ASSIGNMENT REPORT

ON

"Designing and Simulating a Fuzzy based control of Satellite Altitude"

BY

GROUP NO. – 38

NIPUN AGARWAL (2019A8PS0815P)
UDIT AGRAWAL (2019A8PS0814P)
DEEPESH BANSAL (2019A8PS0450P)

APRIL, 2022

Table of Content

Introduction

The geostationary satellite's location drifts owing to a range of factors pushing on it. In nature, these forces are additive. Because satellite communication relies heavily on line of sight, attitude (drift in position) must be managed. It is required to periodically ascertain the exact position of the satellite for this purpose. Once the satellite's location has been calculated, an appropriate correction can be performed using an appropriate attitude control system. A satellite's attitude can be controlled using a variety of approaches. Traditional approaches such as proportional, BangBang controllers, and so on are in use. These controllers have some drawbacks like mathematical complexity, inflexibility, slow response, etc. To overcome some of these drawbacks, fuzzy theory, and fuzzy controllers can give quicker control than standard ones.

The attitude control system determines and regulates a vehicle's orientation in space. An estimator state processes and filters the information given by attitude sensors. As a result, this signal is compared to a reference. The control algorithm will utilize the error between the estimated state and the reference to correctly activate the actuators in order to decrease or eliminate this error.

Generally, a satellite contains three translation motions vertical, horizontal and transverse, and three rotational motions pitch, yaw, and roll by controlling the aileron, rudder, and elevator. To reduce the complexity of analysis, the satellite is usually assumed as a rigid body, and satellite motion consists of a small deviation from its equilibrium flight condition. In addition, the control system of a satellite can be divided into two groups, namely **longitudinal** and **lateral** control. In longitudinal control, the elevator controls pitch or the longitudinal motion of the satellite system. The pitch of the satellite is controlled by an elevator which is usually situated at the rear of the satellite running parallel to the wing that houses the ailerons. Pitch control is a longitudinal problem, and this work presents the design of an autopilot that controls the pitch of a satellite.

This work presents an investigation into the development of pitch control schemes for the pitch angle of a satellite by using a fuzzy logic control. Performance of control strategy, PID, and fuzzy logic tuned PID controller with respect to the pitch angle of satellite longitudinal dynamics are investigated. Simulation is developed within MATLAB/SIMULINK for the evaluation of both control strategies.

Concept & Equation of Satellite Altitude Movement

This section provides a brief description of the modeling of pitch control longitudinal equation of satellite, as the basis of a simulation environment for the development and performance evaluation of the proposed controller techniques.

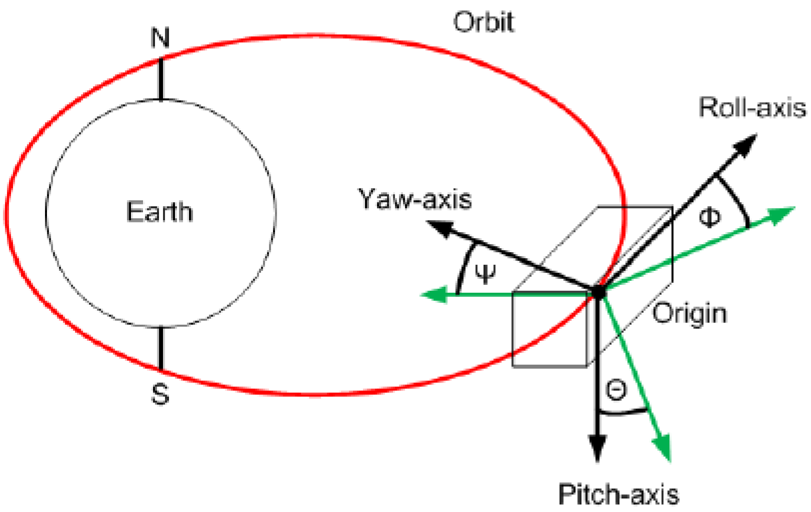

FIGURE 1 | Inertial, local coordinate system, and angles of the satellite

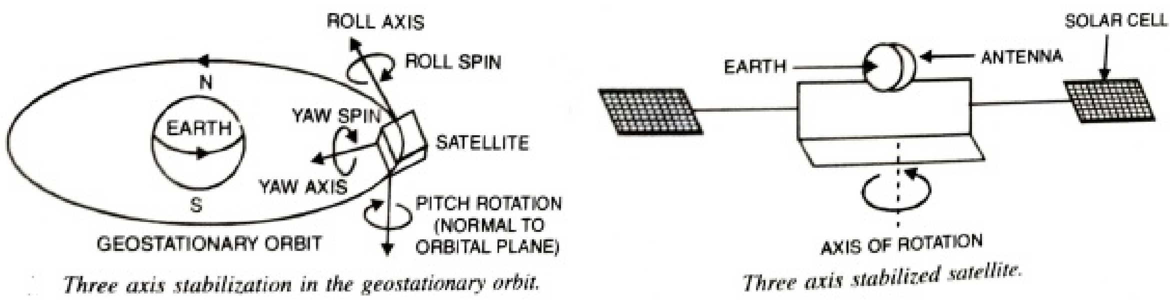

FIGURE 2 | Three-Axis Body Stabilization

The pitch control system considered in this work is shown in Figure 2. Defining some parameters for the satellite system.

X_b, $Y_{b,}$ and Z_b represent the aerodynamics force components. θ, $\varnothing$ and δe represent the orientation of the satellite (pitch angle) in the earth-axis system and elevator deflection angle. The aerodynamics moment components for roll, pitch, and yaw axis are represented as L, M, and N. The terms p, q, and r represent the angular rates about roll, pitch, and yaw axis while the terms u, v, and w represent the velocity components of roll, pitch, and yaw axis. The α and β represent the angle of attack and sideslip.

A few assumptions need to be considered before continuing with the modeling process. First, the satellite is a steady-state cruise at constant altitude and velocity, thus the thrust and drag are canceled out and the lift and weight balance out each other. Second, the change in pitch angle does not change the speed of a satellite under any circumstance.

The longitudinal stability derivatives parameter used are denoted in Table 1.

TABLE 1 | The longitudinal derivative stability parameters

Parameters	X-Force (S^{-1})	Z-Force (F^{-1})	Pitching Moment, (FT^{-1})
Rolling Velocities	X_u = -0.045	Z_u = -0.369	M_u = -0.369
Yawing Velocities	$X_W = 0.036$ $X_{W^\cdot} = 0$	$Z_W = -2.02$ $Z_{W^\cdot} = 0$	$M_W = -0.05$ $M_{W^\cdot} = 0$
Angle of Attack	$X_\alpha = 0$ $X_{\alpha^\cdot} = 0$	Z_α = -355.42 $Z_{\alpha^\cdot} = 0$	M_α = -8.8 $M_{\alpha^\cdot}$ = -0.8976
Pitching Rate	$X_a = 0$	$Z_a = 0$	M_a = -2.05
Elevator Deflection	$X_{\delta e} = 0$	$Z_{\delta e}$ = -28.15	$M_{\delta e}$ = -11.874

The dynamics pressure and dimensional derivative are Q = 36.8lb/ft2, Q_S= 6771 lb, Q_{Sc} = 38596ft.lb, (c / 2*U*0) = 0.016s.

These values are taken from the data from the IRNSS-1I satellite which was one of the satellites to join the IRNSS space segment. Launched on 12 April 2018, by ISRO.

The following set of dynamic equations including force and moment equations are determined to get a transfer function of the pitch control system. **[7].**

The system function thus used for pitch angle (i.e. altitude control) is given by :

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1.151S + 0.1774}{S^3 + 0.739\,S^2 + 0.921S} \tag{1}$$

PID Controller - Basics

The PID controller is the most common form of feedback. It was an essential element of early governors and it became the standard tool when process control emerged in the 1940s. In-process control, today, more than 95% of the control loops are of PID type, most loops are PI control. PID controllers are today found in all areas where control is used. The controllers come in many different forms. There are stand-alone systems in boxes for one or a few loops, which are manufactured by the hundred thousand yearly. Practically all PID controllers made today are based on microprocessors. This has given opportunities to provide additional features like automatic tuning, gain scheduling, and continuous adaptation.

By summarizing the key features of the PID controller, the PID algorithm is described by:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\,\frac{de(t)}{dt}\right) \qquad (2)$$

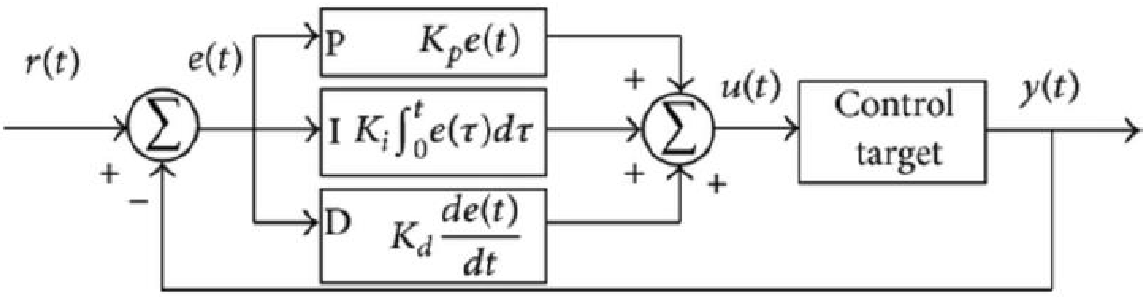

FIGURE 3 | PID Algorithm Visualization

Where y is the measured process variable, r is the reference variable, u is the control signal and e is the control error (e = y_{SP}− y). The reference variable is often called the set point.
The controller parameters are proportional gain K, integral time T_i, and derivative time T_d. The integral, proportional, and derivative parts can be interpreted as control actions based on the past, the present, and the future as illustrated in Figure 4.

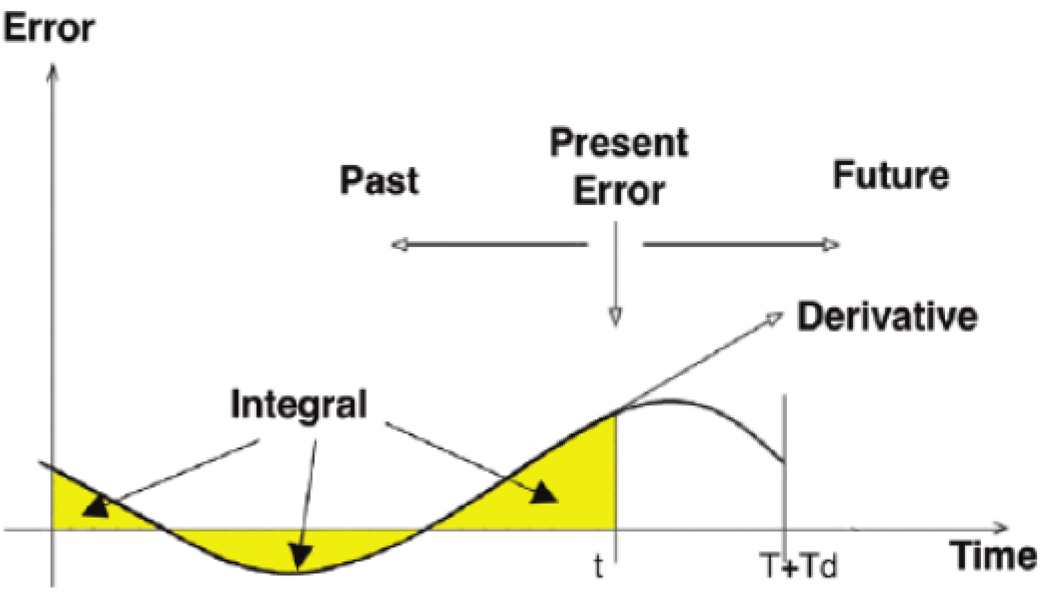

FIGURE 4 | PID Controller control action

PID controllers are probably the most commonly used controller structures in the industry. They do however present some challenges to controlling the system in the aspect of tuning for the gains required for stability and good transient performance. There are several rules used in PID tuning. One example is that proposed by Ziegler and Nichols in the 1940's.

If the limiting value of the gain for stability is K_{crit} and the time period of oscillation is P_{crit}, then the Ziegler-Nichols recommended controller settings are:

$$\begin{bmatrix} K_c = 0.5K_{crit} & for\ I\ control \\ K_C = 0.45K_{crit}\ , T_i = 0.83\ P_{crit} & for\ P\ + I\ control \\ K_C = 0.6\ K_{crit}, T_i = 0.5\ P_{crit}, T_d = 0.125\ P_{crit} & forP + I + D\ control \end{bmatrix} \quad (3)$$

Other popular tuning methods include:

- Cohen-Coon method
- Tyres-Luyben method
- Direct Synthesis based approach
- Trial and Error Method,
  etc…

Fuzzy Logic Controller

Fuzzy logic idea is like the human being's feeling and inference process. Unlike classical control strategy, which is a point-to-point control, fuzzy logic control is a range-to-point or range-to-range control. The output of a fuzzy controller is derived from fuzzifications of both inputs and outputs using the associated membership functions. A crisp input will be converted to the different members of the associated membership functions based on its value. From this point of view, the output of a fuzzy logic controller is based on its membership of the different membership functions, which can be considered as a range of inputs.
Computers can only understand either '0' or '1', and 'HIGH' or 'LOW'. Those data are called crisp or classic data and can be processed by all machines.

The idea of fuzzy logic was invented by professor L. A. Zadeh of the University of California at Berkeley in 1965. This invention was not well recognized until Dr. E. H. Mamdani, who is a professor at London University, applied the fuzzy logic in a practical application to control an automatic steam engine in 1974, which is almost ten years after the fuzzy theory was invented. Implementing the fuzzy logic technique in a real application requires the following three steps:

- Fuzzification: convert classical data or crisp data into fuzzy data or membership functions (MFs).
- Fuzzy Inference Process: combine membership functions with the control rules to derive the fuzzy output.
- Defuzzification: use different methods to calculate each associated output and put them into a table: the lookup table. Pick up the output from the lookup table based on the current input during an application.

Figure 5 illustrates the components of the fuzzy logic system

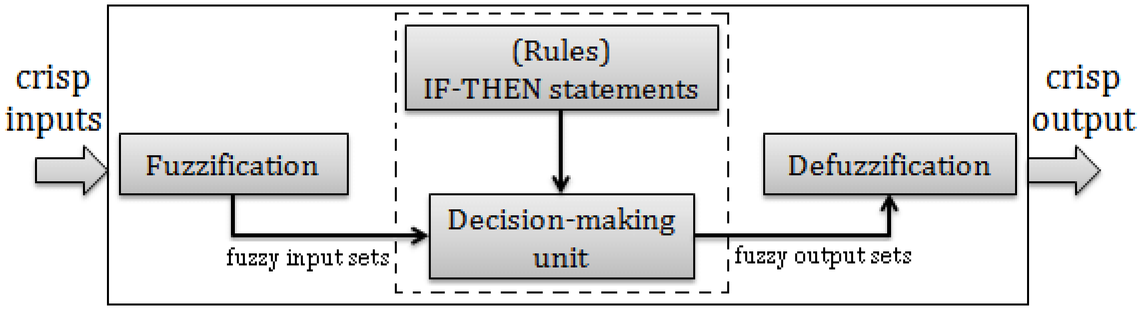

FIGURE 5 | The basic Configuration of Fuzzy logic controller.

Fuzzy inference can be defined as a process of mapping from a given input to an output using the theory of fuzzy sets.

- **Mamdani-style inference:** The most commonly used fuzzy inference technique is the so-called Mamdani method. In 1975, professor Ebrahim Mamdani of London University built one of the first fuzzy systems to control a steam engine and boiler combination. He applied a set of fuzzy rules supplied by experienced human operators. The Mamdani-style fuzzy inference process is performed in four steps: Fuzzification of the input variables, rule evaluation, aggregation of the rule outputs, and finally defuzzification.

- **Takagi-Sagano (T-S) style inference:** The heuristic technique of Mamdani fuzzy control mentioned in the above section lacks the mathematical rigor required to conduct a systematic analysis needed for flight approval although the nonlinear and robust nature of fuzzy control is suited for flight controls. The TS model retains the advantages of the fuzzy control, and it is also constructed in a mathematically rigorous method thus, stability and control analysis has been developed. In the T-S fuzzy model, each rule is represented by a linear time-invariant system, and the fuzzy inference is constructed such that the model is very close to the satellite nonlinear dynamics. While in the case of the T-S fuzzy model the output is computed with a very simple formula (weighted average, weighted sum), Mamdani fuzzy structure requires higher computational effort because of large number of rules to comply with defuzzification of membership functions. This advantage to the T-S approach makes it highly useful despite the more intuitive nature of Mamdani's fuzzy reasoning in terms of dealing with uncertainty.

Conventional PID Controller Design

In this section will be designed a conventional PID controller for satellite pitch control and described in detail. Initially, the PID is designed in a closed-loop system to control the pitch of a satellite. A PID is a generic control loop feedback mechanism widely used in industrial control systems and regarded as the standard control structure of the classical control theory.

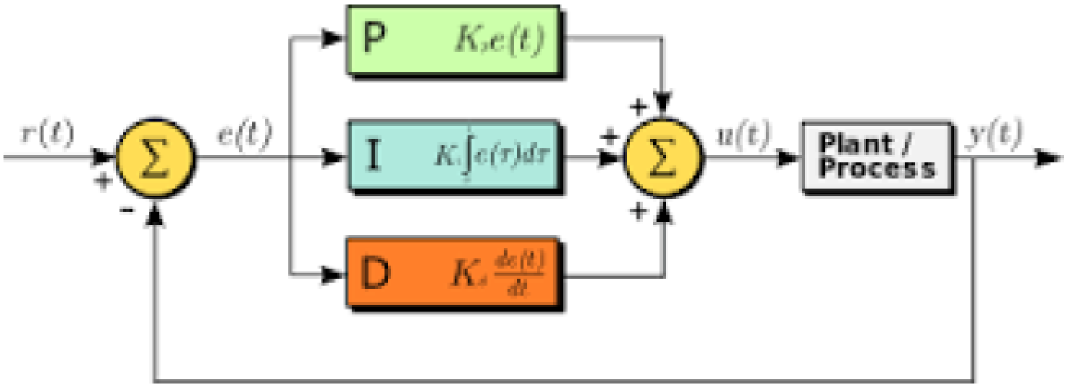

FIGURE 6 | Generic PID Configuration

The effects of increasing a parameter independently of each of the controller parameters, K_P, K_i, and K_d on a closed-loop system are summarized in Table 2.

TABLE 2 | Characteristics of P, I, and D controllers

Parameter Increase	Rise Time	Overshoot	Settling Time	Steady-state Error
K_P	↓	↑	Small change	↓
K_i	↓	↑	↑	Great reduce
K_d	Small change	↓	↓	Small change

In this project, the conventional PID controller has been implemented using an internal Z-N tuning method. In SIMULINK, it is very straightforward to represent and then simulate a mathematical model representing a physical system. The SIMULINK block diagram of the pitch control developed in Equation (1) with PID controller is shown in Figure 7. PID tuning is the process of finding the proper values of K_P, K_i, and K_d gains.

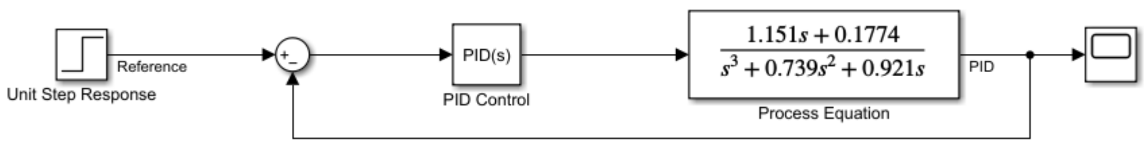

FIGURE 7 | Simulink block diagram of the system with PID controller

The PID control block in Simulink has its parameters (K_P, K_i, and K_d) tuned using Z-N method, as seen in Figure 8.

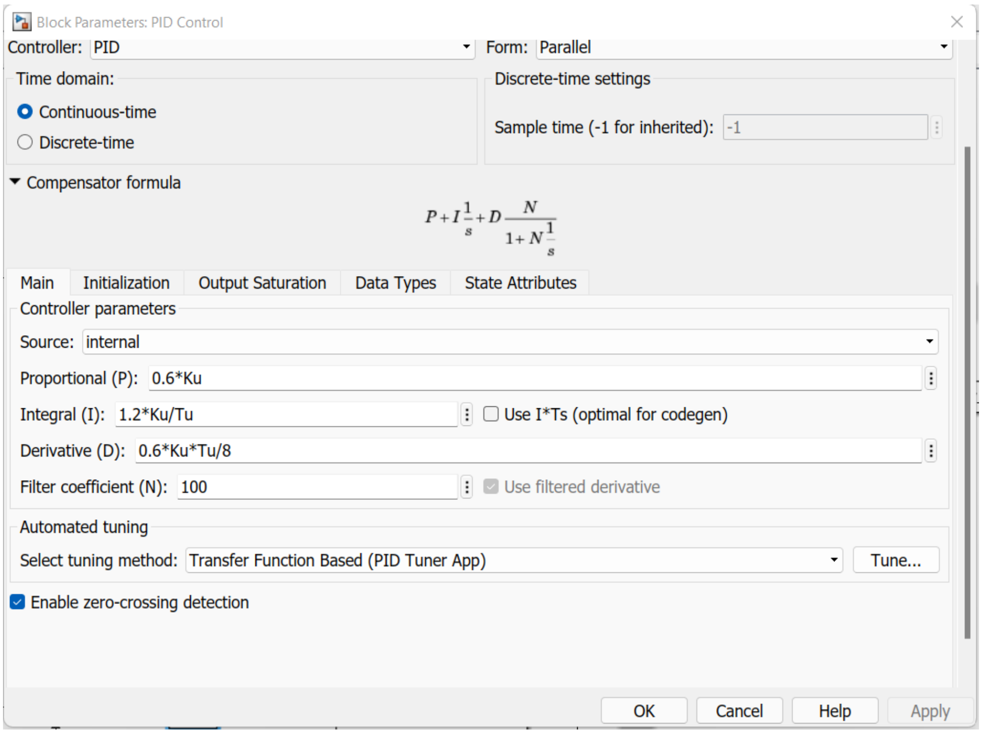

FIGURE 8 | PID control block with parameters tuning

PID Gain Scheduling using Fuzzy Logic

The implementation of Fuzzy logic control in this project is very different from the study that has been carried out earlier. In previous studies, the Fuzzy Logic-based control system was used to replace the PID controller in the system control model. But in our study, the implementation of Fuzzy logic is used as an aid to modify the gain parameters of the PID controller, to have a better performance as compared to the conventional PID controller. One of many benefits of using this type of fuzzy logic implementation in conjunction with PID Controller is that the fuzzy controller is not dependent on the process transfer function for any sort of physically possible plant transfer function the fuzzy-based control action is bound to give a better response.
In this study, we have implemented a study done on Fuzzy gain Scheduling of PID controllers **[8].**

The approach taken here is to exploit fuzzy rules and reasoning to generate controller parameters. It is assumed that K_p and K_d are in prescribed ranges [$K_{p.\ min}$, $K_{p.max}$] and [$K_{d.\ min}$, $K_{d.max}$]respectively.

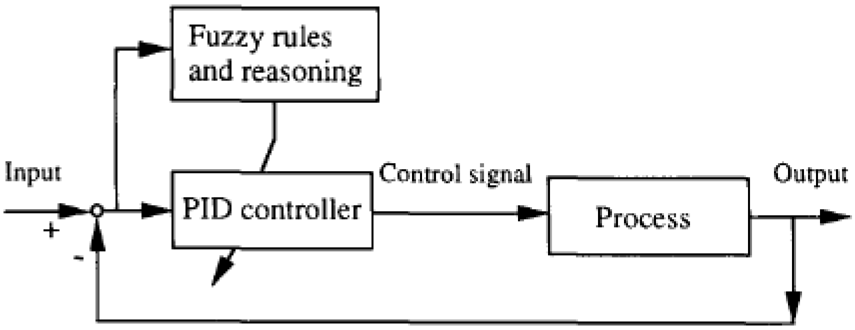

FIGURE 9 | PID control system with a Fuzzy gain scheduler

For convenience, Kp and Kd are normalized into the range between zero and one by the following linear transformation:

$$K'_p = (K_p - K_{p,\min}) / (K_{p,\max} - K_{p,\min})$$

$$K'_d = (K_d - K_{d,\min}) / (K_{d,\max} - K_{d,\min}). \tag{4}$$

In the proposed scheme, PID parameters are determined based on the current **error e(k) and its first difference Δe(k)**. The integral time constant is determined with reference to the derivative time constant

$$T_i = \alpha T_d$$

and the integral gain is thus obtained by

$$K_i = K_p / (\alpha T_d) = K_p^2 / \alpha K_d$$

The input to the fuzzy controller is the error rate e(k) and the first derivative of error rate Δe(k). The output of the fuzzy system is the proportional gain (K_p'), derivative gain (K_d'), and constant factor α.

The membership functions used for the inputs and the outputs are as follows:

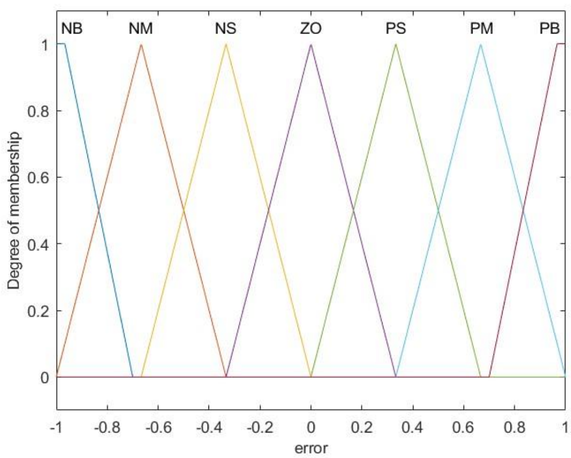

FIGURE 10 | Membership function for e(k)

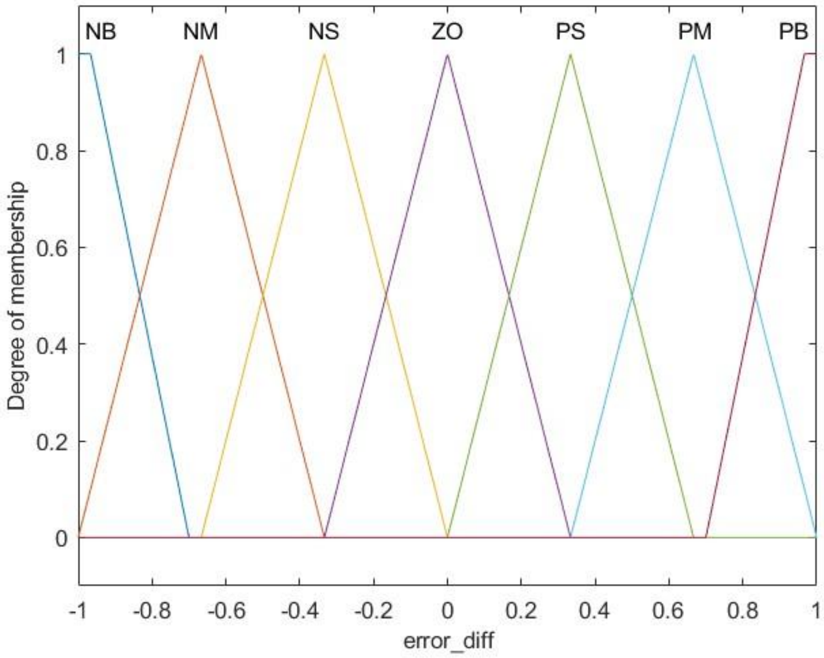

FIGURE 11 | Membership function for Δe(k)

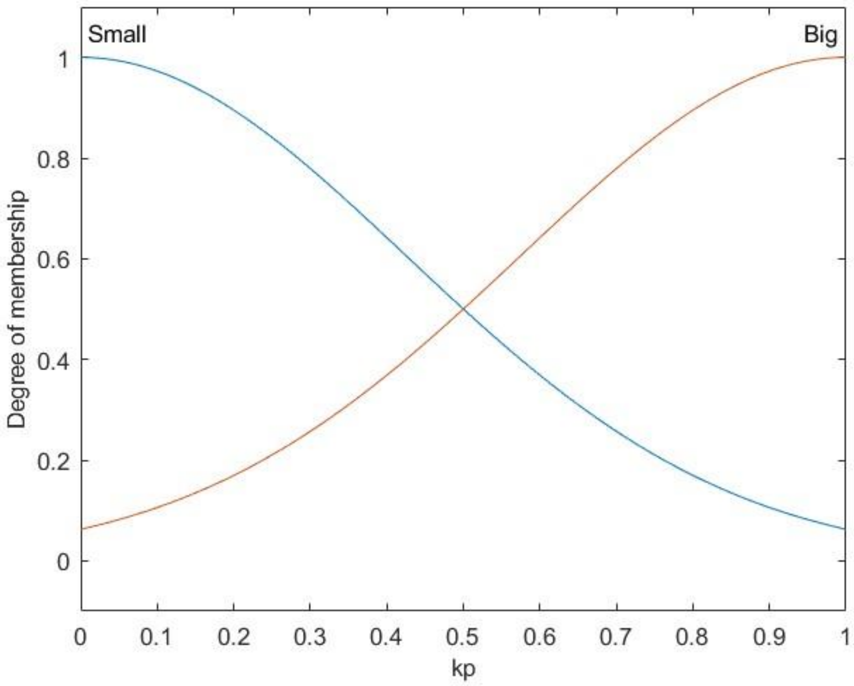

FIGURE 12 | Membership function for K_p'

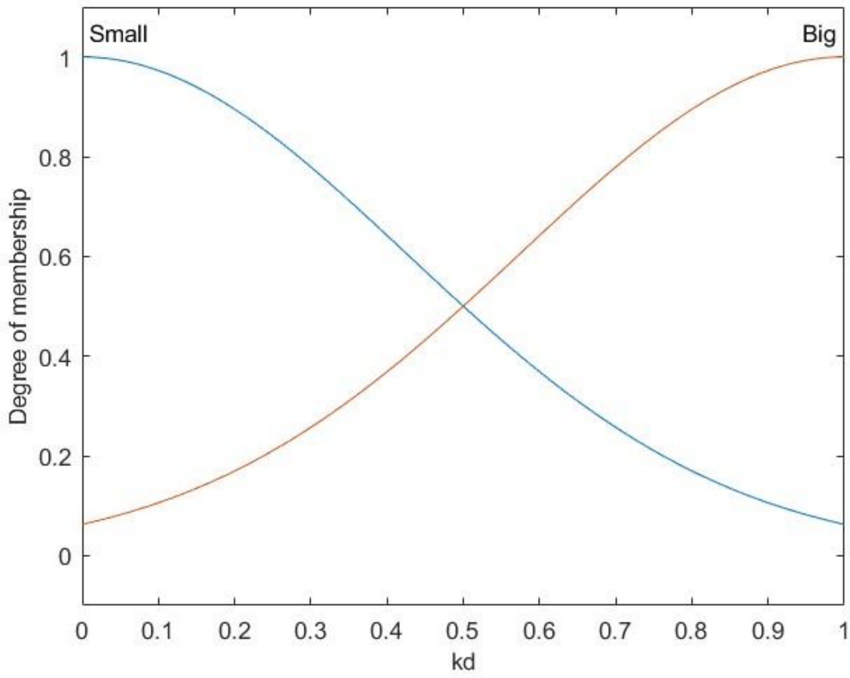

FIGURE 13 | Membership function for K_d'

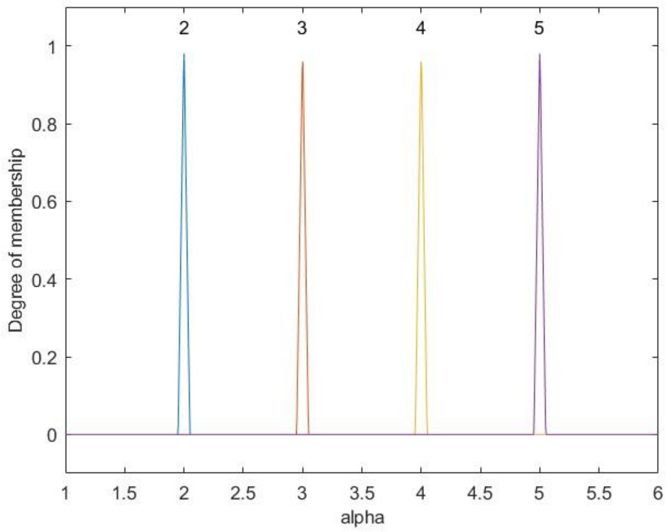

FIGURE 14 | Membership function for alpha(α)

The range of e(k) and Δe(k) is from [-1 1]. The range of output K_p' and K_d' ranges from [0 1]. While the values of $\boldsymbol{\alpha}$ are in the set [2 3 4 5].

Following tables show the Fuzzy logic rules for output:

TABLE 3 | Fuzzy Tuning Rules for K_p'

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
$e(k)$	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

TABLE 4 | Fuzzy Tuning Rules for K_d'

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
$e(k)$	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

TABLE 5 | Fuzzy Tuning Rules for alpha (α)

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
$e(k)$	ZO	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

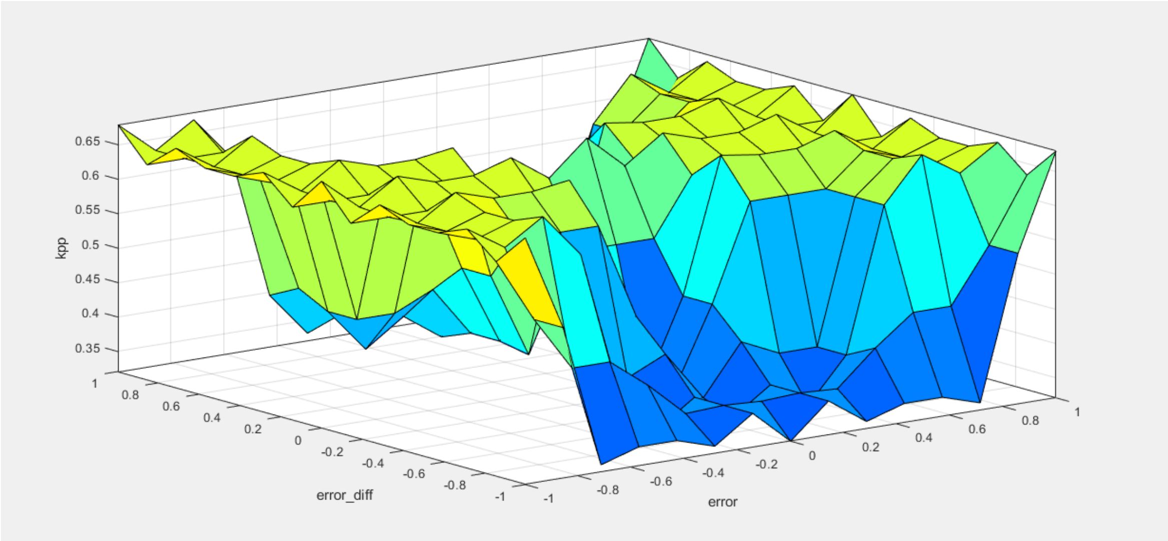

FIGURE 15 | Surface plot for K_p'

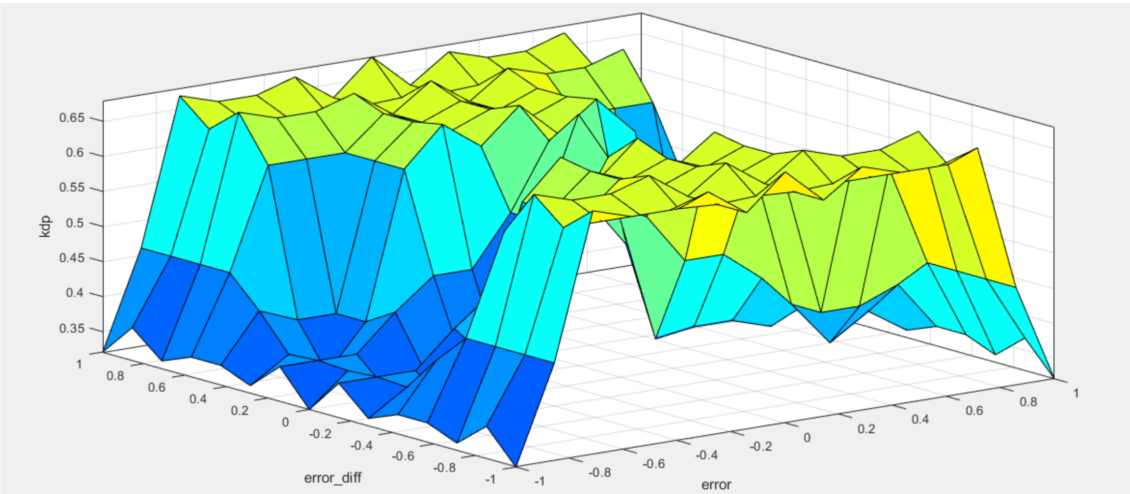

FIGURE 16 | Surface plot for K_d'

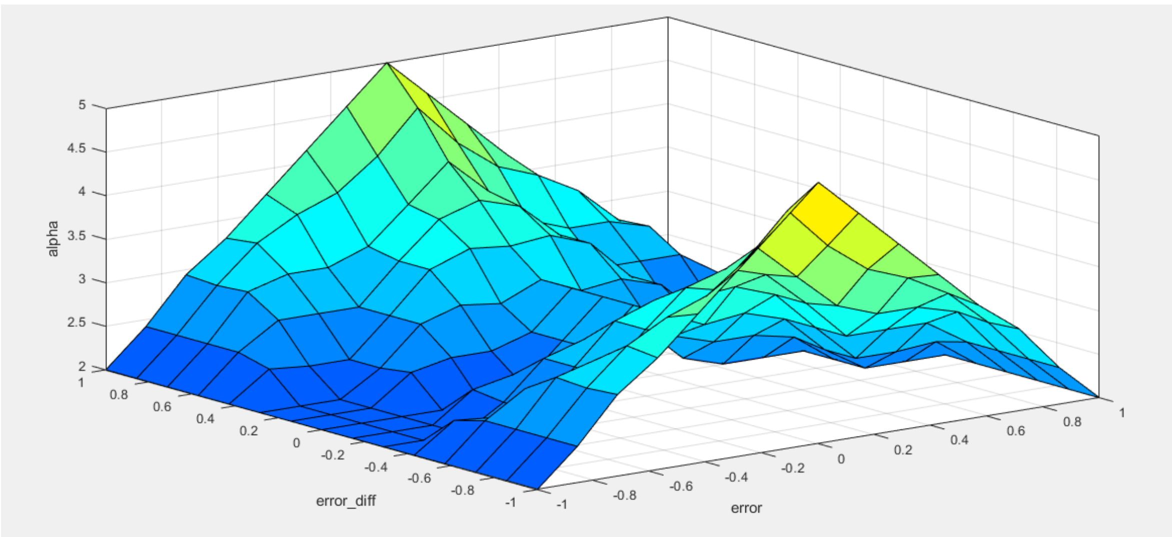

FIGURE 17 | Surface plot for alpha (α)

Results

In this section, the proposed control schemes are implemented and the corresponding results are presented. The conventional PID and FLC controllers are simulated using MATLAB /SIMULINK model R2022a. The simulation results of pitch attitude were obtained under different cases.

- **System Response without Controller:** Using the MATLAB code, the responses of open and close loop of systems are shown in Figure 18.

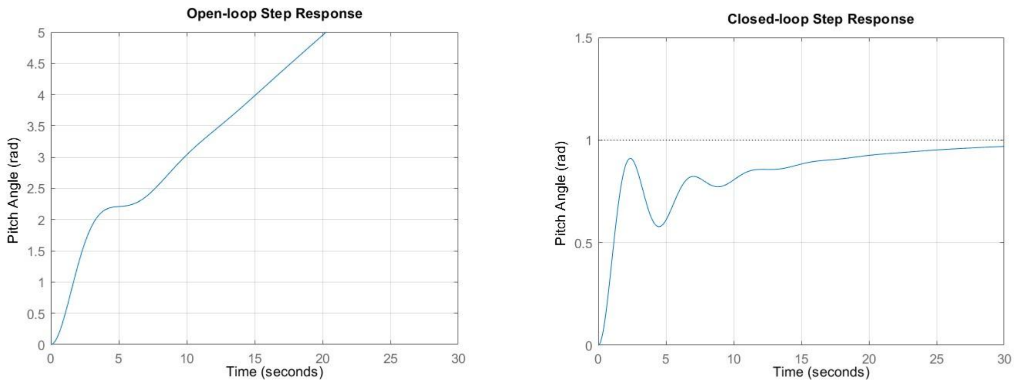

FIGURE 18 | Open and Close loop response without controller

Examination of the above plot indicates that the open-loop system is unstable for a step input, that is, its output grows unbounded when given a step input. The close loop characteristics are rise time =1.788 sec, settling time =35.0896 sec, overshoot = 0, peak = 0.200 rad, peak time = 98.7611 sec.

- **System Response with PID Controller and Fuzzy Logic Tuned PID Controller:** As indicated earlier, the PID controller (without fuzzy logic) has been tuned using Z-N Method.

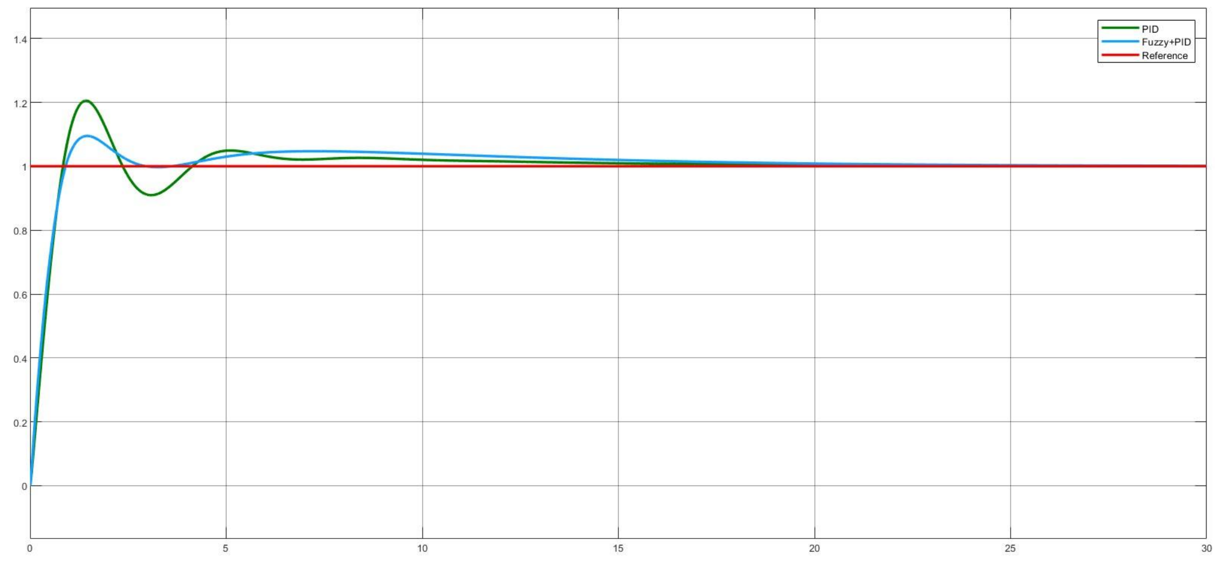

FIGURE 19 | Performance of PID, Fuzzy+PID Controller for unit step response

TABLE 6 | Summary of controller's performance characteristics

Step Response Characteristics	**Conventional PID Controller**	**Fuzzy Logic tuned PID Controller**
Rise Time	0.6384 sec	0.6637 sec
Settling Time	9.8651 sec	14.4760 sec
Settling Min	0.9092	0.9018
Settling Max	1.2052	1.0949
Overshoot	20.4304 %	9.3576 %
Undershoot	0 %	0 %
Peak	1.2052	1.0949
Peak Time	1.43 sec	1.46 sec

Discussion

From the study performed on the altitude control of a satellite using conventional PID Controller, and Fuzzy Logic based PID controller, it can be seen that the Fuzzy Logic-based controller archives a better performance in terms of Peak Overshoot. Where the other parameters like the peak time, and rise time is similar as compared to the conventional PID controller. The only area where Fuzzy based controller's performance is inferior to the conventional PID controller is settling time.

Conclusion

In this study, the conventional PID controller and Fuzzy based PID controller was developed to control the pitch angle of a satellite. Modeling is done on a satellite pitch angle control and a fuzzy controller is proposed successfully. The proposed control schemes have been implemented within a simulation environment in MATLAB /SIMULINK. Pitch control of a satellite is a system that requires a pitch controller to maintain the angle at its desired value. Based on the results, the system responses indicate the performance of the pitch control system using PID-fuzzy logic controller has been improved and satisfied compared to conventional PID controller.

Future Work

The possible future work on this topic could be to develop a fuzzy control system by using interval type 2 fuzzy logic controllers to tune the disturbance rejection of the pitch autopilot system in satellite. Also, the parameters of the fuzzy controller could be optimized using non-conventional optimization techniques like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Ant Colony Optimization (ACO), etc.

References

1. Wu, S-F., et al. "Fuzzy logic based attitude control of the spacecraft X-38 along a nominal re-entry trajectory." *Control Engineering Practice* 9.7 (2001): 699-707.
2. Valdez, Fevrier, Juan Carlos Vazquez, and Fernando Gaxiola. "Fuzzy dynamic parameter adaptation in ACO and PSO for designing fuzzy controllers: the cases of water level and temperature control." *Advances in Fuzzy Systems* 2018 (2018).
3. Chu, Cheng-Wei, et al. "Design of self-heating test platform for sulfide corrosion and oxidation based on Fuzzy PID temperature control system." *Measurement and Control* 54.5-6 (2021): 1082-1096.
4. Gomes, Willer, and Evandro Marconi Rocco. "Design of a fuzzy PID controller for application in satellite attitude control system." *Proc. Workshop on Space Engineering and Technology*. 2012.
5. Hazza, Ali Ahmed Hani, M. Y. Mashor, and Mohammed Chessab Mahdi. "Fuzzy PD and Fuzzy $\text {PD}+\mathrm {I} $ Controllers Design for Attitude Control of Innovative Nano-Satellite." *2021 IEEE 17th International Colloquium on Signal Processing & Its Applications (CSPA)*. IEEE, 2021.
6. Pokle, S. B., K. D. Kulat, and A. G. Keskar. "MATLAB Simulation of a Fuzzy Controller for Attitude Control of a Geostationary Satellite." *IETE Journal of Education* 45.4 (2004): 203-209.
7. Ali, Fawaz Elsiddig Ahmed. *Fuzzy Control System Design for an Aircraft Attitude in Longitudinal Motion*. Diss. Sudan University of Science and Technology, 2017.
8. Zhao, Zhen-Yu, Masayoshi Tomizuka, and Satoru Isaka. "Fuzzy gain scheduling of PID controllers." *IEEE transactions on systems, man, and cybernetics* 23.5 (1993): 1392-1398.

DECLARATION

All the members of Group 38, accept this report and the presentation entirely, without any conflict of interest.

The following task was undertaken by each group member in the completion of this project.

NIPUN AGARWAL (2019A8PS0815P) – Research on the topic, modeling of controllers, simulation and verification of results, tuning parameters of the model, comparison between controllers, Report preparation, and presentation preparation.

UDIT AGRAWAL (2019A8PS0814P) - Report preparation, and presentation preparation

DEEPESH BANSAL (2019A8PS0450P) - Report preparation, and presentation preparation