Intelligent Fuzzy Control in Stabilizing Solar Sail with Individually Controllable Elements

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Received 27 March 2022; Accepted 26 August 2022; Published 12 September 2022

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Fuzzy logical control is a robust and effective control method in industrial fields, which renders it applicable to the attitude control of a solar sail. However, it is hard to apply in black-box and time-varying problem as real solar sail attitude control. Considering the lack of a priori knowledge and the unacceptable manual workload in the design of the fuzzy logical controller (FLC), an intelligent FLC designer (IFLCD) is developed by introducing neural network modelling and automatic design method. Besides, IFLCD also supports self-adaption for better control accuracy. By applying the proposed IFLCD in the attitude stabilization of a solar sail with individually controllable elements (SSICE), an effective solution of unmanned, time-varying, and complex system control method is offered without any mathematical model, which also overcomes the difficulties in FLC design Considering the performance degradation, accident, and distance problems faced by spacecraft, IFLCD can help with more practical problems that are hard be solved by traditional control theory.

1. Introduction

Solar sail, a form of longevous spacecraft without propellant demand [1, 2], attracts numerous aerospace researchers’ attention [3]. Its prolongable peculiarity enables its tremendous potential in diverse interplanetary missions. In recent years, solar sails have been widely introduced in other space missions besides near-Earth experiment and exploration beyond the asteroid belt [4–7]. A square sail is employed as the solar polar orbiter for challenging science missions [8]. Solar sail cooperative formation around \( L_2 \)-type artificial equilibrium points provides a dramatic interplanetary observation point [9]. Wang et al. [10] investigate the problem of multiple solar sail formation around heliocentric displaced orbit via consensus. Due to the harsh space environment, it is inevitable that the spacecraft with long time on-orbit suffers the performance degradation and accident, especially for solar sails. [11–13]. Especially, the force model will be variational and make attitude stabilization failed. The remote distance between earth and solar sail also brings difficulties to the solar sail working in abominable space environment. All of the above problems require solar sail to possess the self-adaptive and unmanned capacity. IKAROS uses dust counters to detect particles impacting on the sail to adjust its controller [13], which can diminish the system error produced by reflectivity variation but needs additional load. NanoSail-D uses distributed layout to avoid risk [11]. Solar sail with individually controllable elements (SSICE) provides attractive decentralized layout and three-axes control torque [14, 15], which is a great choice of configuration design for challenging the problem of stabilizing a time-varying and uncertain system in long voyage. Besides, an appropriate control algorithm is still needed.

As an intelligent, robust, and fault-tolerant control algorithm, the fuzzy logical controller (FLC) can deal with the control of nonlinear, random, and complicated systems in real scenarios, which in comparison to traditional control methods cannot handle efficiently [16–19]. Obviously, FLC can be applied in solar sail attitude control. However, as an expert system, FLC cannot be used without a mathematical model or a priori knowledge [19], which limits its application and makes necessary the leveraging of heuristic design in certain cases. Such an issue becomes more evident when dealing with the control of a black-box and time-varying system because of unacceptable and unrealistic manual workload. To address the above-mentioned deficiency of FLC,
automatic design technology is introduced to the design of FLC [20, 21]. However, the existing methods usually design FLC by learning a large number of existing FLC [22] or modeling the controlled system [23]. The former still needs unacceptable manual workload, while the latter is not practical in attitude control. Moreover, the automatic design method was hardly used in the design of time-varying FLC, which means the design of FLC without a priori knowledge or under time-varying situation is impractical.

To address the above-mentioned deficiency of FLC, an intelligent FLC designer (IFLCD) is proposed in this work. By departing the variational and invariable part in solar sail dynamics and analyzing the invariable part, the theorem of angular momentum, a stable fuzzy logical controller between moment and attitude can be given. Then, by modelling the variational part by neural network, the nonlinearity, coupling, and complexity in variational part can be depicted. By adopting the method of automatic design, the neural network can automatically generate sufficient a priori knowledge as an a priori knowledge source. Combining the controller and the a priori knowledge source, a usable FLC for solar sail can be automatically designed. Besides, a self-adjusting method is applied in IFLCD to diminish stable error coming from trembling [19, 24]. An attitude stabilization simulation is carried out by employing IFLCD in SSICE, and the results demonstrate the feasibility and effectiveness of IFLCD in time-varying and unmanned system.

In this paper, to overcome the difficulties in solar sail missions and the limits of FLC in black-box and time-varying systems, a novel intelligent strategy named IFLCD is proposed for wider application, which is the main contribution of this study. The remainder of this paper is organized as follows. In Section 2, a novel solar sail, SSICE was introduced. Its dynamic decomposition simplifies the design of FLC. In Section 3, the employment of the a priori knowledge source liberates FLC from the unacceptable manual workload. The decomposition of controlled system and the introduction of automatic design method enable FLC to solve the black-box and time-varying control problem automatically. Besides, a self-adaption factor is employed in design for better control accuracy, which is the other contributions of this paper. Moreover, the stability of fuzzy rules is demonstrated in this section. In Section 4, the application of IFLCD in SSICE provides exciting results that can demonstrate the feasibility and effectiveness of IFLCD in time-varying and unmanned system. In Section 5, the comparison reveals that IFLCD possesses a much higher control accuracy with more time consumption, which is still satisfied under time-varying situation.

2. SSICE: A Novel Solar Sail

Because of decentralized layout and three-axis control torque, SSICE possesses the potentials of self-adaptation and attitude control without fuel, which means SSICE is a great choice for space missions. However, the former potential has not been realized in recent works. Facing with the abominable space environment and remote distance between earth and solar sail, an unmanned, self-adaptive, and no-fuel consumption attitude control algorithm is badly needed for solar sail missions. Specifically, in solar sail mission where an operating orbit is closely related to the attitude of a solar sail, high-precision sail stabilization is urgently needed. In this chapter, a brief introduction and dynamic analysis about the platform of the IFLCD, SSICE, will be proceeded.

2.1. Brief Introduction of SSICE. As a square sail, the most prominent features of SSICE include individually controllable elements and an inflatable folding frame. The structural diagram (Figure 1) shows the SSICE and the attitude definition. Four components structurally constitute SSICE: Component A is the spacecraft kernel consisting of effective loads and security devices for loads. Component B is an inflatable frame that links Component A and Component C. Component C is an individual control unit that contains a motor and structure for connection, which is rigidly fixed with the corresponding Component D. Component D is the blade that can reflect solar radiation for generating solar radiation pressure (SRP) to drive SSICE. A pair of Component C and the connected Component D between them compose an individually controllable element, and Component D can be driven by rotating the motors.

In this paper, attitude is defined by describing the Euler rotation from the orbital coordinate system to the body coordinate system of SSICE. As shown in Figure 1, the body coordinate system of SSICE $S_b$ is defined with the origin located at its centroid, $x_b$ axis along the normal direction of the frame plane and pointing to the front, $y_b$ axis in the frame plane and perpendicular to the blades, and $z_b$ axis determined by the right-hand rule. Besides, the orbital coordinate system $S_o$ is defined with the origin located at the centroid of SSICE, $x_o$ axis pointing from the sun to the SSICE, $y_o$ axis in the ecliptic plane, perpendicular to the $x_o$ axis, and $z_o$ axis determined by the right-hand rule. The $S_b$ can be obtained with a “1-2-3” Euler rotation from $S_o$, namely, $S_b \rightarrow t_{1,}\psi (\psi) \rightarrow t_{2,}(0) \rightarrow t_{3,}(\psi) S_o$.

Moreover, the critical parameters of SSICE for simulation are given in Table 1. The parameter determination refers to Table 1 of Ref. [14]. Besides, the solar sail pressure (SRP) model and the force model of blade refer to Ref. [14].

2.2. Dynamic Analysis of SSICE. The body coordinate component in $z$-axis of the infinitesimal is called as $z_h$. Thus, the rotation angle of $i^{th}$ blade at $z_h$ is expressed as

$$\sigma_i(z_h) = \frac{\sigma_{\text{up}} + \sigma_{\text{down}}}{2} + \frac{\left(\sigma_{\text{up}} - \sigma_{\text{down}}\right)}{L_p} z_h \left(-\frac{L_p}{2} \leq z_h \leq \frac{L_p}{2}, \sigma_{\text{up}}, \sigma_{\text{down}} \in \left\{-\frac{\pi}{2}, 0, \frac{\pi}{2}\right\}\right),$$

(1)
where $\sigma_{\text{up}}$ and $\sigma_{\text{down}}$ are the rotation angles of the upper and bottom motors. The normal vector of the blade infinitesimal at $z_h$ is $\{n_i\}_b = [\sin (\sigma_i(z_h)), \cos (\sigma_i(z_h)), 0]^T$. The sunlight vector $r_1$ in the $S_b$ is acquired as
\begin{equation}
\{r_1\}_b = L_{zh}[1, 0, 0]^T = [\cos (\theta) \cos (\psi) - \sin (\psi) \cos (\theta) \sin (\theta)]^T
\end{equation}

The angle between $\{n_i\}_b$ and $\{r_1\}_b$ is computed as
\[ \eta_i = \arccos (\langle \{n_i\}_b \cdot \{r_1\}_b \rangle). \]

Using the simplified solar sail model in Ref. [17], the SRP $dF_i$ on the $i^{th}$ blade at $z_h$ is obtained as
\begin{equation}
\{dF_i\}_b = [dF_{ix}, dF_{iy}, dF_{iz}] = 2Pw_h \cos^2 (\eta) \{n_i\}_b dz_h,
\end{equation}

where $P$ is the SRP and $w_h$ is the width of blade. Setting the body coordinate component in the $y$-axis of $i^{th}$ blade longitudinal centerline as $y_i$, then the SRP torque can be generated by $dF_i$ as
\begin{equation}
\{dM_i\} = [dM_{ix}, dM_{iy}, dM_{iz}] = [0, y_i, z_h] \times \{dF_i\} = [y_i dF_{iz}, z_h dF_{ix} - y_i dF_{ix}]^T.
\end{equation}

Ideally, by integrating (3) and (4), the SRP force and SRP torque generated by the $i^{th}$ blade are obtained. The force and moment on the entire SSICE are obtained by reckoning every blade into counting. However, considering the performance degradation and machine failure [25], actual torque would be different from the ideal value. Obviously, the relationship between rotation angles and actual torque is variational.

According to the theorem of angular momentum, the attitude dynamics of SSICE described in $S_b$ is
\begin{equation}
\{J\}_b \{\dot{\omega}\}_b + \{b\} \{\omega\}_b = \{M\}_b,
\end{equation}

where $\{\omega\}_b$ is the inertial angular velocity of solar sail in $S_b$. Because attitude is described by Euler angles in $S_a$, a necessary transition from angular velocity to Euler angles is derived as
\begin{equation}
\{\omega\}_b = \{\omega^{\text{sun}}\}_b = L_y(\psi)L_z(\theta)L_z(\phi) [\psi, 0, \phi]^T + L_y(\psi)L_z(\theta) [0, 0, 0]^T.
\end{equation}

where $\{\omega^{\text{sun}}\}_b$ is the angular velocity sum of the sail around the sun and solar system rotation. Considering $\{\omega^{\text{sun}}\}_b$ is a small constant, the relationship between SRP torque and Euler angles can be regarded as invariable. With intermediate control variables, SRP torque, the dynamic of SSICE can be divided into invariable and variational parts. Then, an intelligent FLC designer can be applied to automatically design FLC by using the invariable part in dynamic.

### 3. Intelligent FLC Designer

A neural network is trained to satisfy the need of a priori knowledge in FLC design. By executing numerous zero-order oracles of variational part, enough data can be used to train a neural network as an a priori knowledge source. Then, an intelligent FLC designer will be constructed based on the a priori knowledge source, which can automatically design FLC according to different design variables. Moreover, IFLCD can control the...
A method is often ine

ment variables and intermediate control variables are con-

adjusting. Thus, input variables can be divided into environ-

knowledge in SSICE attitude control can be determined.

3.1. A Priori Knowledge Source. By ensuring the intermediate control variables as SRP torque, the concept of a priori knowledge in SSICE attitude control can be determined. Usually, not all input variables are adjustable or worth adjusting. Thus, input variables can be divided into environment variables and control inputs. The a priori knowledge can give out corresponding control inputs while the environment variables and intermediate control variables are confirmed as shown in Figure 2.

Considering the unpredictable performance degradation, the attitude control of SSICE can be regarded as a black-box problem, so that the traditional analytical controller design method is often ineffective. However, expert systems can solve this problem by executing some oracles of black-box and analyzing the data of oracles. Here, only zero-order oracles are needed, which are the mappings between the input and output variables of black-box. Usually, enough zero-order oracles can be used to simulate the black-box itself, but neural network can realize similar function with less oracles. The input of zero-order oracles is environment variables and control inputs, and the output of zero-order oracles is intermediate control variables. To generate the a priori knowledge, a data processing is needed to turn oracles into training dataset as shown in Figure 3. The input of dataset is environment variables and intermediate control variables, and output is control inputs. Subsequently, a training neural network with the dataset when enough data is obtained. The result neural network can generate a priori knowledge as the a priori knowledge source.

3.2. Fuzzy Rules. As shown in Figure 2, the task of the fuzzy rules is obtaining intermediate control variables to make target variables approach zero. Defining two vector quantities of attitude deviation description e and ce as the target variables,

$$
e = [\varphi - \varphi_{tar}, \theta - \theta_{tar}, \psi - \psi_{tar}]^T,$$

$$ce = [\varphi - \varphi_{tar}, \theta - \theta_{tar}, \psi - \psi_{tar}]^T,$$

where \(\varphi_{tar}, \theta_{tar}, \psi_{tar}\), \(\varphi_{ce}, \theta_{ce}, \psi_{ce}\) are values of target Euler angle and Euler angular velocity.

For convenience, in this paper, the type of fuzzy rules is selected as bang-bang control. By setting the boundary values of each interval of e and ce, the intermediate control variable can be distinguished as shown in Table 2. For example, setting CB+ , CM+, CS+, CZ+, CZ+, CS+, CM+, CB+ and B-, M-, S-, Z-, Z+, S+, M+, B+ as (-\(\infty\), -5], (-5, -2], (-2, -0.5], (-0.5, 0], (0, 0.5], (0.5, 2], (2, 5], (5, \(\infty\)) and (-\(\infty\), -2], (-2, -1], (-1, -0.2], (-0.2, 0], (0, 0.2], (0.2, 1], (1, 2], (2, \(\infty\)) respectively. Besides, control gain matrix \(K\) should satisfy the stability requirements below. Then, the target control torques can be determined. If \(e_x\) is 0.5 in S+ interval, \(e_y\) is -3 in CM- interval, and \(M_{tar,x}\) should be \(+K_{26}\). \(M_{tar,y}\) and \(M_{tar,z}\) are both ensured in this method, which means the task of fuzzy rules can be accomplished when appropriate design variables, control gain matrix and boundary values, are given.

Hereby, the stability analysis of fuzzy rules in SSICE is provided. Because solar sail tends to keep its Euler angle and angular velocity near to zero, a linearized equation of the theorem of angular momentum can be deduced as

$$
\begin{bmatrix}
\varphi \\
\omega_x
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\varphi \\
\omega_x
\end{bmatrix}
+ \begin{bmatrix}
0 \\
1
\end{bmatrix}
\begin{bmatrix}
M_{tar,x} \\
M_{tar,y}
\end{bmatrix},
$$

$$
\begin{bmatrix}
\theta \\
\omega_y
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\theta \\
\omega_y
\end{bmatrix}
+ \begin{bmatrix}
0 \\
1
\end{bmatrix}
\begin{bmatrix}
M_{tar,y} \\
M_{tar,z}
\end{bmatrix},
$$

$$
\begin{bmatrix}
\psi \\
\omega_z
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\psi \\
\omega_z
\end{bmatrix}
+ \begin{bmatrix}
0 \\
1
\end{bmatrix}
\begin{bmatrix}
M_{tar,z} \\
M_{tar,y}
\end{bmatrix}.
$$

Besides, split e into \(n_1 + 1\) intervals and split ce into \(n_2 + 1\) intervals by \(n_1\) and \(n_2\) interval boundaries, respectively. The interval boundaries of e are named as \(dl_i\), and the interval boundaries of ce are named as \(cdli\). Then, the control moment can be expressed as

$$
M_x = K_\chi(e, ce) \text{ sign } \left( \sum_{i=1}^{n_1} \text{ sign}(\varphi - dl_i) + \sum_{i=1}^{n_2} \text{ sign}(\omega_x - cdli) \right),
$$

$$
M_y = K_\chi(e, ce) \text{ sign } \left( \sum_{i=1}^{n_1} \text{ sign}(\theta - dl_i) + \sum_{i=1}^{n_2} \text{ sign}(\omega_y - cdli) \right),
$$

$$
M_z = K_\chi(e, ce) \text{ sign } \left( \sum_{i=1}^{n_1} \text{ sign}(\psi - dl_i) + \sum_{i=1}^{n_2} \text{ sign}(\omega_z - cdli) \right).
$$
where $K(e, ce)$ is the gain coefficient function of control moment to ensure which value in $K$ should be used and its sign and sign$(\cdot)$ is the sign function. The stability analysis about $\phi$ and $\omega_x$ is presented as follows.

The Lyapunov function $W$ is built as

$$W = \gamma_t^T \gamma = \phi \omega_x \left[ \begin{array}{c} 0 \\ 0 \\ \frac{1}{J_{xb}} \end{array} \right]^T M_x = 2\omega_x + 2\omega_x M_x = 2\omega_x \left( \phi + K_x(\phi, \omega_x) \text{ sign}(B_{sum}) \right).$$

(11)

To ensure $\dot{W} \leq 0$, the gain coefficient should be chosen in every interval set of $\{\phi, \omega_x\}$, which is obtained by the boundary values of interval set. Suppose $\phi$ is in the interval $[d_{l-1}, d_l]$; the value range of $K(\phi, \omega_x)$ can be deduced as

$$C_{\text{sign}} = \text{sign}(\omega_x) \text{ sign}(B_E) \begin{cases} K(\phi, \omega_x) \leq \inf \{-\phi J_{xb}\} = -d_l J_{xb}, & \text{if } C_{\text{sign}} = 1, \\ K(\phi, \omega_x) = 0, & \text{if } C_{\text{sign}} = 0, \\ K(\phi, \omega_x) \geq \sup \{-\phi J_{xb}\} = -d_{l-1} J_{xb}, & \text{if } C_{\text{sign}} = -1. \end{cases}$$

(12)

According to Lyapunov theorem [26], while the correct values of $K$ are determined, Lyapunov function $W$ will approach 0 over time. The stability about the $x$-axis controller of SSICE can be demonstrated by the second Lyapunov method. Considering that the kinematics equations in the simplified system are decoupled and have similar forms on three axes, a proven stability on any axis can indicate that the whole system is stable.

3.3. Self-Adaption for Reducing Control Error. A fuzzy logical controller works effectively in many fields. However, the steady control error and the control speed parameters as settling time contradict each other in FLC. To overcome this disadvantage, a multilevel fuzzy logical controller is designed. Different boundary values and control gain matrix are provided for faster control or smaller steady control error. Figure 4 shows a control error comparison between a one-layer and a two-layer fuzzy logical controller under the same condition, which indicates that two-layer fuzzy logical controller can reduce control error to one third of the original value with a similar settling time.

Actually, the multilayer FLC is a special form of self-adaptive FLC. Obviously, self-adaptive FLC can play a better role than one-layer FLC. By adjusting the value of design...
variables with the absolute value of target variables, FLC can be adjusted smoothly and the steady control error can be massively reduced. Comparing the result of one-layer FLC with the latter self-adaptive result in Figure 5, although the settling time was increased by 10 times, the steady control error can be reduced by $10^{-5}$ times. The result means that self-adaption can heavily improve the control accuracy with slight more time consumption.

Hereby, the stability analysis of the self-adaption FLC used in SSICE is provided. The self-adaption factor $k_{ad}$ is used to adjust gains and boundary values for control error reduction. The new interval boundaries and gain coefficient function can be expressed as

$$
d_{ad_i} = k_{ad}d_{li},$$

$$cd_{ad_i} = k_{ad}cd_{li},$$

$$K_{ad}(e, ce) = k_{ad}K(e, ce),$$

with the new control moment expressed as

$$B_{sum}^{ad} = \sum_{i=1}^{n_1} \text{sign}(\varphi - k_{ad}d_{li}) + \sum_{i=1}^{n_2} \text{sign}(\omega - k_{ad}cd_{li}),$$

$$M_x = k_{ad}K_x(e, ce) \text{ sign } (B_{sum}^{ad}),$$

$$M_y = k_{ad}K_y(e, ce) \text{ sign } (B_{sum}^{ad}),$$

$$M_z = k_{ad}K_z(e, ce) \text{ sign } (B_{sum}^{ad}),$$

and the derivation of Lyapunov function can be derived as

$$\dot{W} = 2\omega_x \left( \varphi + k_{ad}K_x(\varphi, \omega_x)B_{sum}^{ad} \right).$$

Figure 4: The steady-state error of FLC: (a) one-layer FLC controller; (b) two-layer FLC controller.

Figure 5: The Euler angle variation of SSICE controlled by IFLCD.
By substituting Equation (12) into Equation (13), the numerical relationship that gain coefficient function satisfies is obtained

\[
K^{ad}(\varphi, \omega_s) \leq -d^{ad}J_{sb}, \quad \text{if sign} (\omega_s) \text{sign} \left( \frac{p^{ad}_{\text{sum}}}{h_{\text{sum}}} \right) = 1, \\
K^{ad}(\varphi, \omega_s) = 0, \quad \text{if sign} (\omega_s) \text{sign} \left( \frac{p^{ad}_{\text{sum}}}{h_{\text{sum}}} \right) = 0, \\
K^{ad}(\varphi, \omega_s) \geq -d^{ad}J_{sb}, \quad \text{if sign} (\omega_s) \text{sign} \left( \frac{p^{ad}_{\text{sum}}}{h_{\text{sum}}} \right) = -1. 
\]

(16)

According to Equation (15), the derivation of Lyapunov function is nonpositive. Hence, self-adaption FLC with the self-adaption factor form in Equation (13) has the same stability with FLC in Equation (9). If appropriate gain matrix is confirmed for a FLC, the stability of others FLC ensured by Equation (13) will be demonstrated.

3.4. Intelligent FLC Designer Generating. The function of IFLCD is to produce FLC with given design parameters by utilizing the fuzzy rules and a priori knowledge source. The a priori knowledge will provide the relationship among control inputs, environment variables, and intermediate control variables, and fuzzy rules will provide the information between intermediate control variables and target variables. Using the abilities mentioned above, the control input can be obtained when environment variables and target variables are ensured, which achieves the task of the required FLC. Besides, an updating approach is employed by introducing the method of automatic design, which can update the a priori knowledge source when the real system has changed. Moreover, the self-adaption is utilized in the design variable determination for reducing the steady control error. The structure of IFLCD is shown in Figure 6.

4. Application: Intelligent Stabilization of SSICE

In space, attitude stabilization heavily affects the success of mission. By updating the training data of force model with real data come from sensors, the IFLCD can adjust controller in real time without manpower. Here, two attitude stabilization missions of SSICE are executed by IFLCD. The stabilization results reveal the feasibility and effectiveness of IFLCD in attitude stabilization.

4.1. Simulation Scenario. The working environment of SSICE is set at the Sun-Earth L4 point, in which the solar radiation power is 1370 W/m². An IFLCD is employed for attitude stabilization, which is specifically designed for SSICE with the structure shown in Figure 6. Only the design variables and oracle data are provided, but the real models of SRP and SSICE are unknown.

The type of fuzzy rules is selected as bang-bang control. By analyzing SSICE, the target variables are attitude deviation variables \( \epsilon \) and \( \eta \), the intermediate control variables are \( M_{\text{act}} \), and the control inputs are the motor rotation angles \( \sigma_1, \sigma_2, \sigma_3, \sigma_4 \). In addition, the environment variables, sunlight angle \( \alpha \) and \( \beta \), can be derived from

\[
H = \text{dot}\left( \{r_{\text{sun}}\}_b, z_b\right), \\
\alpha = \text{acos}\left( \text{dot}\left( \{r_{\text{sun}}\}_b, x_b\right) \right), \\
\beta = \begin{cases} 
    \text{acos}\left( \text{dot}\left( \{r_{\text{sun}}\}_b, y_b\right) \right), & H \leq 0, \\
    2\pi - \text{acos}\left( \text{dot}\left( \{r_{\text{sun}}\}_b, y_b\right) \right), & H > 0. 
\end{cases} 
\]

(17)

The a priori knowledge source adopts Back Propagation (BP) neural network, which is simple, effective, and reliable. After executing enough zero-order oracles of the SRP model of SSICE, three layers are employed and the initial value of neural node number is determined as \( 2 \times n_{\text{IC}} + 1 = 11 \) (\( n_{\text{IC}} \) is the dimension of neural network input) according to Kolmogorov’s Mapping Neural Network Existence Theorem [27]. Through a few performance tests, the hidden neural node number value is determined as 16. Besides, the training algorithm is determined as the Levenberg-Marquardt method. Moreover, the training dataset of neural network is taken in every variable direction with appropriate sample interval to ensure that the combination of any possible values of variables can be sampled nearby but sampling points will not converge locally. The datasets parameters are shown in Table 3.
4.2. Results of Invariable Scenario. The initial motion states of SSICE are chosen as \([\varphi, \theta, \psi, \omega_{bx}, \omega_{by}, \omega_{bz}]^T = (\pi/180)[3, 2, 4, 0, 0, 0]^T + 10^{-6} \times [0, 0, 0, 5.5, -3.4, 4]^T\), and target motion states are \([\varphi, \theta, \psi, \omega_{bx}, \omega_{by}, \omega_{bz}]_{\text{tar}}^T = [0, 0, 0, 0, 0, 0]^T\). Here, the attitude stabilization process of SSICE is given.

The profiles of three Euler angles and angular velocities are shown in Figures 5 and 7. As illustrated in Figure 5, the angular error between actual values of Euler angles and target values are near zero after 1500 seconds. The overshoot of \(\varphi\) is less than 1%, the overshoot of \(\psi\) is about 10%, and the overshoot of \(\theta\) is less than 10%. All settling time is below 1400 seconds. Figure 7 indicates target angular velocities can be achieved after 1500 seconds, and the balance can be maintained.

4.3. Results of Time-Varying Scenario. The initial motion states of SSICE are chosen as \([\varphi, \theta, \psi, \omega_{bx}, \omega_{by}, \omega_{bz}]^T = (\pi/180)[1, 1, 0, 0, 0, 0]^T\), and target motion states are \([\varphi, \theta, \psi, \omega_{bx}, \omega_{by}, \omega_{bz}]_{\text{tar}}^T = [0, 0, 0, 0, 0, 0]^T\). Besides, an output with 15% deviation was given from the previous model in the 2200 seconds. Besides, the deviation threshold was set as 10%, and the checking times was set as 10 seconds. Whenever the model deviation exceeds the threshold, the a priori knowledge reconstruction process is initiated. The variation of Euler angles and angular velocities is given. As shown in Figures 8 and 9, IFLCD can avoid the error caused by the changes of the controlled system.

In this chapter, although we do not know the concrete models of SRP and SSICE, a successful attitude stabilization is accomplished by IFLCD. The Euler angle error is controlled on the order of \(10^{-6}\) degree, and the error of angular velocity is controlled on the order of \(10^{-3}\) deg/s. This control is accurate enough for most solar sail missions. In conclusion, IFLCD can be regarded as a feasible and effective method in the attitude stabilization of SSICE under both invariable and time-varying scenarios.
Figure 9: The angular velocity variation of SSICE with varying models.

Figure 10: The Euler angle variation of SSICE controlled by a method in Ref. [15].

Figure 11: The angular velocity variation of SSICE controlled by a method in Ref. [15].
5. Discussion

In order to evaluate the control performance of IFLCD, an attitude stabilization simulation of SSICE under the same condition is carried out by using the control method in Ref. [15] as shown in Figures 10 and 11. However, this control method can only be used on the basis of knowing the mathematical model of SSICE.

The profiles of three Euler angles and angular velocities are shown in Figure 10. As illustrated in Figure 10, the angular error between actual values of Euler angles and target values is near zero after 2000 seconds. The overshoot of $\phi$ is less than 10%, the overshoot of $\psi$ is less than 40%, and the overshoot of $\theta$ is about 40%. All settling times are below 1400 seconds.

By comparing the two simulations, it can be found that the overshoot of IFLCD is much less than the overshoot of method in Ref. [15]. Besides, the control deviation of $\theta$ increases in the first 180 seconds, but IFLCD do not have this bad performance. Moreover, IFLCD has a shorter settling time, which means a faster control speed. The reason why IFLCD can do a better control may come from the specialty of fuzzy logical control. The speed ability and low overshoot characteristics benefit the attitude control of solar sail. Besides, it is obvious that the control performances of $\phi$ in both simulations are much better than those of the others. The differences about settling time and overshoot probably are caused by the differences of control abilities on different axes and the fitting precision of neural network.

In order to evaluate the control performance of IFLCD in time-varying scenario, an attitude stabilization simulation of SSICE under the same initial condition is carried out by using the reconstruction control method in Ref. [25] as shown in Figures 12 and 13. However, the solar sail model used in Ref. [25] is solar sail with numerous discrete elements (SSNDE), which is originated from SSICE.
By comparing the two simulations, it can be found that the overshoot of IFLCD is much less than the overshoot of the method in Ref. [25]. Besides, the stable control errors of IFLCD are much less than those in Figures 12 and 13, but the settling time of IFLCD is quite bigger than that in Ref. [25]. IFLCD spent about 10 times as much time consumption as the method in Ref. [25] for about 100 times more accuracy. Both results can achieve the control target because of the adjustment of the dynamic model of solar sail, namely, the reconfiguration ability of control algorithm. However, IFLCD can achieve a better control accuracy after reconfiguration. Besides, considering the difference between SSICE and SSNDE, the different control performances order of the three axes can be explained by different structure reasonably.

6. Conclusion

Due to the harsh space environment, it is inevitable that the spacecraft with long time on-orbit suffer the performance degradation and accident, especially for solar sails. The remote distance between earth and solar sail also brings difficulties. For overcoming the above difficulties, the potentials of self-adaptation and attitude control without fuel in solar sail with individually controllable elements (SSICE) can be helpful. By introducing the automatic design method and self-adaption into FLC design process, an intelligent FLC designer (IFLCD) is established, which circumvents manual analysis in fuzzy logical controller (FLC) design, allows FLC to be utilized in time-varying scenario, and decreases the stable control error. The application in the attitude stabilization of SSICE reveals the effectiveness and feasibility of IFLCD. Besides, the comparison with the similar approach in solar sail attitude stabilization shows that IFLCD can do a better job in both invariable and time-varying scenarios. As mentioned above, this intelligent algorithm is especially suitable for unmanned, complicated, and time-varying systems. Particularly, IFLCD can be used for other spacecraft control process, which can increase the reliability of the unmanned space missions.

Data Availability

All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Conflicts of Interest

The authors declare that they have no conflict of interest.

Authors’ Contributions

Lin Chen, Ming Xu, and Xiaoyu Fu participated in the research design. Lin Chen and Santos Ramil performed data analysis. Santos Ramil and Xiaoyu Fu contributed to the writing of the manuscript.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (11772024).

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