Adaptive fuzzy logic controller with direct action type structures for InnoSAT attitude control system

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Abstract. This study proposes an adaptive fuzzy controller for attitude control system (ACS) of Innovative Satellite (InnoSAT) based on direct action type structure. In order to study new methods used in satellite attitude control, this paper presents three structures of controllers: Fuzzy PI, Fuzzy PD and conventional Fuzzy PID. The objective of this work is to compare the time response and tracking performance among the three different structures of controllers. The parameters of controller were tuned on-line by adjustment mechanism, which was an approach similar to a PID error that could minimize errors between actual and model reference output. This paper also presents a Model References Adaptive Control (MRAC) as a control scheme to control time varying systems where the performance specifications were given in terms of the reference model. All the controllers were tested using InnoSAT system under some operating conditions such as disturbance, varying gain, measurement noise and time delay. In conclusion, among all considered DA-type structures, AFPID controller was observed as the best structure since it outperformed other controllers in most conditions.

1. Introduction
Development of space technology is one of the main symbols of technological progress in the modern society. Hence, as a developing country, Malaysia is not left behind in becoming one of the countries involved in exploring the fields of satellite technology. With the general success of previous CubeSAT missions, it has inspired the development of new nano-satellite called Innovative Satellite (InnoSAT). Figure 1 shows the external view of InnoSAT.
Generally, the satellite receives interference from various phenomena that occurred in space. These phenomena can disturb the satellite position at any time and condition. Therefore, it is necessary to control the orientation and maintain the stability of satellite by attitude control system (ACS). In order to control satellite's ACS, there are various structures of Fuzzy PID controller that can be applied [1]. However, this paper only focuses on direct action (DA) type structures, which are Fuzzy PI, Fuzzy PD and Fuzzy PID. The DA structures have been chosen because of the simplicity of their operation and their effectiveness for most process.

2. Literature review
Proportional Integral Derivative (PID) controller is well established in classical control systems and it is often used as a benchmark against other types of controllers. Since PID controllers are linear, it is not suitable for strongly nonlinear systems. Thus combination of Fuzzy PID controller is highlighted as a substitute to the classical PID controllers in such cases [1]. There are more types of Fuzzy PID controller structure such as direct action, fuzzy gain scheduling and hybrid type [2]. The direct action type can also be divided into three categories based on the number of inputs, which are single, double and triple as depicted in Figure 2.

![Figure 2. Classification of fuzzy PID controllers](image)

Among Artificial Intelligent (AI) methodologies, Fuzzy Logic Controller (FLC) is the most suitable method for satellite system and accommodates the high level of human knowledge and capabilities in countering uncertain problems. It is seen possible to use FLC properties in developing an expert real time control system for the application of satellite that was exposed to non-probabilistic uncertainties such as sun flare and time dependent noises in measurement [3, 4]. Guan et al. [5] proposed a direct adaptive fuzzy control for stabilizing satellite attitude using Takagi-Sugeno model. The membership function and parameters of rules in fuzzy logic system were adjusted to have on-line adaptive ability. The adaptive law is derived based on Lyapunov method. The satellite also uses three-axis reaction wheel in keeping the attitude of the satellite in stable condition. Even so, the author has also stated that Fuzzy controller does not possess self-learning ability. This makes it hard to deal with uncertainty of the system as well as external disturbance effectively. Simulation results have shown that the proposed control law was able to effectively resist the perturbation and obtain better dynamic performances. The author has proven that direct adaptive fuzzy control does not require mathematical model of controlled object and has faster response as well as small steady state error. Therefore, it is concluded that direct adaptive fuzzy control is capable to deal with the real-time application of satellite attitude. Also, it is believed that this approach is robust towards uncertainty that is affecting the satellite.

In other application, Obaid [6] used different types of controllers structure to analyze and evaluate the performance of the position control for an AC motor. They are used three controllers to achieve the purpose: Classical Proportional-Integral-Derivative (CPID), Fuzzy like Proportional-Derivative (FPD), Fuzzy-like Proportional-Integral (FPI) and Fuzzy-like Proportional-Integral-Derivative (FPID). From the design and simulation results, it can be concluded that FPD provides the system response with zero overshoot. FPI, on the other hand, eliminates the error with a high overshoot and FPID gets the better response for the controlled system.
3. Methodology
For this research, Model Reference Adaptive Control (MRAC) had been applied as the control scheme while PID controller as the adjustment mechanism in the controllers' structure as presented in [7]. The proposed control scheme in Figure 3 does not estimate the plant parameters but directly estimates the controller parameters [8]. The MRAC scheme consists of two loops, which are inner and outer loops. The inner loop is the representation of a common feedback signal where the output signal from the process will be the input of the controller. The outer loop consists of the adjustment mechanisms that function to regulate error signal and signal back to the controller. In MRAC scheme, one block of stabilizer is added. It acts as a lead compensator in order to stabilize the InnoSAT plant. In addition, it can improve the stability of the system when the satellite is exposed to disturbance. In this condition, different controller structure will use different stabilizer because AFLC will be tested until the best parameters of stabilizer are found. The desired system's behavior is specified by a reference model and the parameters of the controller are adjusted based on the error model following error, \( e_m \) defined by:

\[
e_m(t) = y_m(t) - y(t)
\]

where \( y(t) \) is the InnoSAT output.

![Figure 3. Modified model reference adaptive control scheme](image)

The equation for a general second order linear continuous time reference model is given by the following differential equation [8]:

\[
y_m(t) = a_{m_1}y_m(t - 1) - a_{m_2}y_m(t - 2) + b_{m_1}r(t - 1) + b_{m_2}r(t - 2)
\]

where \( r(t) \) is reference input and \( y_m(t) \) is reference model output. In this research, parameter values for MRAC that have been chosen are \( a_{m_1} = 1 \), \( a_{m_2} = 0.15 \), \( b_{m_1} = 0.15 \) and \( b_{m_2} = 0 \). Mechanism for selecting the parameters in the MRAC can be obtained by the root locus stability.

This research aims to improve the performance of FLC by proposing a new adjustment mechanism for all controller structures, which is similar to PID error. This controller is selected because of it is well known, simple, easy to use and does not require the plant model [9, 10]. In order to obtain a good performance, PID error adjustment mechanism will adjust the UOD boundaries accordingly based on the way that the adaptation is performed, which is governed by Equation 3.

\[
\dot{\theta}(t) = 0.5e(t) + 0.01\Sigma e(t) + 0.4\Delta e(t)
\]

For these applications, trial and error techniques are used in selecting the parameter for \( \dot{\theta}(t) \). A different format and value of \( \dot{\theta}(t) \) is required for different objectives. The formulation depends on the system design criteria, which includes minimizing overshoot and settling time. The combinations of
these parameters are found to be adequate for most stable systems. Equations below show how the parameter UOD is adjusted by $\hat{\theta}(t)$:

$$f = f_0 + \hat{\theta}(t)$$  \hspace{1cm} (4)
$$m = m_0 + \hat{\theta}(t)$$  \hspace{1cm} (5)
$$n = n_0 + \hat{\theta}(t)$$  \hspace{1cm} (6)
$$s = s_0 + \hat{\theta}(t)$$  \hspace{1cm} (7)
$$l = l_0 + \hat{\theta}(t)$$  \hspace{1cm} (8)

where the origin parameter of UOD is defined as $[f_0, m_0, n_0, s_0, l_0]$ in range of -4 to 4 and adjusted by $\hat{\theta}(t)$ to produce new parameter of UOD, which is defined as $[f, m, n, s, l]$. The parameters of the controller need to be continuously adjusted in order to force towards a stable behaviour of satellite system.

For this study, only two methods in DA type will be applied, which are double and triple inputs, since single input is known to be not practical to reduce the overshoot and settling time [11]. They are three controllers had been proposed, which are Fuzzy PI (FPI) and Fuzzy PD (FPD) for double input structure, and conventional Fuzzy PID (FPID) for triple input structure. Each controller has their own advantages and disadvantages along with their own setting parameters. The main purpose of this study is to find out which controller structure is more effective. The structure of the double input fuzzy PD controller is presented in Figure 4. The input controller with scaling gain is derived using Equation 9 and Equation 10. Fuzzy PD controller outputs, $u(t)$ function as the control command in stabilizing the attitude of the satellite. In order to gain better performance, the scaling gains of the input Fuzzy PID must be tuned properly.

$$E = \left(k_p \times e(t)\right)$$
$$\Delta E = \left(k_d \times \Delta e(t)\right)$$  \hspace{1cm} (9)

where $k_p$ and $k_d$ are proportional and derivative gains, respectively. Chosen value for the parameters were $k_p = 0.01$ and $k_d = 0.99$, which were suitable since the Fuzzy PD controller demonstrated the performance required by the specification. Performance of Fuzzy PD controller was greatly influenced by the changes of scaling gains of the controller inputs. The impact of setting the value of scaling gain can be summarized as follow [12]:

a) The speed response of the system will improve when the input scaling gain, $k_p$ for $e(t)$ is increased. However, there is limitation to the amount of increment of $k_p$. If the value is too large, the overshoot will be large and the settling time could be longer (increase).

b) As for $k_d$ for $\Delta e(t)$, the bigger input scaling gain, the smaller overshoot will be obtained. The input scaling gain, $k_d$ is believed to have significant effect in reducing overshoot. However, this will cause the system to be slow in response. Each fuzzy parameter is tuned manually in suitable range of values.

It is rather difficult for a Fuzzy PD type controller to remove the steady state error and hence Fuzzy PI type controller is seen as more practical in real applications [13]. Fuzzy PI controller system also has two inputs like a Fuzzy PD controller but it has integral input $\int e(t)$ as in Figure 5. The integral input is defined in Equation 11. All parameters such as fuzzy set, UOD, membership function and rule are the same as Fuzzy PD controller.
The chosen value is considered suitable since an increase in value of $k_i$ may cause large overshoot and even make the system unstable [14]. These parameters are tuned manually with a small value to make sure the system remains stable. Then, the control signal for input controller is obtained by:

$$\Sigma E(t) = k_i \times \Sigma e(t)$$  \hspace{1cm} (11)

where $k_i$ is integral gain which equals to 0.01.

Although a fuzzy PI controller is able to improve steady state performance, it is known to give poor performance in transient responses especially for higher order systems [15]. On the other hand, Fuzzy PD controller often finds it difficult to remove the steady state errors in many cases. Hence, it is better to combine and construct a Fuzzy PID when the goal cannot be achieved by using only Fuzzy PD or Fuzzy PI type controller as shown in Figure 6. This is the main reason why the conventional fuzzy PID was built and that is to overcome this drawback. The conventional Fuzzy PID controller requires three inputs, which are error, change of error and integral of error. However, only one error is used where change of error and total of error are derived from the original error.

Meanwhile $\phi(t)$, $\theta(t)$ and $\Psi(t)$ are the outputs from InnoSAT plant for roll, pitch and yaw axes. The discrete models of three axes InnoSAT plants with small Euler angle such as proposed by [16]:

$$\phi(t) = 2 \times \phi(t-1) - \phi(t-2) + K_p (t) \times 15.29 \times \left( u_{\phi} (t-1) + u_{\phi} (t-2) \right) + 15.29 \times \left( u_{d\phi} (t+1) + u_{d\phi} (t-2) \right)$$  \hspace{1cm} (12)

$$\theta(t) = 2 \times \theta(t-1) - \theta(t-2) + K_p (t) \times 10.04 \times \left( u_{\theta} (t-1) + u_{\theta} (t-2) \right) + 10.04 \times \left( u_{d\theta} (t+1) + u_{d\theta} (t-2) \right)$$  \hspace{1cm} (13)

$$\Psi(t) = 2 \times \Psi(t-1) - \Psi(t-2) + K_p (t) \times 15.1 \times \left( u_{\psi} (t-1) + u_{\psi} (t-2) \right) + 15.1 \times \left( u_{d\psi} (t+1) + u_{d\psi} (t-2) \right)$$  \hspace{1cm} (14)

where $K_p(t)$ is a varying gain, $u_s(t)$ is controller output and $u_d(t)$ is constant disturbance torque.

4. Simulation results

The simulation results for InnoSAT plant based on direct action (DA) type for step and square input signal are shown in Figure 7. The controllers involved in the DA type are Adaptive Fuzzy PD (AFPD), Adaptive Fuzzy PI (AFPI) and Adaptive Fuzzy PID (AFPID). From the figure, it shows all controllers can follow the model reference output smoothly. Table 1 represents the numerical value for the step response analysis of all controllers. From here, it is observed that performance of AFPID controller is
better than the performance of AFPD and AFPI, which indicates that AFPID is faster in time response than both controllers. Based on simulation results from adaptive neuro controller for satellite attitude control system [16], it is still acceptable for the percent overshoot to be more than 10% in the satellite system.

The simulation results indicated that the overshoot was reduced after the first cycle of square wave input with unity gain. It was thus proven that the proposed adjustment mechanism worked efficiently to reduce the error between output reference and actual output system. Based on this result, it showed that AFPID controller had provided the best response with small overshoot for all axes as compared to AFPD and AFPI controllers. AFPD controller had presented better tracking performances than AFPI.

### Figure 7. Performance comparison for InnoSAT Euler model with unity gain

| System Characteristics | Adaptive Fuzzy PD | Adaptive Fuzzy PI | Adaptive Fuzzy PID |
|------------------------|-------------------|-------------------|-------------------|
|                        | Roll (ϕ) | Pitch (θ) | Yaw (Ψ) | Roll (ϕ) | Pitch (θ) | Yaw (Ψ) | Roll (ϕ) | Pitch (θ) | Yaw (Ψ) |
| Rise Time (s)          | 9.96    | 11.36   | 10.00   | 10.83   | 11.54   | 10.89   | 8.36    | 8.91    | 8.37    |
| Delay time (s)         | 6.86    | 7.50    | 6.90    | 6.75    | 6.82    | 6.83    | 5.42    | 6.10    | 5.46    |
| Settling Time (s)      | 97.46   | 94.17   | 97.70   | 131.16  | 81.41   | 131.34  | 79.58   | 68.57   | 79.38   |
| Overshoot (%)          | 34.73   | 30.20   | 35.04   | 41.12   | 31.91   | 41.42   | 13.69   | 16.04   | 13.87   |
| Negative Overshoot (%) | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       |

### Table 1. Step response analysis of direct action type controllers
based on tuning parameter of scaling gain. AFPI, on the other hand, had the slowest response due to
the presence of integral action where only small values of integral action could be used since larger
value could increase the time response and cause oscillation to occur. However, the overshoot for all
controllers had decreased slightly during the second cycle.

In square wave input response, the performance of the controller was evaluated based on the mean
square error (MSE). MSE is defined as the average of the squared errors between actual and estimated
readings in a data sample. The equation for calculating the MSE value can be written as:

\[
MSE = \frac{1}{n} \sum_{t=1}^{n} (y_m(t) - y_p(t))^2
\]  

(15)

where \(y_m(t)\) is the desired value implied by an estimator, \(y_p(t)\) is the true value of the quantity being
estimated and \(n\) is the number of data used for simulation. Smallest value of MSE will be considered
as the best performance. Table 2 shows the result of MSE for DA type controllers with unity gain. It
can be observed that AFPID controller obtained the smallest value of MSE for all axes.

Table 2. MSE for direct action type controllers with unity gain

| Controller | Roll (\(\phi\)) | Pitch (\(\theta\)) | Yaw (\(\Psi\)) |
|------------|----------------|-----------------|--------------|
| AFPD       | 0.0129         | 0.0141          | 0.0132       |
| AFPI       | 0.0126         | 0.0099          | 0.0129       |
| AFPID      | 0.0027         | 0.0042          | 0.0028       |

During the simulation process, the controllers were further tested by adding varying gain, noise,
disturbance and delay as shown in Figure 8 until Figure 10. The range of signal for high gain was from
1 till 1.5 for time between 0 s and 500 s, while range of low gain from 1 till 0.5 for time between 501 s
till 1000 s. Figure 11 represents the simulation results where the proposed control design methods
were able to follow the reference input signal successfully even with the presence of varying gain
effect. At high gain, it seems that all controllers were capable of following the reference input but at
700 s, a slight oscillation occurred due to the controllers not able to cope with the lowest valley of low
gain.

Next, the controller was subjected with measurement noise as shown in Figure 12. The result points
out that all of the DA type controllers were capable of handling noise signals and could maintain their
stability with small oscillation. Figure 13 shows the output response of InnoSAT system with 5% of
step disturbance. Here, AFPI and AFPD controllers showed the large deviation at the beginning and
the ending of the disturbance where the amplitude reached up to 50% and above for three axes. As for
the AFPID controller, the results showed that the deviation was a quarter than that of AFPI and tend to
be consistent for all three axes.

Figure 8. Varying gain

Figure 9. Measurement noise at the plant output
A sample time delay with value of 1 was introduced to the system in order to present the effect of delay, which normally will occur in real time. Based on Figure 14, the overall output systems tend to follow the reference input smoothly. It is somewhat difficult to distinguish the performance of the controllers in the effects of delay because the output responses only had small occurring changes where the overshoot and negative overshoot were slightly increased. Thus, MSE analysis is important to counter this situation by displaying the results such in Table 3. Based on Table 3, it clearly shows that AFPID controller outperformed the other controllers for all axes.
Figure 13. Performance comparison for InnoSAT Euler model with disturbance

Figure 14. Performance comparison for InnoSAT Euler model with delay

Table 3. MSE for direct action type controllers with delay

| Controller | Mean Square Error (MSE) |
|------------|------------------------|
|            | Roll (\(\phi\)) | Pitch (\(\theta\)) | Yaw (\(\Psi\)) |
| AFPD       | 0.0162              | 0.0167              | 0.0165          |
| AFPI       | 0.0153              | 0.0120              | 0.0157          |
| AFPID      | 0.0040              | 0.0057              | 0.0040          |

5. Conclusion
From the analysis that has been done, it was found that InnoSAT system with AFLC is suitable for all cases. Simulations and analyses of DA type have shown that the performance of dynamic positioning system can be substantially improved from Adaptive Fuzzy PI (AFPI), Adaptive Fuzzy PD (AFPD) and Adaptive Fuzzy PID (AFPID) where the output system has shown the capability in tracking the reference model closely. By comparing the DA type controllers, the performance of AFPID controller has shown a good result for ACS where the controller has proven its capability in tracking step and square input reference. As conclusion, the application of the AFPID controller is selected as the best controller in DA type since this controller is able to control the movement of satellite along with three axes stabilization technique that consist of roll, pitch and yaw axes.

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