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# Improved Reliability, Accuracy and Failure Minimization of spacecraft satellite architecture by using Fuzzy Logic

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**ABSTRACT**

This paper enlightens the functionality of the traditional PID controller in relation with the proposed intelligent controller based on fuzzy concepts for the supervision of the attitude of nonlinear spacecraft satellite architecture. The attitude being nonlinear in nature, is a major limitation for any practical space craft satellite system. This restricts the usage of conventional PID controller due to its high settling time with the dangerous oscillations and high peak overshoot, which in turn depreciates the performance of the system. Also, for the economic factors in terms of saving of on-board fuel is also a major requirement. This could be achieved by minimum time for control and response. This necessitates the fuzzy based intelligent controller which overdrafts this limitation.

Due to severe oscillations in transient period, PID controller produces a very high peak overshoot of greater than 80%, which is very dangerous to the system. The proposed fuzzy logic intelligent controller can efficiently remove the severe oscillations and provides very soft operation in transient conditions. Also, the steady state error is very minimum around -6.5%.

Hence, conventional PID controller should not be used for the attitude control of spacecraft which is nonlinear in nature. So, the proposed intelligent controller based on fuzzy logic ideology is highly preferable for the above problem.

***Index Terms***: Nonlinear attitude supervision, PID controller, Fuzzy based controller, Transient output investigation, MATLAB/Simulink

## 1. INTRODUCTION

The swift boost in intricacy of electronic parts and the requirement for handy low rating devices that have the potential to run in traumatic scenarios make the outlook of highly precision products demanding. To achieve great deal of assurance even under callous working scenarios hardware and computer programming fault-resistant outlook methodology is used.

In system reliability forecast system basic reliability and operational reliability is forecasted on the basis of the forecasted value of per unit contained in the model. It first, constructs system reliability flowchart containing series model, shunt model etc., and accordingly calculates process reliability. This paper makes investigative study on the concept of cumulative forecast of durability and reliability, and it is a huge accompaniment to the presented reliability forecast method.

The fuzzy logic control improvises the characteristics of a system by revising the inputs of that particular system according to the bunch of guidelines or rules, which indicates the working of the corresponding

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system. The system works or rather is controlled by the various principles of mechanical engineering, electrical engineering, chemical engineering or a mixture of any of these engineering trades. Fuzzy control removes the need of mathematical model and clearly relies on a particular set of rules that indicates the properties of a small portion of any system. At the end, the rules are binded together through the process of inference to inculcate the preferred response [1].

In this paper, we have depicted the fuzzy based intelligent controller for the supervision of an attitude of a spacecraft satellite system and its advantages over the traditional PID controller.

## 2. SATELLITE ATTITUDE CONTROL SYSTEM

A simplified but a practical model with an integrator scheme is having two poles at (0, 0) of s- plane to characterize a satellite scheme in space has been explained in various papers. This model enlightens the falling performance of a satellite after process and used to reveal the functional structure of satellite characteristics under distinguished situations all the way through this paper. This non-discrete model is logical and is embodied with an input sampler connected with Zero Order Hold (ZOH) and an analog to digital converter at its terminals so that a digital computer control is realizable.


**Figure 1: Model of spacecraft-satellite system**


**Figure 2: Input-Output relation of spacecraft-satellite system**

It includes ZOH (Zero Order Hold) transfer function also. It can be quoted clearly by the model shown in equation (1).

$$G(s) = \frac{\left(-e^{-Ts}\right)}{s^2} \tag{1}$$

Where, T = Total time for sampling = 1 × 10-4 Sec

The zero-order hold is an algebraic model of the non-ideal signal reformationwith the help of a traditional digital-to-analog converter. That means, it converts a discrete time signal into a continuous time signal by holding each sample portion for one sample interval. Reformation is the process of regaining continuous time signals from a sequence of given samples. Same set of samples can have different continuous time signals. Hence, reformation is not a unique phenomenon. Sample and hold is the function of holding every sample for a sampling time period T to create a signal reformation [2].

Attitude control refers to the utilization of the known measurements and a reference to manipulate the demanded torque that will make the equivalence between the reference value and measured state. The attitude control of rigid systems had become the priority over the last ten years. The significant applications are the attitude control of rigid spacecraft system and aircraft body. Spacecraft systems are required to show active and highly accurate sliding and indicating maneuvers that compels the spacecraft to swing at a very extensive amplitude path. These significant features necessitate the use of nonlinear spacecraft model. This nonlinear model is clearly indicated by Euler's dynamic formula, which is used to indicate the time progress of the rotating velocity vector and another equation which deals Kinematics and delivers the time derivatives of the direction angles with respect to rotating velocity vector. The significant factors responsible for any attitude control system are: Firstly, Prior angular rates must be damped utmost 2 hours after separation from launcher. Secondly, an orientation mode indicating towards earth's center must be present. The attitude must be supervised accurately [3].

## 3. MATHEMATICAL MODELING AND PROBLEM FORMULATION

The mathematical model of a non-linear spacecraft satellite system is given by dynamic equation and Kinematic equation [4].

The dynamic equation is a relation between moment of inertia, angular velocity, torque and angular acceleration. The torque acting on a satellite as per Euler is given by:

$$I\dot{w} + w \times Iw = T \tag{2}$$

The standardized equation for satellite dynamics can be developed with satellite inertia matrix Is, angular momentum of the wheels h, external torque Next. All these parameters are with respect to the satellite coordinate system [5].

$$\frac{d}{dt}(I_s w) + \dot{h} = N_{ext} - wI_s w - wh \tag{3}$$

Or

$$w = -I_s^{-1}(wI_s w) - I_s^{-1}wh - I_s^{-1}h + I_s^{-1}N_{ext} \tag{4}$$

Manipulating the cross product as a matrix operation using S(w)

$$S(w) = \begin{bmatrix} 0 & -w_3 & w_2 \\ w_3 & 0 & -w_1 \\ -w_2 & w_1 & 0 \end{bmatrix} \tag{5}$$

Using (5) in (4)

$$w = -I_s^{-1}S(w)I_s w - I_s^{-1}S(\mathrm{w})h - I_s^{-1}h + I_s^{-1}N_{ext} \tag{6}$$

The effective nonlinear dynamic model of the satellite is governed by the control torque in the body coordinate system Nctrl and is equal and opposite to rate of change of angular momentum of wheels. The combined satellite model with nonlinear dynamics and kinematics is shown in Figure 3 below.

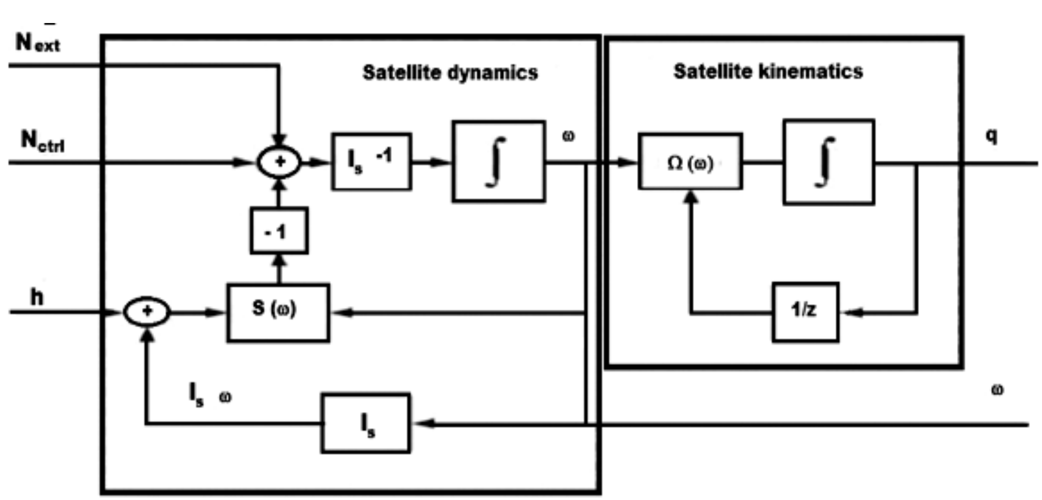


**Figure 3: Satellite model with nonlinear dynamics and kinematics**

$$h = -N_{ctrl} \tag{7}$$

Hence, (6) becomes

$$w = -I_s^{-1} S(w) I_s w - I_s^{-1} S(\mathrm{w}) h + I_s^{-1} N_{ctrl} + I_s^{-1} N_{ext} \tag{8}$$

The Kinematic equation is a relation between the attitude parameter to the angular velocity. The spacecraft attitude can be modeled given by:

$$q = \frac{1}{2}\Omega q = \frac{1}{2}\begin{bmatrix} 0 & w_3 & -w_2 & w_1 \\ -w_3 & 0 & w_1 & w_2 \\ w_2 & w_1 & 0 & w_3 \\ -w_1 & -w_2 & -w_3 & 0 \end{bmatrix} q \tag{9}$$

In order to decouple the effect of other terms with q4, (9) can be written as below:

$$\frac{d}{dt} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = -\frac{1}{2}\begin{bmatrix} 0 & -w_3 & w_2 \\ w_3 & 0 & -w_1 \\ -w_2 & w_1 & 0 \\ w_1 & w_2 & w_3 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} +$$

$$\frac{1}{2}\begin{bmatrix} q_4 & 0 & 0 \\ 0 & q_4 & 0 \\ 0 & 0 & q_4 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} \tag{10}$$

Manipulating the above equation, we get (11) as below:

$$\frac{d}{dt}\begin{bmatrix} g \\ q_4 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} -S(w) \\ -w^T \end{bmatrix} g + \frac{1}{2} q_4 \begin{bmatrix} I_{3X3} \\ 0 \end{bmatrix} w \tag{11}$$

If the wheel's axis is inclined with the satellite body coordinate system, then denoting the inertia of wheel by J, rotational velocity of the wheel by ww, torque by Nw and wheel momentum by h. Hence, mathematically we can write

$$h = \frac{d}{dt}(Jw_w) = N_w \tag{12}$$

The control torque on the satellite is given by:

$$N_{ctrl\_sat} = -h = -\frac{d}{dt}(Jw_w) \tag{13}$$

If the wheel is not inclined with the coordinate system of satellite body, the axis passing through the shaft of the wheel is adjusted with respect to the coordinate system of satellite body. The vector indicating about the angular momentum of wheel with respect to coordinate system of the satellite body is a major requirement [6]. The projection of angular momentum in all 3 directions, clearly indicate the components of momentum with respect to coordinate system of satellite body. The projection is a column matrix, whose direction cosines are given by (14).

$$\begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix} = \begin{bmatrix} a_{1w} \\ a_{2w} \\ a_{3w} \end{bmatrix} [h]_{w1} \tag{14}$$

The merged dynamic and kinematics equations (4) and (11), give the general nonlinear model for satellite angular travel, as given below.

$$\frac{d}{dt}\begin{bmatrix} w \\ g \\ q_4 \\ h \end{bmatrix} = \begin{bmatrix} I_s^{-1}(-S(w)I_s w - S(w)h + N_{ctrl} + N_{dist}) \\ -\frac{1}{2}S(w)g + \frac{1}{2}q_4 I_{3X3^w} \\ -\frac{1}{2}w^T g \\ -N_{ctrl} \end{bmatrix} \tag{15}$$

The major demerit about this nonlinear model is that the satellite architecture does not include the results of flexibility.

It should be clearly noted that the non-static model has architecture that is not dependent on the choice of coordinate system. As long as all the parameters are taken with respect to the same coordinate system, the composition of the equation will remain unchanged. The consequences caused by rotation of measurand and reference coordinate for the inertia factors are accomplished by rotating various parameters in the non-static equation [7].

## 4. SIMULATION

### 4.1. System Design with PID Controller

An approach extensively used in engineering control is PID controller. But the value selection for the Kp, Ki, Kd gains is constantly demanding. To select these values numerous tuning algorithms have been correlated, but still it is an important problem to choose particular algorithm for establishing PID gain values for the particular scheme for a particular process control [8].

Figure 4 shows the system with PID controller (16) shows the algebraic description of a general PID controller.

$$U(t) = K_p e(t) + \frac{K_p}{T_1}\int_0^t e(t)\,dt + K_p T_D \frac{de(t)}{dt} \tag{16}$$

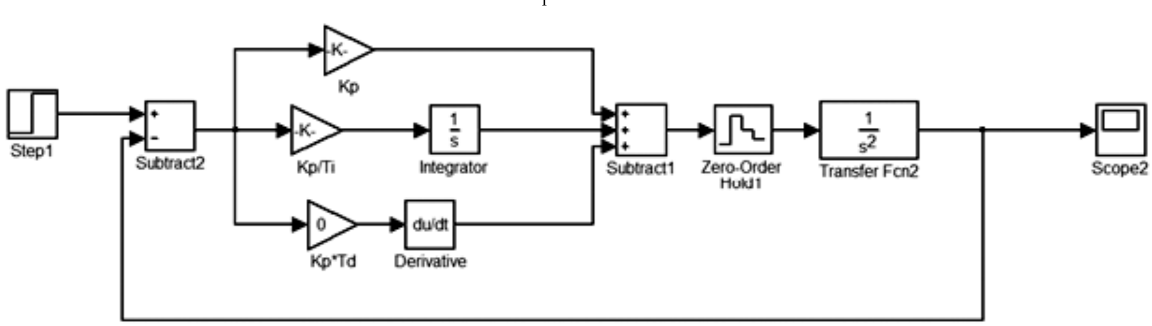


**Figure 4: System Design with PID Controller**

Where,

U(t) = Control force applied to the plant

KP = Proportional Gain

KI = $\frac{K_p}{T_1}$ = Integral Gain

KD = KP × TD = Derivative Gain.

We use P for faster response, I for static response and D for transient response. For D, we always look out for peak overshoots, rise time and other transient parameters which should be minimized. For I, static error is the major concern and it should be zero for a better response. The transients on the other way round should not be alarming. To reach steady state conditions at faster rate, PD-Controller and in order to minimize ESS, PI-Controller has been used. Whereas while using PID-controller, fast steady state conditions and minimum steady state error can be covered. Hence, selection of optimized combination of algorithms, controllers and tuning of gains can be done as per useful specifications [9].

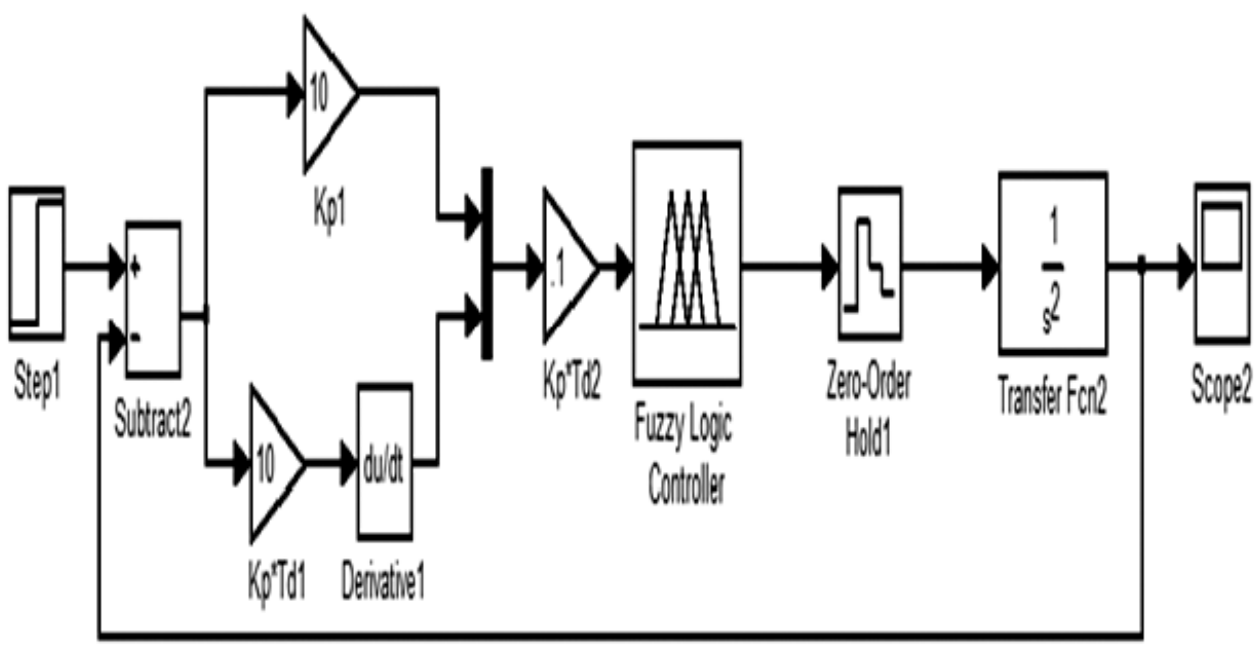


**Figure 5: System Design with Fuzzy Logic Controller**

Figure V shows the proposed design of intelligent system with fuzzy logic controller. Fuzzy controllers are known for absorbing the nonlinearities of the system and work well for the real system. They are very powerful techniques in the field of system control, especially when the systems have large uncertainties and strong nonlinearities [10]. Also the fuzzy controller is independent of the precise algebraic model of the controlled process. It approximates the plant's unknown dynamics. PID controllers are often incorporated into the programmable logic controllers (PLCs) that are used to control many industrial processes. Unfortunately, the PID meshes that are incorporated in rocket control system are in significant need of observation and adjustment since they can easily become improperly tuned due to the rocket specifications variations and operating scenario changes. There is an important requirement to create process for the auxiliary tuning of PID controllers. Hybridization of PID and fuzzy controller provides the beneficial sides of both categories [11].

## 5. RESULTS AND DISCUSSIONS

**Table 1**
**Effect of Increasing Gain**

| *Parameter (Gain)* | *Rise Time (Tr)* | *Overshoot (Mp)* | *Settling Time (Ts)* | *Error (Ess)* |
|---|---|---|---|---|
| KP | Fall | Rise | Small Change | Fall |
| KD | Minor Fall | Fall | Fall | No Change |
| KI | Fall | Rise | Rise | Fall Significantly |

The utilization of these KP, KI, and KD values will result in the changes in the actual output with respect to the desired output. In general, the correlation will be as per the Table.I. From the table, it is concluded that PD-Controller allows in reaching steady state conditions very fast, PI-controller helps in minimizing steady state error, and PID-controller covers all the merits of individual control actions. Hence, it is a choice of selecting proper combination of the controllers and the algorithm for tuning of the controller gains according to the desired characteristics.

### 5.1. PID Parameter Tuning Method

For setting up the values of KP, KI, and KD, a tuning method called Ziegler Nichols method has been used [12]. Using this method, calculate the value of Critical gain (KC) and Critical Time period (TC). After obtaining critical gain and critical time period, gain values of KP, KI, and KD can be calculated by using formulas enlisted in Table 2.

**Table 2**
**Ziegler-Nichols Tuning Formulas for PID Process Parameter Gains**

| *Parameter* | *Tuning Formula* |
|---|---|
| TI | $TI = \frac{T_c}{2}$ |
| TD | $T_D = \frac{T_c}{8}$ |
| Kp | $K_p = 0.6\ X\ K_C$ |
| KI | $K_I = \frac{K_p}{T_I}$ |
| KD | $K_D = K_p\ X\ T_D$ |

#### *5.1.1. System Design With Fuzzy Logic Controller*

In this section, we compare the performance of the PID controller and fuzzy logic controller for nonlinear satellite's attitude control. The time response of the system is the output of the closed loop system as a function of time [13]. However, we present one simulation that compares the response of the design with PID controller, as shown in Figure 4, to the response of the design with fuzzy logic controller, as shown in Figure 5. In addition, we compare the dynamic performance of the design with PID controller to the design with fuzzy logic controller on the basis of time response plot shown in Figure 6.

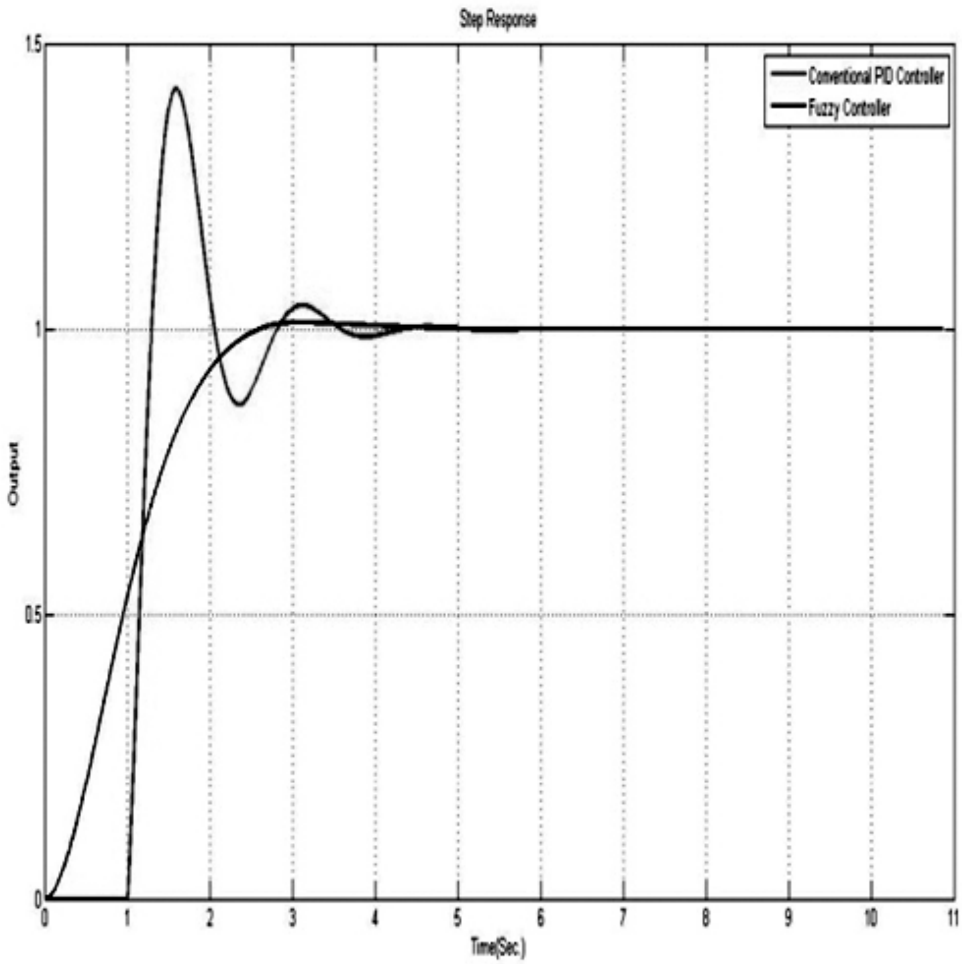


**Figure 6: Time Response Plot of design with PID Controller vs Fuzzy logic Controller**

These parameters are called as time domain specifications, can evaluate the effectiveness of proposed controller. These parameters are.

Rise Time (Tr)

Settling Time (TS)

Steady state error (ESS)

Overshoot (MP)

The ideal characteristics of system response should have the characteristics of abrupt rising, less delay time, fast settling, stability and zero steady state error [14]. On basis of these parameters, comparison has been tabulated as Table 3.

**Table 3**
**Comparison of various domain specifications**

| *Parameter* | *Conventional* | *Fuzzy* |
|---|---|---|
| Rise time | 1.15 | 0.93 |
| Peak time | 2.95 | 1.73 |
| Overshoot | 47% | 4% |
| Steady state error | 0 | 0 |

The performance of the two systems has also been compared on the basis of four error criteria namely Integral of error (IE), integral of average of error (IAE), integral of square of error (ISE), integral of time average of error (ITAE), integral of time square of error (IAE) and the results are tabulated in Table 4. [15]

**Table 4**
**Comparing Various Error Criteria**

| *Error* | *Conventional* | *Fuzzy* |
|---|---|---|
| IE | 1.008 | -0.001975 |
| IAE | 1.04 | 0.4343 |
| ISE | 0.6974 | 0.1719 |
| ITAE | 0.6353 | 0.05253 |
| ITSE | 0.7477 | 0.7315 |

## 6. CONCLUSION

In this paper, an intelligent controller is used based on the segmentation of fuzzy logic concepts for supervising attitude control system of a spacecraft which is nonlinear in nature. The following observations can be made from the results.

1) Due to severe oscillations in transient period, PID controller produces a very high peak overshoot of greater than 80%, which is very dangerous to the system.
2) The proposed fuzzy logic intelligent controller can efficiently remove the severe oscillations and provides very soft operation in transient conditions. Also, the steady state error is very minimum around -6.5%.

Hence, conventional PID controller should not be used for the attitude control of spacecraft which is nonlinear in nature. So, the proposed intelligent controller based on fuzzy logic ideology is highly preferable for the above problem.

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