for various applications, such as telecommunication, broadcasting relays, region navigation, environmental monitoring and scientific exploration [1]. Station-keeping flight is a unique feature of an airship, in contrast to a fixed-wing aircraft. Station-keeping flight can ensure long endurance at a desired position for high-resolution images and surveying information with minimal operational cost, which effectively supports the disaster guard and public security [2,3].

With the rapid progress of airship technologies, an advanced flight control system plays a key role in the development of the autonomous airship. Considering the nonlinear dynamics and model uncertainties, difficulty in maneuvering an airship to keep at a position with desired attitude motion poses a problem. Therefore, station-keeping attitude control remains a key technical challenge for an autonomous airship. Several control approaches for airships have been proposed in extant literature, including nonlinear control [4-6], sliding mode control (SMC) [7,8], robust control [9,10], adaptive control [11-13], intelligent control [14-18], and so on. However, studies on attitude control for station-keeping airships have rarely been documented in domestic and foreign published works.

The current paper proposes a novel attitude control scheme for a station-keeping airship using feedback linearization and fuzzy sliding mode control (FSMC). Feedback linearization can decouple the nonlinear system into a linear system and provide a linear and decoupling form [5], thus simplifying the control system design. SMC effectively addresses the control problem of systems with nonlinearities, uncertainties, and bounded external disturbances because it results in a sliding mode on a predefined hyper plane of the state-space. However, the undesirable chattering phenomenon often results from the switching of the discontinuous control law from one to another [19]. To attenuate chattering, the fuzzy set theory is introduced into SMC to construct the FSMC for tuning the control gains. In the FSMC system, the control gains vary along with the sliding surface at all times according to the fuzzy rules, thus effectively attenuating the SMC chattering. Moreover, the stability of the closed-loop control system is proven using the Lyapunov theorem, and the effectiveness of the proposed control scheme is demonstrated through simulation results.

2. Modeling and Formulation.

2.1. **The ZY-1 airship.** The current paper considers the ZY-1 airship with a mission altitude of 0.5km [20]. The aerodynamic-shaped hull and the four fins arranged in a cross orientation comprise the airframe assembly. The hull is composed of an air-pressurized envelope to maintain its shape, and internal divided bags filled with helium as a buoyant gas. Two air ballonets are installed inside the hull. These ballonets can be blown up with air and deflated, respectively, during descent and ascent operations. Propulsive propellers are mounted on the bottom of the airship, and are also used as vector-trust control. The payload bay is mounted on the bottom of the hull. The geometric configuration of the airship is summarized in Table 1 [20].

FIGURE 1. The ZY-1 airship [20]

TABLE 1. Dimension of the ZY-1 airship

Parameters	Value
Length, m	25.0
Maximum diameter, m	7.57
Volume of the hull, m^3	750.0
Surface area, m^2	480.38
Fineness ratio of the hull	3.3
Location of maximum diameter, m	9.84

2.2. **Formulation of attitude motion.** The motion of an airship is typically presented by a set of kinematics and dynamics equations that describe its evolution in a six degrees-of-freedom (6-DOF) space [21]. The coordinate frames are depicted in Figure 2. $O_eX_eY_eZ_e$ is an earth-fixed inertial frame, with the origin on the surface of the earth, the X-axis pointing north, the Y-axis pointing east, and the Z-axis pointing downward. $o_bx_by_bz_b$ is the body-fixed frame, with the origin at the center of volume, the x-axis pointing forward, the y-axis pointing right, and z-axis pointing downward. The vector $\boldsymbol{r}_G = [x_G, y_G, z_G]^{\mathrm{T}}$

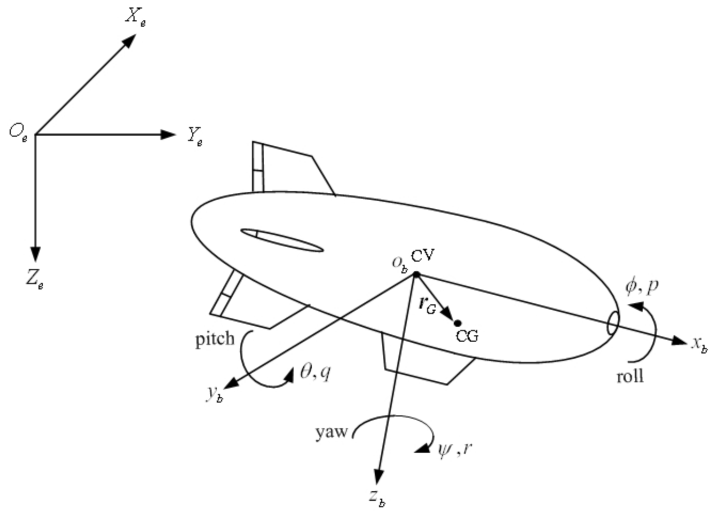


FIGURE 2. Coordinate frames and attitude motion of an airship

denotes the distance from the center of volume (CV) to the center of gravity (CG). Under the established coordinate frames, the attitude motion of an airship can be described by its angle and angular velocity over time [22]. The attitude is described using the Euler angles $\boldsymbol{\Omega} = [\theta, \psi, \phi]^{\mathrm{T}}$, where θ is the pitch angle, ψ is the yaw angle and ϕ is the roll angle, and the attitude angles are valid in the interval $(-\pi/2, \pi/2)$. The angular velocities are given by $\boldsymbol{\omega} = [p, q, r]^{\mathrm{T}}$, where p, q and r are the rolling, pitching and yawing angular velocities, respectively.

From the kinematics and dynamics equations of an airship [23,24], the mathematical model of station-keeping attitude motion is derived as follows:

$$\begin{cases} \dot{\theta} = q\cos\phi - r\sin\phi \\ \dot{\psi} = \sec\theta(r\cos\phi + q\sin\phi) \\ \dot{\phi} = p + (r\cos\phi + q\sin\phi)\tan\theta \\ \dot{p} = (c_1 r + c_2 p)q + c_3(L - z_G G\cos\theta\sin\phi) + c_4 N \\ \dot{q} = c_5 pr - c_6(p^2 - r^2) + c_7(M - z_G G\sin\theta) \\ \dot{r} = (c_8 p + c_2 r)q + c_4(L - z_G G\cos\theta\sin\phi) + c_9 N \end{cases} \tag{1}$$

where $c_1 = \frac{I_{xz}^2 - I_z(I_y - I_z)}{I_{xz}^2 - I_x I_z}$, $c_2 = -\frac{(I_x - I_y + I_z)I_{xz}}{I_{xz}^2 - I_x I_z}$, $c_3 = \frac{-I_z}{I_{xz}^2 - I_x I_z}$, $c_4 = \frac{-I_{xz}}{I_{xz}^2 - I_x I_z}$, $c_5 = \frac{I_z - I_x}{I_y}$, $c_6 = \frac{I_{xz}}{I_y}$, $c_7 = \frac{1}{I_y}$, $c_8 = \frac{I_x(I_y - I_x) - I_{xz}^2}{I_{xz}^2 - I_x I_z}$, and $c_9 = \frac{-I_x}{I_{xz}^2 - I_x I_z}$, where G is the airship gravity; I_x, I_y and I_z are the moments of inertia about ox, oy and oz; I_{xz} is the product of inertia about the oxz plane; and L, M, N are the moments of rolling, pitching and yawing, respectively.

The selected state variable, input, and output of the control system are as follows:

$$\begin{aligned} &\boldsymbol{x} = [x_1, x_2, x_3, x_4, x_5, x_6]^{\mathrm{T}} = [\theta, \psi, \phi, p, q, r]^{\mathrm{T}}, \\ &\boldsymbol{U} = [u_1, u_2, u_3]^{\mathrm{T}} = [I_z L + I_{xz} N, M, I_{xz} L + I_x N]^{\mathrm{T}}, \\ &\boldsymbol{H}(x) = [h_1(\boldsymbol{x}), h_2(\boldsymbol{x}), h_3(\boldsymbol{x})]^{\mathrm{T}} = [\theta, \psi, \phi]^{\mathrm{T}}. \end{aligned}$$

Mathematical model (1) can then be expressed as the following nonlinear system [5]:

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{F}(\boldsymbol{x}) + \boldsymbol{G}(\boldsymbol{x})\boldsymbol{U} \\ \boldsymbol{y} = \boldsymbol{H}(\boldsymbol{x}) \end{cases} \tag{2}$$

where

$$\boldsymbol{F}(\boldsymbol{x}) = \begin{bmatrix} -r\sin\phi + q\cos\phi \\ \sec\theta(r\cos\phi + q\sin\phi) \\ p + \tan\theta(r\cos\phi + q\sin\phi) \\ (c_1 r + c_2 p)q - c_3 z_G G\cos\theta\sin\phi \\ c_5 pr - c_6(p^2 - r^2) - c_7 z_G G\sin\theta \\ (c_8 p + c_2 r)q - c_4 z_G G\cos\theta\sin\phi \end{bmatrix}, \boldsymbol{G}(\boldsymbol{x}) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{-1}{I_{xz}^2 - I_x I_z} & 0 & 0 \\ 0 & \frac{1}{I_y} & 0 \\ 0 & 0 & \frac{-1}{I_{xz}^2 - I_x I_z} \end{bmatrix}.$$

3. Attitude Control System Design.

3.1. Control strategy. The control objective is to design the control law that drives the airship to asymptotically tracking a desired attitude. The control inputs are designed to make the airship follow the commanded attitude. The commanded attitude is assumed to be $\boldsymbol{y}_d = [\theta_d, \psi_d, \phi_d]^{\mathrm{T}}$, and the system output $\boldsymbol{y}$ is required to follow the commanded attitude under the control input, i.e. $\lim_{t\to\infty} |\boldsymbol{y} - \boldsymbol{y}_d| = 0$.

The present section proposes a control scheme for station-keeping attitude motion using feedback linearization and FSMC. First, the nonlinear attitude control system is decoupled into three decoupling single-input single-output (SISO) subsystems using the differential geometry theory. Second, the SMC law is designed for each subsystem. Furthermore, in order to attenuate chattering, a fuzzy system is used to tune the control gains, with switching sliding surface function and its derivative as fuzzy control inputs and control gain as fuzzy control output. Figure 3 depicts the block diagram of the control system.

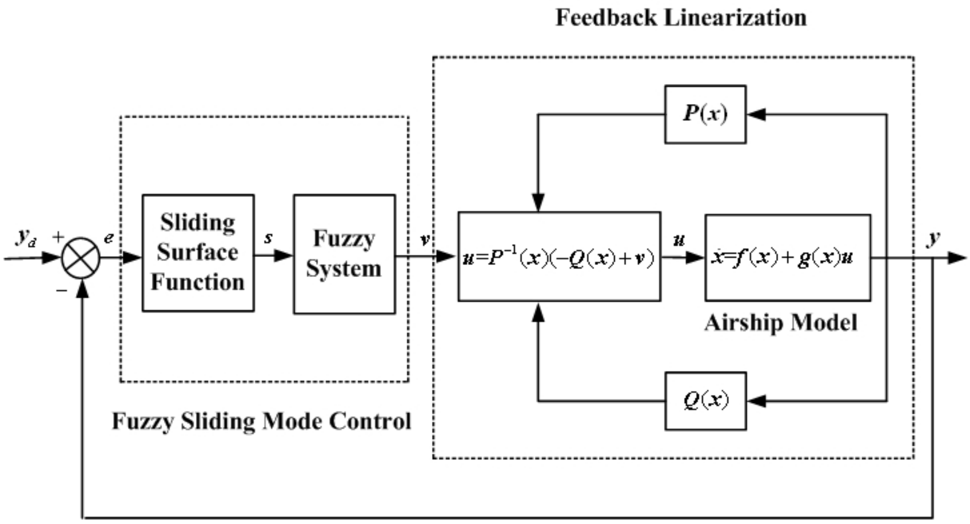


FIGURE 3. The control system block diagram

3.2. Feedback linearization. Consider a class of nonlinear system

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x})\boldsymbol{u} \\ \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x}) \end{cases} \tag{3}$$

where $\boldsymbol{x} \in R^n$ is the system state, $\boldsymbol{u} \in R^m$ is the system input, $\boldsymbol{y} \in R^m$ is the system output, $\boldsymbol{g}(\boldsymbol{x}) = [g_1(\boldsymbol{x}), \cdots, g_m(\boldsymbol{x})]$, $g_i(i = 1, \cdots, m)$ is an n-dimensional sufficiently smooth vector field, $\boldsymbol{f}(\boldsymbol{x}) \in R^n$ is a sufficiently smooth vector field, and $\boldsymbol{h}(\boldsymbol{x}) = [h_1(\boldsymbol{x}), \cdots, h_m(\boldsymbol{x})]^{\mathrm{T}}$, $h_i(\boldsymbol{x})$ $(i = 1, \cdots, m)$ is a sufficiently smooth scalar function.

Definition 3.1. *Lie Derivative*
If $\boldsymbol{f}$ *and* $\boldsymbol{h}$ *are both sufficiently smooth vector fields, the Lie derivative of* $\boldsymbol{h}$ *can be defined with respect to* $\boldsymbol{f}$ *as [25]*

$$\boldsymbol{L_f h}(\boldsymbol{x}) = \sum_{i=1}^{n} \frac{\partial h}{\partial x_i} f_i(\boldsymbol{x}) \tag{4}$$

Definition 3.2. *Relative degree*
For the nonlinear system defined by Equation (3), if the following conditions are satisfied for all $\boldsymbol{x} \in R^n$ *in the neighborhood of* $\boldsymbol{x}_0$ *[25]:*
(1) $L_{gj} L_f^k h_i(x) = 0, \quad (1 \le i \le m, 1 \le j \le m, 0 \le k < r_i - 1)$
(2) The $m \times m$ *matrix*

$$\boldsymbol{P}(\boldsymbol{x}) = \begin{bmatrix} L_{g1} L_f^{r_1 - 1} h_1(\boldsymbol{x}) & \cdots & L_{gm} L_f^{r_1 - 1} h_1(\boldsymbol{x}) \\ L_{g1} L_f^{r_2 - 1} h_2(\boldsymbol{x}) & \cdots & L_{gm} L_f^{r_2 - 1} h_2(\boldsymbol{x}) \\ \cdots & \cdots & \cdots \\ L_{g1} L_f^{r_m - 1} h_m(\boldsymbol{x}) & \cdots & L_{gm} L_f^{r_m - 1} h_m(\boldsymbol{x}) \end{bmatrix} \tag{5}$$

is nonsingular at $x = x_0$*. The nonlinear system (3) is then said to have a relative degree* $r = \sum_{i=1}^{m} r_i$.

Lemma 3.1. *The nonlinear system (3) is feedback linearizable if a sufficiently smooth function* $\boldsymbol{h} \in R^m$ *exists such that the system has the relative degree* $r = \sum_{i=1}^{m} r_i = n$ *[25].*

Lemma 3.2. *The nonlinear system (3) is said to be feedback linearizable if there exists an input feedback and a diffeomorphism* $\boldsymbol{T}(\boldsymbol{x})$ *exists, such that the change of variables* $\boldsymbol{z} = \boldsymbol{T}(\boldsymbol{x})$ *transforms system (3) into the following form*

$$\begin{cases} \dot{\boldsymbol{z}} = \boldsymbol{A z} + \boldsymbol{B v} \\ \boldsymbol{y} = \boldsymbol{C z} \end{cases} \tag{6}$$

with $(\boldsymbol{A}, \boldsymbol{B})$ *controllable, where* $\boldsymbol{A}$, $\boldsymbol{B}$, *and* $\boldsymbol{C}$ *are all linear matrices [25].*

Theorem 3.1. *The nonlinear attitude control system (2) is input-output feedback linearizable if proper input and coordinate transform are selected based on the differential geometry theory.*

Proof: According to the **Definitions 3.1** and **Definition 3.2**, we calculate that the relative degree of the system (2) is $r = 6$, with $r_1 = r_2 = r_3 = 2$. According to Equation (5), the decoupled matrix

$$\boldsymbol{P}(\boldsymbol{x}) = \begin{bmatrix} 0 & \frac{\cos\phi}{I_y} & \frac{-\sin\phi}{I_{xz}^2 - I_x I_z} \\ 0 & \frac{\sin\phi}{I_y \cos\theta} & \frac{\cos\phi}{(I_{xz}^2 - I_x I_z)\cos\theta} \\ \frac{1}{I_{xz}^2 - I_x I_z} & \frac{\tan\theta \sin\phi}{I_y} & \frac{\tan\theta\cos\phi}{I_{xz}^2 - I_x I_z} \end{bmatrix} \tag{7}$$

is nonsingular at the equilibrium state. Therefore, the nonlinear attitude control system (2) satisfies the conditions in **Lemma 3.1**, i.e., system (2) has the relative degree $r = 6$, which equals to the rank of the system state.

According to **Lemma 3.2**, the coordinate transform $\boldsymbol{T}(\boldsymbol{x})$ was chosen as

$$\boldsymbol{T}(\boldsymbol{x}) = \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \\ \xi_5 \\ \xi_6 \end{bmatrix} = \begin{bmatrix} \theta \\ -r\sin\phi + q\cos\phi \\ \psi \\ \frac{1}{\cos\theta}(r\cos\phi + q\sin\phi) \\ \phi \\ p + \tan\theta(r\cos\phi + q\sin\phi) \end{bmatrix} \tag{8}$$

and the input transform of the system (2) was selected as

$$\boldsymbol{u} = \boldsymbol{P}^{-1}(\boldsymbol{x})[-\boldsymbol{Q}(\boldsymbol{x}) + \boldsymbol{v}] \tag{9}$$

where $\boldsymbol{Q}(\boldsymbol{x}) = [\ L_f^2 h_1(\boldsymbol{x}) \quad L_f^2 h_2(\boldsymbol{x}) \quad L_f^2 h_3(\boldsymbol{x})\ ]^{\mathrm{T}}$, $\boldsymbol{v} = [v_1 \quad v_2 \quad v_3]^{\mathrm{T}}$.

With the aforementioned coordinate and input transform, the nonlinear attitude control system (2) can be transformed into the following linear system [5,25]:

$$\begin{cases} \dot{\boldsymbol{\xi}} = \boldsymbol{A}\boldsymbol{\xi} + \mathbf{B}\boldsymbol{v} \\ \boldsymbol{y} = \boldsymbol{C}\boldsymbol{\xi} \end{cases} \tag{10}$$

where $\boldsymbol{\xi} = [\boldsymbol{\xi}_1, \boldsymbol{\xi}_2, \boldsymbol{\xi}_3, \boldsymbol{\xi}_4, \boldsymbol{\xi}_5, \boldsymbol{\xi}_6]^{\mathrm{T}}$, $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are all in Brunovsky standard form with relevant rank.

Remark 3.1. *The mathematical model of attitude motion of a station-keeping airship is derived in the form of a nonlinear system. This nonlinear attitude control system can be decoupled into three linear and decoupling subsystems by selecting proper input and coordinate transform based on the differential geometry theory. Therefore, the control system based on the decoupled linear system can be developed, thus simplifying the control system design significantly.*

3.3. **Fuzzy sliding mode control.** The nonlinear attitude control system (2) has been decoupled into three SISO subsystems of Equation (10) through feedback linearization. The three decoupled linear subsystem of pitching, yawing, and rolling channels can be expressed as:

$$\begin{cases} \dot{\xi}_j = \xi_{j+1} + v \\ y = \xi_j \end{cases} \quad (j = 1, 3, 5) \tag{11}$$

According to the decentralized control theory, the SMC for each subsystem can be designed.

Let $\boldsymbol{y}_d = [\theta_d, \psi_d, \phi_d]^{\mathrm{T}}$ denote the commanded attitude and $\boldsymbol{y} = [\theta, \psi, \phi]^{\mathrm{T}}$ denote the system output. The system error can then be defined as

$$e = y_{id} - y_i, i = 1, 2, 3 \tag{12}$$

A sliding surface for the subsystem is selected as follows:

$$s_i = c_i e_i + \dot{e}_i \tag{13}$$

The sliding surface equation is $c_i e_i + \dot{e}_i = 0$. By selecting a proper c_i, the sliding surface would gain the desired characteristics.

Substituting Equation (12) into Equation (13) will yield the following equation:

$$s_i = c_i(y_{id} - y_i) + (\dot{y}_{id} - \dot{y}_i) \tag{14}$$

Adopt the following reaching law [7]

$$\dot{s}_i = -k_i s_i - \varepsilon_i \mathrm{sign}(s_i),\ k_i > 0, \varepsilon_i > 0 \quad (i = 1, 2, 3) \tag{15}$$

The principle by which to determine ε_i and k_i is to set ε_i as small and k_i as large to accelerate the speed of normal movement and prevent the states from surpassing the switching surface. This condition prevents the occurrence of great chattering.

From Equation (11), Equation (14) and Equation (15), the SMC law is obtained as follows:

$$v_i = -c_i(\dot{y}_i - \dot{y}_{id}) + \ddot{y}_{id} - k_i s_i - \varepsilon_i \text{sign}(s_i) \tag{16}$$

By substituting v_i into Equation (9), the control input $\boldsymbol{u}$ of system (2) can be obtained.

Theorem 3.2. *Global asymptotic stability of the sliding surface dynamics is guaranteed by adopting the reaching law in Equation (15).*

Proof: The Lyapunov function is defined as follows:

$$V = \frac{1}{2} s^T s \tag{17}$$

Considering that V is positively definite and unbounded, the global asymptotic stability of s will be assured if

$$\dot{V} = s\dot{s} < 0 \tag{18}$$

Substituting Equation (13) and Equation (15) into Equation (18), the following equation is obtained

$$\dot{V} = s\dot{s} = s[-ks - \varepsilon \text{sign}(s)] = -ks^2 - \varepsilon |s| \tag{19}$$

Considering that both ε and k are constants exceeding zero, the following can be obtained from Equation (19):

$$\dot{V} = -ks^2 - \varepsilon |s| < 0 \tag{20}$$

Therefore, the global asymptotic stability of the sliding surface dynamics is proven via Equation (20).

The reaching law in Equation (15) is adopted in designing the SMC. If $s \to 0$, then $ks \to 0$. However, when $s \to 0$, the term $\varepsilon \text{sign}(s)$ does not reach zero. The system state generates chattering because of the repeated switching of the sliding surface, and the chattering intensity is determined by the gain ε. To accelerate the reaching phase and reduce chattering while maintaining the sliding behavior, the fuzzy system is used to solve the chattering problem. Select s and $\dot{s}$ as the fuzzy control inputs, and let ε be the fuzzy control output. Therefore, the control gain ε can be tuned according to the change in s and $\dot{s}$ through the fuzzy rules.

The fuzzy sets of input and output variables are both defined as $\{NB, NS, ZO, PS, PB\}$, where NB is negative big, NS is negative small, ZO is zero, PS is positive small, and PB is positive big. The corresponding membership functions of these fuzzy set labels are depicted in Figure 4.

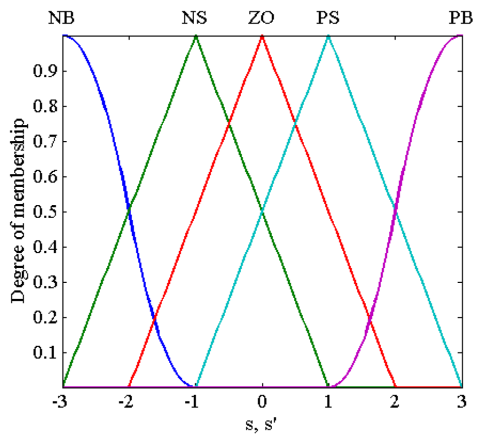


Figure 4. Membership functions for inputs

Suppose the fuzzy system in the current paper is constructed from the following IF-THEN rules [26]:

$$R^{(j)}: \text{IF } s \text{ is } F_s^j \text{ and } \dot{s} \text{ is } F_{\dot{s}}^j \text{ THEN } \varepsilon \text{ is } B^j$$

where F_s^j is the set of s, $F_{\dot{s}}^j$ is the set of $\dot{s}$, and B^j is the output of the j-th fuzzy rule.

When the state trajectories deviate from the sliding surface, if $\dot{s}$ is large, the control gain ε should be increased to reduce chattering. When the state trajectories approach the sliding surface, if $\dot{s}$ is large, the control gain ε should be decreased to reduce chattering. Introducing the scaled modulus s and $\dot{s}$, the following fuzzy rules are proposed, as shown in Table 2.

TABLE 2. Fuzzy control rules

$s/\dot{s}$	*NB*	*NS*	*ZO*	*PS*	*PB*
NB	*PB*	*PB*	*PB*	*PS*	*ZO*
NS	*PB*	*PB*	*PS*	*ZO*	*ZO*
ZO	*PS*	*PS*	*ZO*	*NS*	*NS*
PS	*ZO*	*ZO*	*NS*	*NB*	*NB*
PB	*ZO*	*NS*	*NB*	*NB*	*NB*

The output ε is obtained through the center-of-area defuzzifier

$$\varepsilon = \frac{\sum_{j=1}^{m} \mu(B^j) \cdot B^j}{\sum_{j=1}^{m} \mu(B^j)} \tag{21}$$

where $\mu(B^j)$ is the membership function of B^j.

The FSMC can then be obtained using the above-mentioned fuzzy system. The control gain ε can be tuned using the fuzzy rules, which can attenuate the chattering effectively. The SMC input v can be obtained from Equation (16), and the control input of system (2) can be calculated by substituting v into Equation (9).

4. **Simulation Results.** The present section illustrates the performance of the designed attitude control system through numerical simulation. The control system was simulated by using the variable step Runge–Kutta integrator in MATLAB. The model parameters of the airship [22] are given in Table 3.

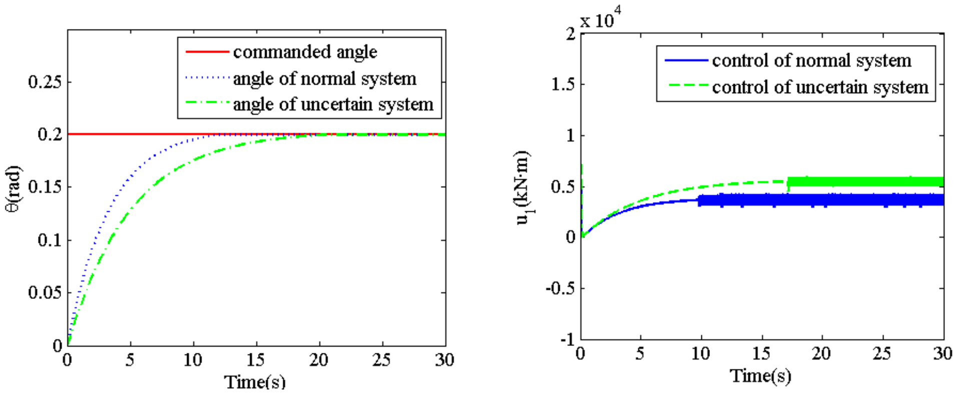
TABLE 3. Model parameters of the airship

parameter	value	parameter	value
m/kg	239	I_x/kgm^2	833.2
I_y/kgm^2	13229.5	I_z/kgm^2	12826.7
I_{xz}/kgm^2	1047.6	x_G/m	0
y_G/m	0	z_G/m	0.902

The commanded attitude angles are selected as $\boldsymbol{\Omega}_d = [\theta_d \ \ \psi_d \ \ \phi_d]^{\mathrm{T}} = [0.2\text{rad} \ \ 0.3\text{rad} \ \ 0.1\text{rad}]^{\mathrm{T}}$, and the initial values of the attitude angles and angular velocities are set to be zero at the initial time. To prove the robustness of the proposed control system, the airship model are assumed to have uncertainty of the order of 10% on the inertia parameters, i.e. $\Delta \boldsymbol{I} = [0.1I_x, 0.1I_y, 0.1I_z, 0.1I_{xz}]^{\mathrm{T}}$. Simulation experiments of the control system are accomplished using the control parameters listed below

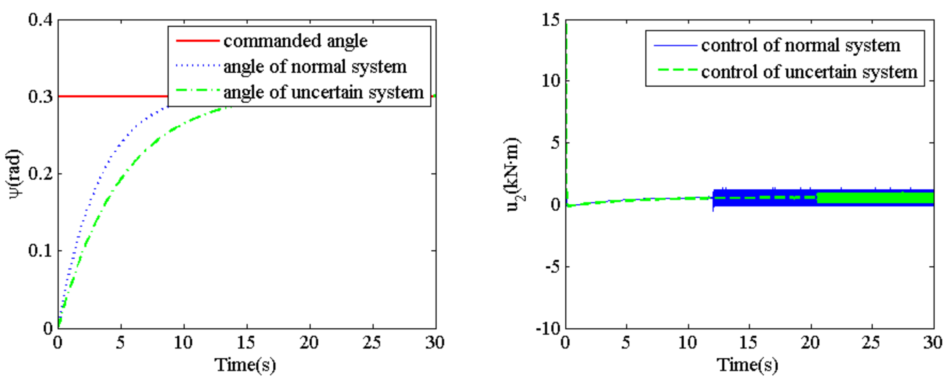
$$\begin{cases} c_1 = 10, \ c_2 = 20, \ c_3 = 15 \\ k_1 = 0.2, \ \ k_2 = 0.8, \ k_3 = 0.5 \end{cases}$$

Simulation results for the airship attitude control of the SMC are shown in Figures 5 to 7. The system output tracks the commanded attitude effectively, confirming that the SMC is effective for station-keeping attitude control. However, the chattering phenomenon is evident as seen from the transition curves of the control inputs. Figures 8 to 10 represent the simulation results for the airship attitude control of the FSMC. The system output tracks the commanded attitude precisely despite the parametric uncertainties. As seen from the transition curves of the control inputs in Figures 8(b) to 10(b), the FSMC is demonstrated to attenuate chattering effectively by tuning the control gains. The contrast simulation results indicate that the proposed FSMC has better performance compared with the SMC.



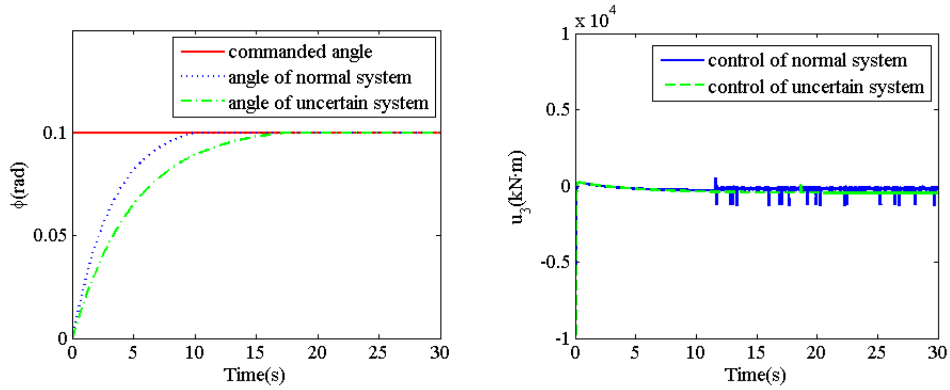
(a) (b)

FIGURE 5. (a) Pitch angle responses to SMC and (b) pitching control inputs of SMC



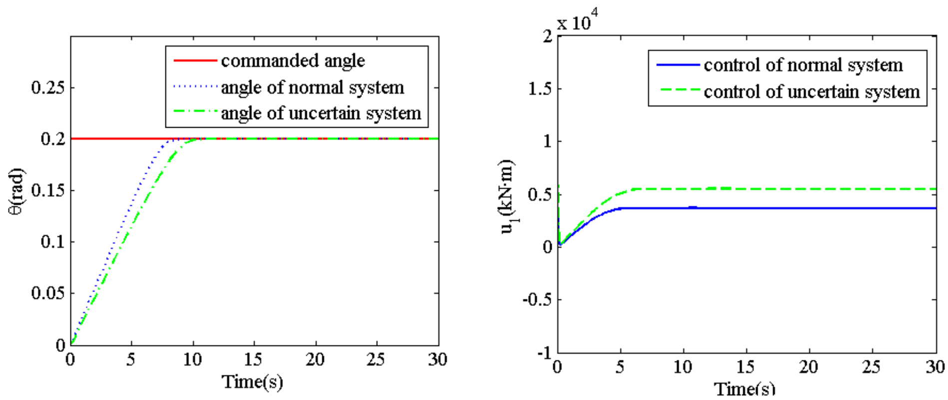
(a) (b)

FIGURE 6. (a) Yaw angle responses to SMC and (b) yawing control inputs of SMC



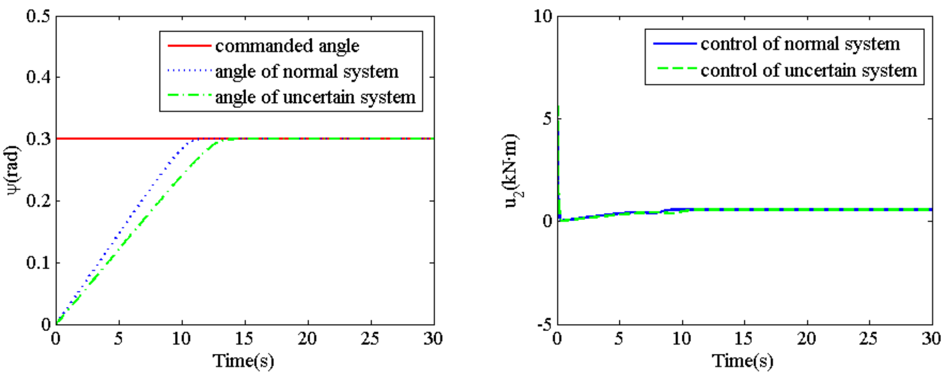
(a) (b)

FIGURE 7. (a) Roll angle responses to SMC and (b) rolling control inputs of SMC



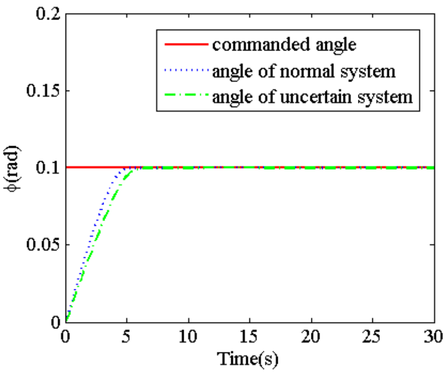
(a) (b)

FIGURE 8. (a) Pitch angle responses to FSMC and (b) pitching control inputs of FSMC

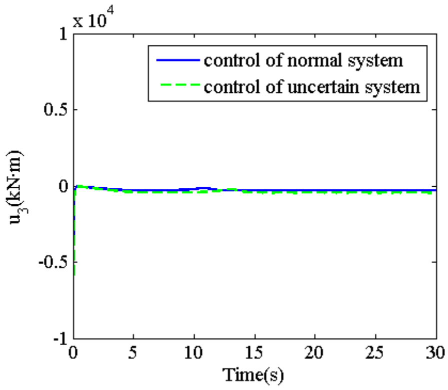


(a) (b)

FIGURE 9. (a) Yaw angle responses to FSMC and (b) yawing control inputs of FSMC



(a)



(b)

FIGURE 10. (a) Roll angle responses to FSMC and (b) rolling control inputs of FSMC

5. **Conclusions.** This paper investigates the attitude control scheme for a station-keeping airship. The nonlinear attitude control system is decoupled into three SISO linear subsystems using the differential geometry theory. The FSMC approach is proposed to design the attitude control system for the station-keeping airship. Using the FSMC, the control gains are tuned according to fuzzy rules, thus attenuating the chattering effectively. Simulation results demonstrate that the attitude control system tracks the commanded angle precisely in the presence of model uncertainties. Contradicting results indicate that the proposed FSMC has better performance against the SMC. The proposed control scheme provides a promising approach for the attitude control system design of an autonomous airship.

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