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ATTITUDE CONTROL FOR A NANO SATELLITE BY USING FUZZY AND APPROACHING INDEX SWITCHING ALGORITHM

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ABSTRACT

This paper presents a comparison between the approaching index switching algorithm (AISA) and a fuzzy controller for attitude control in a nanosatellite in 3-axes. AISA is designed to switch between two different controls based on an index value. The first controller accelerates the system to reach the desired angle. The other controller is decelerating the system before approaching the desired angle. A reaction wheel (RW) is used to provide the torque required to rotate the satellite about its axis. The purpose of the controller is to change the rotational speed of the RW so that the satellite points in the correct direction. This comparison reveals that the AISA controller is much more efficient in maneuvering and accurate in contrast to fuzzy control. The control effort is preserved by 66% compared to the fuzzy control effort. This shows that the use of this type of intelligent control system represents a significant advantage over the conventional control systems currently used for satellite attitude control.

KEYWORDS: Attitude Control, AISA, Fuzzy, Nano Satellite, Dynamics Model

التحكم فى توجه قمر صناعى صغير عن طريق استخدام المنطق الترجيحي ومؤشر التحول الخوارزميه

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الملخص

في هذا البحث ، تُظهر مقارنة بين مؤشر التحول الخوارزميه (AISA) ووحدة التحكم الترجحى للتحكم في توجه قمر صناعي صغيرحيث أن وحدة التحكم AISA أكثر كفاءة في المناورة وأكثر كفاءة من أجهزة التحكم الترجحىو ايضا تتميز بدقة أفضل و توفر الجهد المطلوب حيث يقل الجهد الى نسبه تصل إلى(٦٦٪) من الجهد المطلوب من المتحكم الترجحى. تم تصميم AISA للتبديل بين عنصري تحكم مختلفين بناءً على قيمة مؤشر. تمثل وحدة التحكم الأولى إخراج النظام الذي يصل إلى القيمة المحددة في أسرع وقت ممكن ، بينما تمثل وحدة التحكم الأخرى يكبح النظام ليصل الى الزاوية المطلوبة. يوضح هذا أن استخدام هذا النوع من نظام التحكم الذكي يمثل ميزة كبيرة على أنظمة التحكم التقليدية المستخدمة حاليًا للتحكم في اتجاه القمر الصناعي.

الكلمات المفتاحية : التحكم فى التوجه, مؤشر التحول الخوارزميه, المتحكم الترجحى, قمر صناعى صغير, نموذج الديناميكيات

1. INTRODUCTION

The Attitude Determination and Control Subsystem (ADCS) is accountable for preserving the orientation of the spacecraft in space, in addition to enabling the required maneuvers. Attitude stabilization refers to maintaining the orientation of a satellite in space. Attitude maneuvering is the reorientation process in which one attitude changes into another. The ADCS collects positions from the attitude sensors then processes them to locate the spacecraft's current attitude. The ADCS compares the current position to the desired position and uses the difference between them to activate the appropriate actuator using the specified algorithm to eliminate or reduce errors. The attitude actuation systems have many types of actuators, like thrusters or reaction wheel. From the actuator perspective, actuator control is applied using reaction wheels [1-6], control moment gyroscopes (CMG) [7-10], and thrusters. A reaction wheel is a type of flywheel primarily used by satellites for attitude control. It is an inertial device that transmits torque to the satellite by changing its own angular momentum. It consists of an electric motor attached to a flywheel. When the reaction wheel changes its velocity in one direction during acceleration it causes the satellite to rotate in the opposite direction.

In [11], a classical proportional-integral-derivative (PID) control algorithm for a momentum exchange device is proposed. Recent satellite control research includes linear and nonlinear control [12-16], adaptive control [17-20], fuzzy control [21-24], and others. A decent overview of many governance approaches for attitude control, such as [25]. The focus of this paper is to design a feedback controller for attitude control using the AISA introduced in [26]. However, this paper uses a different switching strategy when using the two controllers, as shown in the next section.

The paper is organized as follows: Linear equation of attitude control dynamics and kinematics of the satellite in 3-axes, as shown in Fig. 1, with reaction wheels. A method to control the index-switching algorithm has been proposed. The simulation was applied to a nano satellite model (CubeSat) around 3-axes.

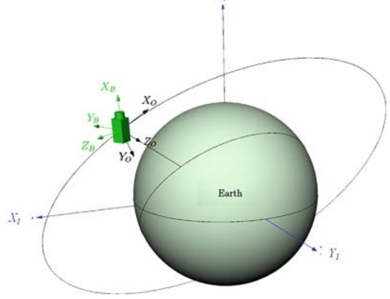


Fig. 1. Satellite representation along with the Orbital (Xo, Yo, Zo) and Inertial (XI,YI, ZI) reference frames. (XB, YB, ZB)

2. GOVERNING EQUATIONS

To derive the attitude-dynamics equation of motion for a three-axis stabilized satellite, we must consider the position kinematics in space. The attitude dynamics equations are derived from the Euler moment equations. The mathematical model of the satellite attitude is described by the kinematic and kinetic equations of motion [27], now introduced. The Moment of Momentum of body Particle.

$$h = i(\omega_x I_{xx} - \omega_y I_{xy} - \omega_z I_{xz}) + j(\omega_y I_{yy} - \omega_x I_{yx} - \omega_z I_{yz}) + k(\omega_z I_{zz} - \omega_x I_{zx} - \omega_y I_{zy}) \quad (1)$$

Where I is the moment of inertia of the satellite, and ω is angular velocity.
The desired linearized attitude dynamics equations of motion:

$$\begin{cases} T_{cx} = I_x \varphi^{\cdot\cdot} + 4\omega_0^2(I_y - I_z)\varphi - \omega_0 \theta^{\cdot}(I_y - I_z)\varphi + \\ \quad \omega_0(I_y - I_z - I_x)\psi^{\cdot} + h_{wx}^{\cdot} + \theta^{\cdot}\psi^{\cdot}(I_z - I_y) \\ T_{cy} = I_y \theta^{\cdot\cdot} + 3\omega_0^2(I_z - I_x)\theta + \varphi\psi\omega_0^2(I_z - I_x) + \varphi\varphi^{\cdot}\omega_0(I_x - I_z) \\ \quad +\psi\psi^{\cdot}\omega_0(I_z - I_x) + h_{wy}^{\cdot} + \psi^{\cdot}\varphi^{\cdot}(I_x - I_z) \\ T_{cx} = I_z \psi^{\cdot\cdot} + \omega_0^2(I_y - I_x)\psi + \omega_0 \theta^{\cdot}(I_x - I_y)\psi + \\ \quad \omega_0(I_z + I_x - I_y)\varphi^{\cdot} + h_{wz}^{\cdot} + \varphi^{\cdot}\theta^{\cdot}(I_y - I_x) \end{cases} \quad (2)$$

Where T_{cx}, T_{cy}, and T_{cz} are introduced as the values of the control torque and ω_0 is orbit angular velocity. Here (φ, θ, and ψ) are the Euler angles (roll, pitch, and yaw) that determine the satellite position relative to the reference frame here chosen as Earth as shown in **Fig.2**. The $\varphi^{\cdot}$, $\theta^{\cdot}$, and $\psi^{\cdot}$ as the body angular rates.

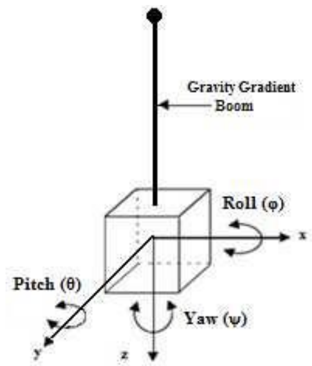


Fig. 2 Roll (φ), Pitch (θ) and Yaw (ψ) Angles in body frame

3. CONTROL DESIGN

3.1.State Space Model

The dynamics equation of a satellite can be approximated in state space form

$$\dot{x} = Ax + Bu \quad (3)$$

A is the plant matrix is given by

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ \frac{4\omega_0^2(I_y - I_z)}{I_x} & 0 & 0 & 0 & 0 & \frac{\omega_0(I_y - I_z - I_x)}{I_x} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{3\omega_0^2(I_z - I_x)}{I_y} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & \frac{\omega_0(I_z + I_x - I_y)}{I_z} & 0 & 0 & \frac{\omega_0^2(I_y - I_x)}{I_z} & 0 \end{bmatrix} \tag{4}$$

State variable substitutions

$$x = [\varphi \quad \varphi^{\cdot} \quad \theta \quad \theta^{\cdot} \quad \psi \quad \psi^{\cdot}]^T \tag{5}$$

B is the control matrix and is given by

$$B = \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{I_x} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{1}{I_y} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{I_y} \end{bmatrix} \tag{6}$$

u Is the input reaction wheel control and is represented by the form

$$u = [h^{\cdot}_{wx} \quad h^{\cdot}_{wy} \quad h^{\cdot}_{wz}]^T \tag{7}$$

3.2.Approaching Index Switching

The index is a quantitative measure of how close the output is to the reference set point. The value of the index is represented as

$$Ʀ(t) = {e(t)}/{r} \tag{8}$$

Where e (t) is the error at time t and r is the desired value of the reference set. Starting at a value of one, the system moves to the final destination where the value of the index is zero. The switch should be done at a value Ʀs which is defined by 0< Ʀs <1.

We need to define the switching policy and implement the switching process. The switching decision can be expressed as follows:

$$\begin{cases} if: Ʀ(t) \leq Ʀs & switch\ to\ controller\ I \\ else & switch\ to\ controller\ II \end{cases}$$

The AISA is an index of the exchange between two controllers. As controller I is supposed to enable the system to have a quick response, when the system is drawing close to the attitude reference, relying on the values of the index Ʀ(t) is in contrast with Ʀs till Ʀ(t)≤ Ʀs, the system changes to controller II which is supposed to enable the system to attain the attitude reference without overshoot**. Fig.3** shows the block diagram of switching algorithm.

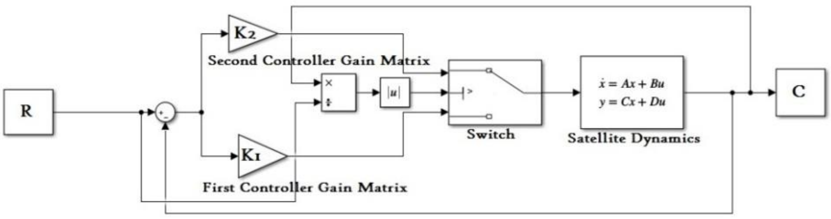


Fig. 3. The switching algorithm

Each reaction wheel in the satellite has its own controller represented as Controller I

$$\begin{cases} \dot{h}_{w_{I}x} = K_{p_{I}x}\emptyset \\ \dot{h}_{w_{I}y} = K_{p_{I}y}\theta \\ \dot{h}_{w_{I}z} = K_{p_{I}z}\psi \end{cases} \tag{9}$$

Where K_{p_I} are the gains for each reaction wheel for first control.
Controller II

$$\begin{cases} \dot{h}_{w_{II}x} = K_{p_{II}x}\emptyset + K_{d_{II}x}\dot{\emptyset} \\ \dot{h}_{w_{II}y} = K_{p_{II}y}\theta + K_{d_{II}y}\dot{\theta} \\ \dot{h}_{w_{II}z} = K_{p_{II}z}\psi + K_{d_{II}z}\dot{\psi} \end{cases} \tag{10}$$

Where $K_{p_{II}}$ and $K_{d_{II}}$ are the gains for each reaction wheel for second control.

3.3.Fuzzy Controller

The fuzzy logic controller consists of three necessary steps: fuzzification, fuzzy reasoning, and defuzzification. The inputs to the fuzzy controller are the attitude error and change in attitude error as shown in. The primary operation of the inference method is to decide the values of the controller output based on the contributions of every rule in the rule base. It is essential to pick the suitable linguistic variables, which formulate the fuzzy control policies in order to enhance the overall performance of the fuzzy controller as shown in Fig. 4.

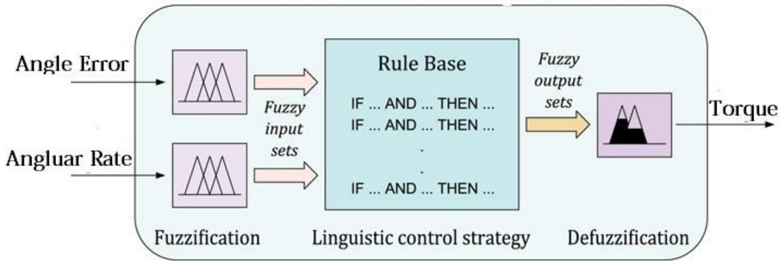


Fig. 4. Fuzzy controller scheme.

3.3.1 Design of Fuzzy Control Rules

Control parameter description domains are categorized into elementary fuzzy sets, which can be defined as positive large (PL), positive small (PS) negative large (NL), negative small (NS), and zero in qualitative terms (Z) as shown in Fig. 5, Fig. 6 and Fig. 7.

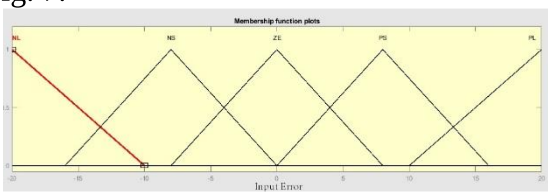


Fig. 5. Error Input

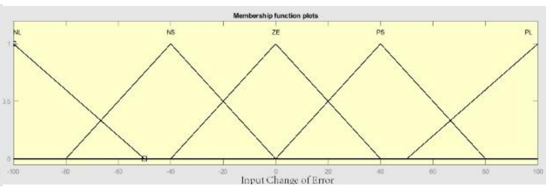


Fig. 6. Change of Error Input

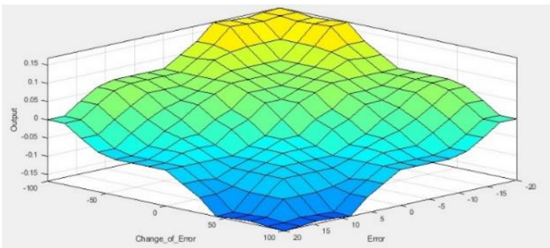


Fig. 7. Output Surface

Each set is then defined by a membership function that takes on a membership function. The values are between zero and one. With some differentiation in gain factors and membership functions. This controller is applied to the three axes roll, pitch, and yaw angles of attitude control system. In order to modify the scaling factors for both angle error and angular rate error, these maximum error with change in the error values are used, the value of the performance scaling factor is chosen to accelerate the plant reaction with the lowest possible overshoot. The fuzzy control rules are designed shown in TABLE 1.

TABLE 1: Rule Base for Controller Roll, Pitch and Yaw Angles

		Error				
		NL	NS	ZE	PS	PL
Change of Error	NL	PL	PL	PS	PS	ZE
	NS	PL	PS	PS	ZE	NS
	ZE	PS	PS	ZE	NS	NS
	PS	PS	ZE	NS	NS	NL
	PL	ZE	NS	NS	NL	NL

3.4 Stability Analysis

Numerically, we can determine the stability of the state-space model by finding the eigenvalues of the state-space A matrix. First, let's analyse whether the system without any control is stable. The eigenvalues of the system matrix A determine the stability. The eigenvalues of the matrix are the values that are the solutions of $\det(A - \lambda I) = 0$. Where the eigenvalues

$$\lambda = [0 \quad 0.0021 \quad -0.0021 \quad 0 \quad 0 + 0.0019i \quad 0 - 0.0019i]^T \tag{11}$$

From equation 11, it is clear that one of the poles is in the positive real part, which means that the system is unstable as shown **Fig .8**.

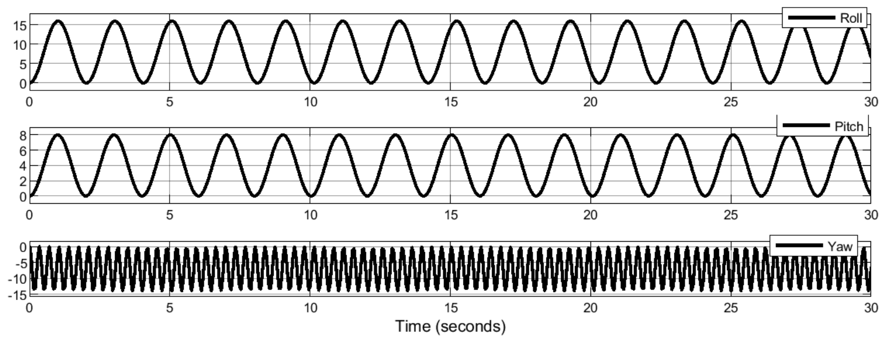


Fig.8. Attitude Angle for Nano Satellite without any Control.

The stability and time-domain performance of a closed-loop feedback system mainly depends on the positions of the eigenvalues of the matrix $(A - BF)$, which are equal to the closed-loop poles. Since matrices A and BF are both 6x6, the system has 6 poles.

$$u = -Fx \tag{12}$$

The AISA is an index of the exchange between two controllers, where F_I and F_{II} the first is and second controller gain matrix.

$$F_I = \begin{bmatrix} K_{p_I x} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & K_{p_I y} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & K_{p_I z} & 0 \end{bmatrix}$$

$$F_{II} = \begin{bmatrix} K_{p_{II}x} & K_{d_{II}x} & 0 & 0 & 0 & 0 \\ 0 & 0 & K_{p_{II}y} & K_{d_{II}y} & 0 & 0 \\ 0 & 0 & 0 & 0 & K_{p_{II}z} & K_{d_{II}z} \end{bmatrix} \tag{13}$$

The eigenvalues of the matrix $(A - BF_I)$ for the first controller

$$\lambda_I = [0 + 0.21\mathrm{i} \quad 0 - 0.21i \quad 0 + 0.71 \quad 0 - 0.71\mathrm{i} \quad 0 + \ 0.22\mathrm{i} \quad 0 - \ 0.22\mathrm{i}]^T \tag{14}$$

The eigenvalues of the matrix $(A - BF_I)$ for the second controller

$$\lambda_{II} = [-0.3 + 0.2\mathrm{i} \quad -0.3 - 0.2\mathrm{i} \quad -1.2 + 0.65\mathrm{i} \quad -1.2 - 0.65\mathrm{i} \quad -0.3 + 0.2\mathrm{i} \quad -0.3 - 0.2\mathrm{i}]^T \tag{15}$$

From eigenvalues λ_I and λ_{II} it can be seen that for the first controller, all real part is zero, the system behaves as an undamped oscillator. For final stage the second controller eigenvalues λ_{II}, all poles in the real part is negative, which means that the system is stable and behaves as a damped oscillator as shown in figures in the next section.

4. SIMULATION

In this part, the simulation results of the nano satellite obtained using fuzzy and AISA are discussed. The simulation of a nano satellite CubeSat rotates around 3-axes by using three reaction wheels. The parameters of the CubeSat and reaction wheels are presented in TABLE 2.

TABLE 2: Parameters of the CubeSat Model

Parameters	Description	Value	
I_{xx}	Inertia in x-axis	0.1043	kg·m^2
I_{yy}	Inertia in y-axis	0.1020	kg·m^2
I_{zz}	Inertia in z-axis	0.0031	kg·m^2
ω_0	Orbit angular velocity	1.083*10^-3	rad/sec
T_m	RW Maximum torque	2*10^-3	N.m

The simulation was carried out in attitude control around 3 axes using the AISA controller and compared with the fuzzy controller for the CubeSat, taking into account that there was no effect of the disturbance torque and through a small angle.

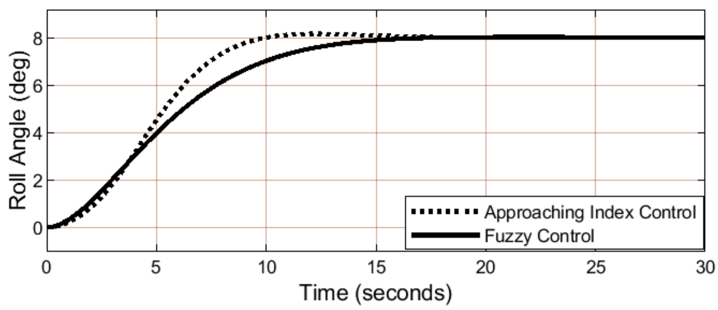


Fig.9. Attitude Angle Around Roll Axis.

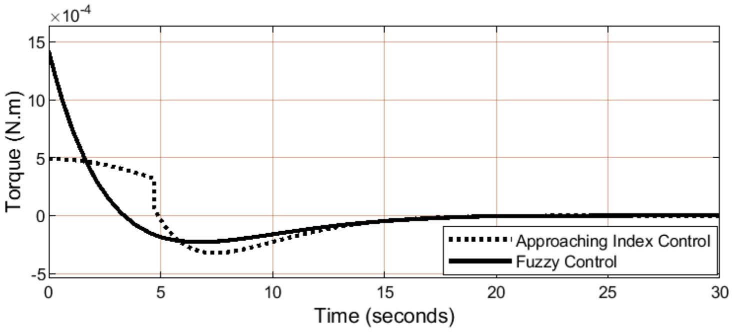


Fig.10. Control Effort of CubeSat Around Roll Axis.

TABLE 3: Attitude Roll Angle Using AISA and Fuzzy Controller

	AISA	**Fuzzy**
$\mathbf{t_s}$	11 s	17 s
$\mathbf{e_{ss}}$	0.5%	0.18%
$\mathbf{T_c}$	0.76 m N.m	1.4 m N.m

From Fig.9, Fig.10, and TABLE 3 the simulation results of attitude roll angle using the AISA controller and the fuzzy controller, it is clear that the AISA controller is faster in settling time and has better performance in accuracy than the fuzzy. The control effort in fuzzy $T \cong 1.4\ \mathrm{mN.m}$ is higher than the control effort in ASIA $T \cong 0.76\ \mathrm{mN.m}$. The index switch of ASIA in the roll axis is RS =35%, so the switch occurs at an attitude angle of $\emptyset = 2.8\ \mathrm{deg}$ and a time of $t \cong 3.8$ sec.

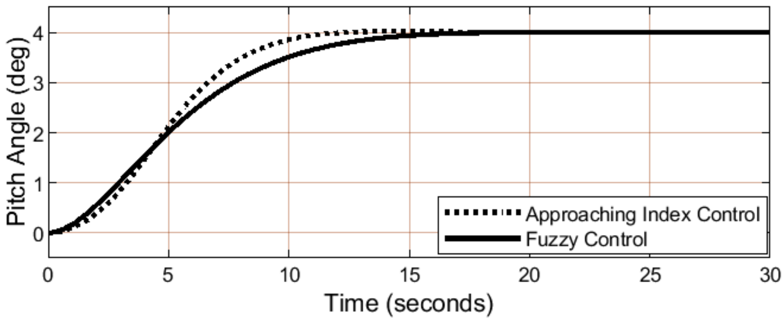


FIG.11. Attitude Angle Around Pitch Axis.

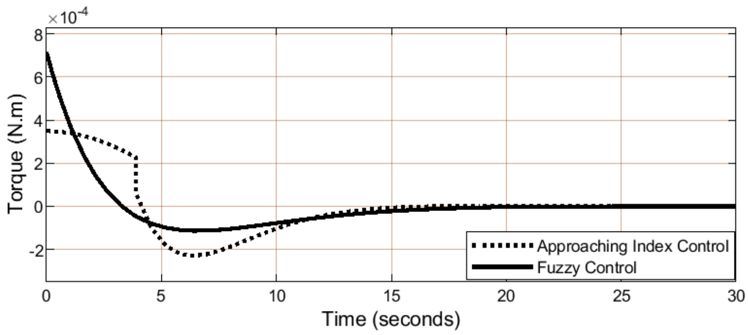


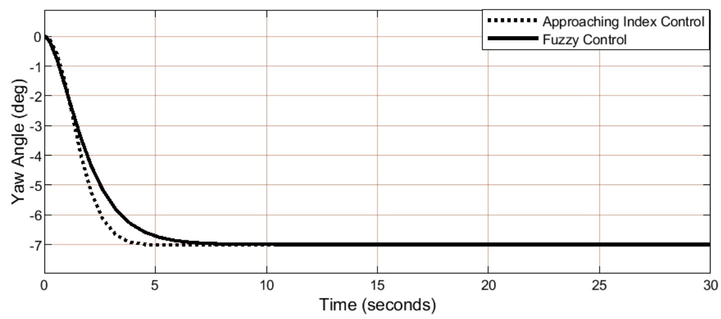
Fig.12. Control Effort of CubeSat Around Pitch Axis.

TABLE 4: Attitude Pitch Angle Using AISA and Fuzzy Controller

	AISA	Fuzzy
t_s	12.5 s	17.5 s
e_{ss}	0.17%	0.2%
T	0.35 m N.m	0.715 m N.m

From Fig.11, Fig.12, and TABLE 4 the simulation results of attitude pitch angle using the AISA controller and the fuzzy controller, it is clear that the AISA controller is faster in settling time and has better performance in accuracy than the fuzzy at the same torque effort. The control effort in fuzzy $T \cong 0.715\ \mathrm{mN.m}$ is higher than the control effort in ASIA $T \cong 0.35\ \mathrm{mN.m}$. The index switch of ASIA in the pitch axis is RS =35%, so the switch occurs at an attitude angle of $\theta = 1.4$ deg and a time of $t \cong 3.9$ sec.

Fig.13. Attitude Angle Around Yaw Axis



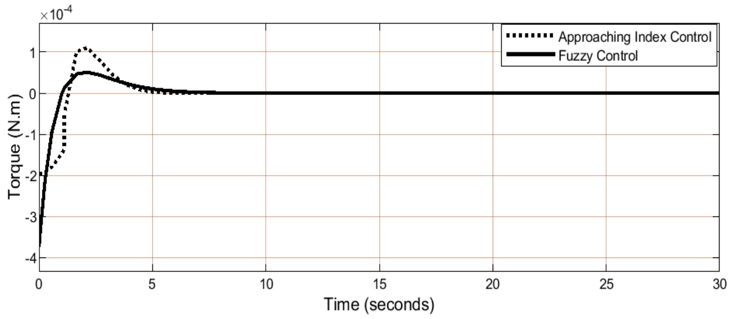


Fig.14. Control Effort of CubeSat Around Yaw Axis.

TABLE 5: Attitude Yaw Angle Using AISA and Fuzzy Controller

	AISA	**Fuzzy**
t_s	4.5 s	6.8 s
e_{ss}	0.001%	0.02%
T	-0.19 m N.m	-0.35 m N.m

From Fig.13 and Fig.14, the simulation results of attitude yaw angle using the AISA controller and the fuzzy controller, it is clear that the AISA controller is faster in settling time and has better performance in accuracy than the fuzzy at the same torque effort. The control effort in fuzzy $T \cong -0.35\ \text{mN.m}$ is higher than the control effort in ASIA $T \cong -0.19\ \text{mN.m}$. The index switch of ASIA in the yaw axis is R_S=35%, so the switch occurs at an attitude angle of $\psi = -3.1\ \text{deg}$ and a time of $t \cong 1.1$ sec,

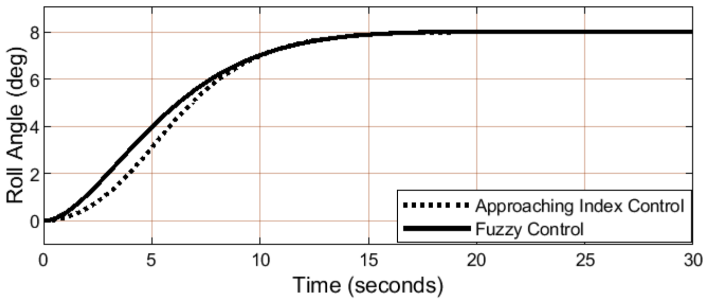


Fig.15. Attitude Angle for CubeSat

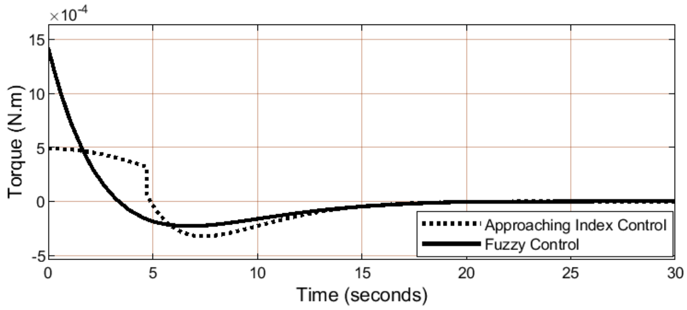
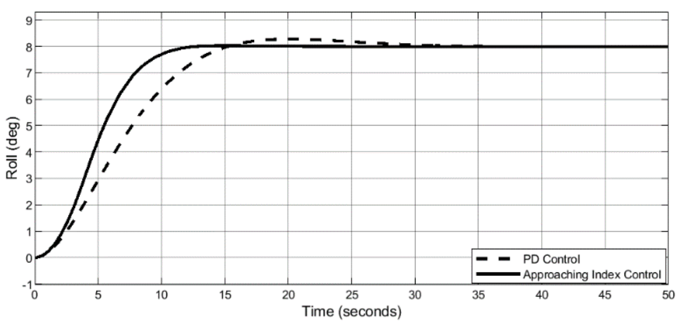


Fig.16. Control Effort of CubeSat

If the gains of the AISA controller changed to match the same performance of the fuzzy controller, it would be noticed that the control effort decreased by 66% compared to the Fuzzy control effort. The control effort in Fuzzy control is started at Torque $T = 1.4mN.m$ and in ASIA control $T = 0.48mN.m$ as shown in Fig.15 and Fig. 16.

Fig.17. Attitude Angle Around Roll Axis using PD and AISA



From Fig.17, the simulation results of attitude angle using the AISA controller and the PD controller, it is clear that the AISA controller is faster in settling time than the PD controller without overshoot, at the same control gains and torque effort. The settling time of the AISA controller (ts = 11.4s) is less than 65% of the settling time of the PD controller (ts = 32.7s).

5. CONCLUSION

In this paper, the AISA is used to perform controllers for attitude control systems. Then its performance compared with fuzzy controller. The AISA is a very simple algorithm that changes between two different controllers' parameter sets based on a predefined switching policy. Simulation results using linear equation of Euler's dynamics equation show a much better accuracy in attitude control system using the AISA controller and a reduction in settling time and control effort compared to the fuzzy controller. This type of controller has proven its effectiveness at various attitude angles.

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