Integrated attitude estimation and control of satellite with thruster actuator using ANFIS

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Abstract

This paper proposed a new estimation and control strategy to control the satellite attitude. As the attitude control strategy plays an essential role in the different kinds of space missions, scientists try to improve the performance of the satellite attitude system, regardless of the expense. In this study, we proposed an adaptive neuro-fuzzy integrated (ANFIS) satellite attitude estimation and control system. A pulse modulator is used to generate the right ON/OFF commands of the thruster actuator. To evaluate the performance of the ANFIS controller in closed-loop simulation, an ANFIS observer is used to estimate the attitude and angular velocities of the satellite using a magnetometer, sun sensor, and rate gyro data. Besides, a new ANFIS system will be proposed and evaluated that can simultaneously control and estimate the system. The performance of the ANFIS controller is compared with the optimal PID controller in a Monte Carlo simulation using different initial conditions, disturbance, and noise. The simulations are performed to verify the ANFIS controller's ability to decrease settling time and fuel consumption in comparison with the optimal PID controller. Also, examine the ANFIS estimator, and the results demonstrate the high skill of these designated observers. Moreover, we proposed an integrated ANFIS estimator and controller for satellite attitude control and estimation in the presence of noise and uncertainty, which can reduce the computational effort and offer smooth actuator actions.

Keywords: Integrated control and estimation; Adaptive neuro fuzzy; Noise; Uncertainty

1. Introduction

Satellite attitude control plays a significant role in most space missions. Therefore, the development of an accurate and stable controller is an essential part of conducting a space mission (Ismail & Varatharajoo, 2010; Inamori, et al., 2011) and it is challenging to design a satellite attitude control system able to perform precisely in the presence of noise and uncertainty in the space. In this paper, we propose an ANFIS controller using quaternion feedback with Thruster. The most advanced satellite attitude control techniques use the concept of quaternion feedback (Fossen, 2002; Tavakoli & Assadian, 2018). Different linear and nonlinear attitude control strategies based on quaternion feedback were considered (Antonsen, 2004; Topland & Gravdahi, 2004). The quaternion feedback approach also used to stabilize the attitude of microsatellites (Kristiansen, et al., 2009).
In recent years, a vast majority of control techniques have been used to control satellite attitude tightly (Kang, et al., 2017; Aleksandrov, et al., 2018; Yang, 2019). Li et al. (Li, et al., 2017) studied a robust finite-time control algorithm for controlling satellite attitude in uncertainty. Xiao et al. (Xiao, et al., 2017) developed a control with a simple structure to perform an attitude maneuver in case of disturbances and uncertain inertia parameters. Vatankhahghadim and Damaren (Vatankhahghadim & Damaren J, 2017) have adopted the passivity rate for the hybrid attitude control of a spacecraft using magnetic torques and thrusters. Eshghi and Varatharajoo studied a combined energy and attitude control system (Eshghi & Varatharajoo, 2017).

Several different types of optimal controllers have been used to enhance the satellite attitude control system Zhang Fan et al. (Fan, et al., 2002) To improve the accuracy of a small satellite, and an attempt was made to optimize the attitude control model. In another study, Wisniewski and Markley (Wisniewski & Markley, 1999) studied the optimal magnetic attitude control. Arantes et al. (Arantes Jr, et al., 2009) have tried to analyze and design a reaction thruster attitude controller and then improve the performance of the control subsystem. All these optimal controls inevitably led to a specific mathematical model, leading to inappropriate behavior compared to external pulses in the comparison simulation state. More importantly, an optimal controller may not be able to perform the task in the presence of uncertainties.

The adaptive control method is one of the most influential models that can deal with the problem of uncertainty (Shi, et al., 2019). In this regard, Wen et al. (Wen, et al., 2017) used an adaptive attitude controller to control the agile spacecraft. An adaptive controller was used to manage the satellite attitude by solar radiation from Lee and Singh (Lee & Singh, 2014). In another research, they (Lee & Singh, 2009) a non-insecure, equivalent, adaptive satellite attitude controller that uses the sun's radiation pressure. All of these adaptive control logics are model-based, and although they can work accurately with uncertainties, they cannot work with different dynamic models. Determining the satellite attitude has been the primary concern of many studies in recent decades (Zhang, et al., 2013; Cao & Li, 2016; Zeng, et al., 2014). Kouyama et al. (Kouyama, et al., 2017) used an image fitting method to determine the satellite attitude, which, of course, follows an exact map projection. They used this method together with the classic onboard sensors. Wu et al. (Wu, et al., 2017) proposed a process by which the problem of orientation based on a single sensor observation can be solved.

The enormous ability of fuzzy logic to solve various mathematical problems of modeling, control, and estimation is undeniable. Daley and Gill (Daley & Gill, 1986) used the self-organizer fuzzy logic controller (SOC) to model and control a flexible satellite with a significant dynamic coupling of the axes efficiently. Mukherjee et al. (Mukherjee, et al., 2017) used fuzzy logic to control the attitude of earth-pointing satellites, in which they used the genetic algorithm to optimize the performance of their proposed nonlinear fuzzy PID controller. In the other research, Huo et al. (Huo, et al., 2016) proposed an adaptive fuzzy fault tolerance attitude control for a rigid spacecraft. In recent years, fuzzy logic has been used for a variety of satellite attitude estimation purposes
(Guo & Zhong, 2015). Cui and et al. (Cui, et al., 2019) worked on a fuzzy adaptive system for tracking control of a nonlinear system. For example, Ran et al. (Ran, et al., 2015) studied an adaptive fuzzy fault tolerance control for rigid spacecraft attitude maneuvers. Sun et al. (Sun, et al., 2017) used an adaptive fuzzy estimator for spacecraft attitude determination.

In this paper, an ANFIS (adapted neuro-fuzzy inference system) (Jang, 1993) controller is introduced to control and estimate the satellite attitude. Integrated estimation and control of satellite attitude using ANFIS lead to reducing fuel consumption, computational effort, and settling time, also increasing the smoothness of actuator actions in the presence of noise, uncertainty, and external disturbance. In turn, eliminates systematic errors and sound that are unavoidable in classical approaches also can improve the performance of satellites in space missions.

The organization of this paper is as follows. First, a summary of the satellite attitude dynamics is given. Then we provide a brief overview of the PID controller design for control systems. Next, the general ANFIS structure and the learning algorithms will be discussed. Subsequently, we talk about the compositions of the ANFIS controller and satellite attitude estimator. Finally, an ANFIS integrated control and estimation subsystem are introduced to reduce the complexity of the control system, and we examine the usefulness of this model by comparing the proposed model results with those of the classical controller.

2. Modelling the system

A. System Dynamics

In this section, we introduce equations of motion of a satellite with Euler equation and quaternion kinematics. The Euler equation of the rigid body satellite attitude around its principal axis coordinates is: (Wie, 1998)

\[
\begin{align*}
I_1 \dot{\omega}_1 &= M_c + M_d - (I_3 - I_2)\omega_2 \omega_3 \\
I_2 \dot{\omega}_2 &= M_c + M_d - (I_1 - I_3)\omega_1 \omega_3 \\
I_3 \dot{\omega}_3 &= M_c + M_d - (I_2 - I_1)\omega_2 \omega_1
\end{align*}
\]

(1)

Where \(\omega_1, \omega_2 \) and \(\omega_3 \) are the elements of angular velocity vector of satellite. \(I_1, I_2, \) and \(I_3 \) are the moments of inertia about the principal axis. \(M_c \) and \(M_d \) are control and disturbance moments, respectively, which are expressed in the body frame.

For kinematic representation, the quaternion vector \(\vec{q} = (q_1, q_2, q_3, q_4) \) is utilized, which is defined as follows:
\[
\begin{bmatrix}
q_1 \\
q_2 \\
q_3
\end{bmatrix} = \sin \frac{\theta}{2} \begin{bmatrix}
e_1 \\
e_2 \\
e_3
\end{bmatrix}
\]

Where \( q \) is the rotation angle about the Euler axis \( \vec{e} = (e_1,e_2,e_3) \). The kinematic differential equation for quaternions is as follows:

\[
\begin{align*}
\dot{q}_1 &= \frac{1}{2} (\omega_3 q_2 - \omega_2 q_3 + \omega_1 q_4) \\
\dot{q}_2 &= \frac{1}{2} (-\omega_3 q_1 + \omega_1 q_3 + \omega_2 q_4) \\
\dot{q}_3 &= \frac{1}{2} (\omega_2 q_1 - \omega_1 q_2 + \omega_3 q_4) \\
\dot{q}_4 &= \frac{1}{2} (-\omega_1 q_1 - \omega_2 q_2 + \omega_3 q_3)
\end{align*}
\]

(2)

B. Measurements

The sun sensor and the magnetometer are the sensors used in this study to estimate the setting. To simulate the magnetometer sensor (magnetic field), we consider height, latitude, longitude, and date as inputs, and the magnetic field vector is calculated as inertia frame using the IGRF11 model (Finlay & al., 2010). Then, transform the magnetic field into the body frame including a random white noise:

\[
\vec{B}^B = C_B^B \vec{B}^I + \vec{n}_B
\]

(3)

The rotation matrix \( C_B^B \), is computed using the quaternion vector:

\[
C_B^B = \begin{bmatrix}
1 - 2(q_2^2 + q_3^2) & 2(q_1 q_2 + q_3 q_4) & 2(q_1 q_3 - q_2 q_4) \\
2(q_1 q_2 - q_3 q_4) & 1 - 2(q_1^2 + q_3^2) & 2(q_2 q_3 + q_4 q_4) \\
2(q_1 q_3 + q_2 q_4) & 2(q_2 q_3 - q_1 q_4) & 1 - 2(q_1^2 + q_2^2)
\end{bmatrix}
\]

(4)

The attitude measurement needs only the direction of the magnetic field.
\( \vec{\mu}_B = \frac{\vec{B}}{|\vec{B}|} \).

The sun vector direction in inertial frame \( \vec{\mu}'_s \) can be found by the following formulation (A. Vallado, 1997):

\[
JD = 367\text{year} - \text{INT}[\frac{7(\text{year} + \text{INT}\left(\frac{\text{month} + 9}{12}\right))}{4}] + \text{INT}\left(\frac{275\text{month}}{9}\right) + \text{day} \times 1721013.5 + \frac{\text{second}}{60} + \frac{\text{minute}}{60} + \frac{\text{hour}}{24}
\]

\[ T = (JD - 2451545.0) / 36525 \]

\[ l_M = 280.4606184 \times 36000.77005361T \]

\[ M = 357.5277233 \times 35999.05034T \]

\[ l_{\text{ecliptic}} = l_M + 1.914666471 \times \sin(M) + 0.019994643 \sin(2M) \]

\[ e = 23.439291 \times 0.0130042T \]

\[ \vec{\mu}'_s = (\cos l_{\text{ecliptic}} \cos e \sin l_{\text{ecliptic}} \sin e \sin l_{\text{ecliptic}}) \]

in which the JD is Julian Day based on the date and time (year, month, day, hour, minute and second), \( T \) is the Julian centuries, \( l_M \) is mean longitude of the sun, \( M \) is the mean anomaly of the sun, \( l_{\text{ecliptic}} \) is the ecliptic longitude of the sun, and \( e \) is the tilt angle of the Earth rotation axis.

Similar to the magnetometer, the output of the sun sensor as the direction of the sun vector in body frame \( \vec{\mu}'_s \) can be computed as follows:

\[
\vec{\mu}_S = C^b_l \vec{\mu}'_S + \vec{n}_S \tag{6}
\]

In addition, to provide the angular velocity measurements, a three-axis rate-gyro with random white noise is used.
3. **Adaptive Neural Fuzzy Inference System**

**A. Fuzzy logic**

Most traditional tools for modeling, thinking, and arithmetic is crisp, deterministic, and precise, so yes or no type instead of more or less typical. In conventional dual logic, for example, a statement may be true or false and nothing in between. For the first time, L.A.Zadeh (Zadeh, 1965) proposed a fuzzy logic that contained "true," "false," and "partially true." He emphasized that real situations are often not precise and deterministic.

A fuzzy control system is based on fuzzy logic that analyzes input values in the form of logical variables that assume continuous costs between 0 and 1. The fuzzy logic was first used by Mamdani and Assilian (Mamdani & Assilian, 1975) in the engineering problem. Rather than designing algorithms that explicitly define the control action as a function of the control input variables, the developer of a fuzzy controller writes rules that associate the input variables with the control variables through expressions of linguistic variables. After all, laws have been defined, and the control process begins with the calculation of all rule sequences. Then the consequences are summarized into a fuzzy set that describes the possible control actions.

**B. ANFIS**

Generally, fuzzy control logic has two main approaches;

1: Mamdani (Mamdani & Assilian, 1975)

2: Takagi-Sugeno (Sugeno & Takagi, 1985). The basis of ANFIS as an adaptive network-based fuzzy system is the Takagi-Sugeno fuzzy system (Jang, 1993) method. Its inference system corresponds to a set of fuzzy IF-THEN rules that have a learning ability to approximate non-linear functions.

ANFIS is a combination of neural networks and fuzzy systems. ANFIS has become a compelling simulation method that uses both fuzzy and neural network methods. Recently, ANFIS modeling has become widespread in various space missions (Gupta, et al., 2016; Wang Ting, 2013; Hanafy, et al., 2014).

The most important feature of the ANFIS controller is the ability to handle a free model system that allows the use of real data and, more importantly, the design of a controller based on the provided real data. The other considerable superiority of the ANFIS system is the required number of input variables for control and estimation. The Simplicity of modeling compared to classical modeling, along with the advantage of this method in the presence of noise and uncertainty compared to PID controllers, which makes our proposed model more acceptable. The ANFIS has 5 layers (Figure 1) as follows:

Define membership function
\[ O_{1,i} = m_{A_i}(x) \quad \text{for } i=1,2 \]
\[ O_{2,i} = \omega_i = m_{A_i}(x)m_{B_i} \quad i = 1,2 \]

Product of the membership function for each input.

Normalizing the output of layer 2.

\[ O_{3,i} = \bar{\omega}_i = \frac{\omega_i}{\omega_1 + \omega_2} \quad i = 1,2 \]

Then

\[ O_{4,i} = \bar{\omega}_i f_i = \bar{\omega}_i (p_i x + q_i y + r_i) \]

summation of all outputs in layer 4.

\[ O_{5,i} = \sum \bar{\omega}_i f_i = \frac{\sum \omega_i f_i}{\sum \omega_i} \]

Fig. 1 ANFIS Structure
C. Hybrid learning algorithm

Least Square Gradient Reduction is used to train the ANFIS system (locating the membership function parameters) the pattern between the inputs and the output data.

Each learning level is divided into two parts. In the forward stage, the inputs and outputs of each layer are calculated, then the ANFIS system can provide the optimal coefficients. Finally, in the backward step, the parameters of the ANFIS system would be updated.

D. PID Controller

The control moment vector by using PID controller can be computed as:

\[ M_c = K_p q_e + K_d \omega + K_q \int q_e dt + K_\omega \int \omega dt \]  

(7)

By considering this constraint

\[ |M_c| \leq M_{e_{\max}} \]  

(8)

This constraint guarantees the appropriate signal command to input the modulator for ON-OFF command of the thrusters with torque \( M_{e_{\max}} \).

4. ANFIS Controller and Estimator

A. ANFIS Controller

Control input variables are angular velocity and quaternion errors, and the control output variable is the control torque \( M_c \) (Figure 2).

![Figure 2 Block diagram of ANFIS controller](image-url)
After a system supplies the input and output variables with a PID controller, the collection of this data is repeated several times, considering 15 different initial conditions (each simulation for 20 seconds with 0.01 second sampling time). The initial quaternions and initial angular velocities are changed to provide a wide range of data for ANFIS learning. After that, the ANFIS controller training process begins, and the ANFIS system learns the path from the inputs to the outputs. Now the ANFIS controller can work with all initial conditions.

B. **ANFIS Estimator**

This article uses the sun sensor and magnetometer outputs to estimate attitude. Thus, data for ANFIS estimation learning from these two sensors are provided both in the body (sensor) and in the inertia frame (calculation) (Figure 3). Several different scenarios are considered to offer an extensive database for learning the ANFIS estimator.

![Figure 3 Block diagram of ANFIS observer](image)

C. **Combined Control and Estimation using ANFIS**

Both the ANFIS estimator and the ANFIS controller are used in the loop in this study. The nesting simulations show the performance of these two ANFIS subsystems working simultaneously (Figure 4).
Finally, as mentioned in the introduction, the primary purpose of this study is to evaluate the performance of an ANFIS system as a combination of estimator and controller instead of two separate subsystems (ANFIS estimator and ANFIS controller). As shown in (Figure 5), for this ANFIS subsystem, input variables are the inputs of the estimator (sensor data), and output variables are the outputs of the controller (control torque). The ANFIS integrated control, and estimation subsystem receives data read by the sun sensor and the magnetic sensor as input variables and then passes the control torque directly to the system dynamics (Figure 6).

Figure 4 Block diagram of the combined ANFIS observer and controller

D. Integrated Control and Estimation using ANFIS

Figure 5 Block diagram of the integrated ANFIS controller and observer
5. Evaluation of ANFIS control and estimation

We consider a small satellite with the moments of inertia of Table 1. To study the performance of attitude estimation and control of satellite using ANFIS. For all simulations, the final simulation time is selected to be 20 seconds, and the sampling time for evaluation is 0.01 sec. The initial sample conditions and the desired attitude are provided, as in Table 2.

| Table 1 Nominal and indeterminate moments of inertia (in Kg.m²) |
|---------------------------------------------------------------|
| I_x  | I_y  | I_z  |
| Moments of Inertia | 1.5 | 2.6 | 3 |
| Moments of Inertia in case of uncertainty | 2.5 | 4 | 3.3 |

| Table 2 Sample initial condition (this initial condition is not in the training set) |
|-----------------------------------------------------------------------------------------------------|
| w_x | w_y | w_z | f | q | y |
| unit | Rad/s | Deg |
| Initial condition | 0.0125 | 0.05 | 0.075 | 10 | 5 | 10 |
| Desired condition | 0 | 0 | 0 | 5 | 0 | 0 |
A. ANFIS Performance Comparison

Because the simulations are for stabilization of satellite attitude on zero condition, the essential characteristics of the results are the settling time of control, the control effort (fuel consumption), and the steady-state error. Therefore, we selected them as the criteria for comparison of the results.

The comparison of time histories of control moments for PID and ANFIS is shown in (Figure 7). then, we present the trajectory of the Euler angles in Figure 8. From (Figure 7), it is evident that the ANFIS controller produces smoother control actions. Moreover, the path of the attitude angles using the PID controller has larger over-shoot values.

The numerical results of the comparison of the ANFIS controller and PID controller are provided in Table 3 with/without noise and uncertainty. It is clear from this table that the fuel consumption of the ANFIS controller is 12% lower than PID, even if there is no uncertainty and measurement noise. The presence of noise and uncertainty induces more fuel consumption (20% and 17%, respectively).

The PID parameters were regulated to have the same settling time with a 1% error for both controllers, which makes it easier to compare the performance of ANFIS and PID controller.

|                      | X axe | Y axe | Z axe | Total  |
|----------------------|-------|-------|-------|--------|
| **Without noise and uncertainty** |       |       |       |        |
| ANFIS                | 0.1282| 0.4149| 0.7194| 1.2625 |
| PID                  | 0.1279| 0.4612| 0.8489| 1.4380 |
| **Considering noise** |       |       |       |        |
| ANFIS                | 0.1732| 0.4157| 0.7198| 1.3087 |
| PID                  | 0.2098| 0.5289| 0.8976| 1.6363 |
| **Considering uncertainty** |       |       |       |        |
| ANFIS                | 0.1910| 0.5447| 0.7991| 1.5348 |
| PID                  | 0.1992| 0.7302| 0.9143| 1.8437 |
Figure 7 Comparison of control moment in (a) X (b) Y and (c) Z directions using ANFIS and PID.
Figure 8 Comparison of Euler angles (a) $\phi$ (b) $\theta$ and (c) $\psi$ using ANFIS and PID controller.
B. Command Modulation

We evaluate the performance of the ANFIS controller using the real thruster actuator with ON-OFF commands. Thus, a PWPF (Pulse-Width Pulse-Frequency) modulator is used to transform the continuous control moment command to the ON-OFF commands. The trajectory of the attitude angles and the thruster commands are shown in Figure 9 and Figure 10, respectively. It is clear that the limit of thrust results in a slower approach to the final attitudes. However, the results are acceptable, considering both uncertainty and measurement noise exist.

![Figure 9 Euler angles time history using PWPF modulator](image)

Figure 9 Euler angles time history using PWPF modulator
C. **Monte Carlo Simulation**

In this work, we used Monte-Carlo simulation to analyze the robustness of the proposed integrated ANFIS estimator and controller. A random initial condition (between -15 and +15 degrees) is considered in addition to the random noise and random uncertainty (I 1 Kg.m²). The attitude control error of Euler angles of time=20 sec is shown in figure 11 for 200 iterations. The maximum control error is less than 0.02 degrees error, which is considerably low.
6. Conclusion

In this paper, we presented an ANFIS (adaptive neuro-fuzzy inference system), controller and estimator, to estimate and control the satellite attitude, under the existence of uncertainty and noise. The other significant ability of the proposed system was predicting necessary states accurately via ANFIS observer. We recorded the data of a satellite in several different conditions (noise and uncertainty) to train the observer.

Results show that the integrated ANFIS controller and estimator offered less fuel consumption, and also more smoothness actuator actions. The perfection performance of the proposed combined ANFIS estimator and controller was verified under the existence of noise and uncertainty. Results of using synchronous control and estimation ANFIS simulator show that although both stages (monitoring and evaluation) were done in one-step, the performance of the integrated system is similar to the combined controller and estimator. Due to the confirmed capabilities of the ANFIS controller and observer, we could conclude that it works with black-box systems efficiently. It means that the determined dynamic is not essential, which
makes it possible to use this proposed ANFIS system for unknown space bodies as well as fast parameter varying space objects (like space robots and manipulators).
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