Predictive Fuzzy Logic Controller for Agile Micro-Satellite

A. Bellar, M.K. Fellah, A.M. Si Mohammed, M. Bensaada, L. Boukhris

***Abstract*—**This paper presents the use of the predictive fuzzy logic controller (PFLC) applied to attitude control system for agile micro-satellite. In order to reduce the effect of unpredictable time delays and large uncertainties, the algorithm employs predictive control to predict the attitude of the satellite. Comparison of the PFLC and conventional fuzzy logic controller (FLC) is presented to evaluate the performance of the control system during attitude maneuver. The two proposed models have been analyzed with the same level of noise and external disturbances. Simulation results demonstrated the feasibility and advantages of the PFLC on the attitude determination and control system (ADCS) of agile satellite.

***Keywords*—**Agile micro-satellite; Attitude control; fuzzy logic; predictive control

I. INTRODUCTION

THE orientation requirements of a satellite are determined by its mission: telecommunications, optical imagery, scientific research, and meteorology to name a few. The mission also dictates the orientation of various satellite hardware components. Solar arrays are oriented toward the sun, thermal radiators are pointed at deep space, and antennas are pointed at their intended targets. A satellite's ability to orient its mission critical hardware components, as well as its payload, are all incumbent upon the performance of the spacecraft's ADCS.

Active attitude determination, in short, is the satellite's attitude measurement compared to a mission driven desired value. The difference between the attitude measurement and the desired value is the satellite's attitude error. The purpose of the ACS is to generate a corrective torque that will null this error. Because external disturbances will occur, and because both measurements and corrections will be imperfect, the corrective cycle will continue indefinitely [1]. Reaction wheels are a common choice for active spacecraft attitude control. For accuracy and moderately fast manoeuvrability, reaction wheels are the preferred attitude control system (ACS) because they allow continuous and smooth control while inducing the lowest possible disturbance torques [2]. In the mode of control, an electric motor mounted to the spacecraft spins a freely rotating wheel; as the reaction wheel changes its rate of rotation in one direction it causes the spacecraft to rotate in the opposite direction.

The electric motor rotates the wheel in response to a correction command computed as part of the spacecraft's feedback control loop [1].

An extensive research was done to design attitude of the satellites using classical control techniques. However these types of controllers have a limited capability and they are usually linear and require an accurate model. The proportional integral derivative (PID) can work well for first and second order system but for system with long time delays, large uncertainties and harmonic disturbances a more sophisticated control is needed [3], [4].

For nonlinear problems, many existing experiments have demonstrated that a FLC has good performance in dealing with the additive noise. As a result, fuzzy control is usually applied to a complex system whose dynamic model is not well defined or not available at all. In addition to handling nonlinear problems, the fuzzy control can also enhance the robustness of system. However, when it comes to certain other situations, such as large delay, the control performance of the FLC is deteriorated. An alternative solution to these problems is to adopt a predictive control [5]. The design of the PFLC is initially started with the designation of Basic FLC with two inputs and single output system. After that, a Predictive FLC is designed to compensate the effects of time delay which occurs in the satellite system. The predictor is a one step-ahead predictor which estimates the required control at the next sampling time and applies to the system at current sampling time.

Our work focused particularly on the use of the predictive fuzzy logic control approach applied to the actuators used in practice, and the extended Kalman filter (EKF) to estimate the overall attitude [6]. We explain one of the ways to control the attitude of the satellite using predictive fuzzy logic control method.

In order to test the effectiveness of the PFLC and its robustness in the presence of disturbances, as application, we used an agile satellite, three reaction wheels along the roll, pitch and yaw axis for which we will be developed this controller.

II. SATELLITE ATTITUDE DYNAMICS

The angular momentum of a spacecraft may be written as [7]:

$$\mathbf{H} = \mathbf{I}\boldsymbol{\omega}_{\mathrm{B}}^{\mathrm{I}} + \mathbf{h} \tag{1}$$

Where **I** is the inertia tensor, $\boldsymbol{\omega}_{\mathrm{B}}^{\mathrm{I}}$ is angular velocity vector in the body fixed coordinate frame, and **h** is the total angular momentum exchange devices. According to the Newton's 2nd law, the rotational equations of motion of such a spacecraft may be written in the body fixed frame as [7]:

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$$\mathbf{I}\dot{\boldsymbol{\omega}}_{B}^{I} + \boldsymbol{\omega}_{B}^{I} \times \mathbf{I}\boldsymbol{\omega}_{B}^{I} = \mathbf{T}_{c} + \mathbf{T}_{ext} \tag{2}$$

Where $\mathbf{T}_c$ is the control torque, and $\mathbf{T}_{ext}$ is the sum of other external torques acting on the spacecraft (i.e. gravity gradient torque, solar radiation pressure, etc.). The control torque for a spacecraft controlled using momentum exchange devices may be written as:

$$\mathbf{T_c} = -\dot{\mathbf{h}} - \omega \times \mathbf{h} \tag{3}$$

Where $\dot{\mathbf{h}}$ is the angular momentum exchange device. Additional differential equations that relate body rates to the attitude parameters (i.e., quaternion, Euler angles, etc.) are also needed to describe the spacecraft attitude.

The rate of change of the quaternion is given by [7]

$$\dot{\mathbf{q}} = \boldsymbol{\Omega}\ \boldsymbol{\omega}_{B}^{o} \tag{4}$$

$$\boldsymbol{\Omega} = \frac{1}{2}\begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{bmatrix} \tag{5}$$

Where $\boldsymbol{\omega}_{B}^{o} = [\omega_{ox}\ \omega_{oy}\ \omega_{oz}]^{T}$ is body angular velocity vector referenced to orbital coordinates.

The angular body rates referenced to the orbit coordinates can be obtained from the inertially referenced body rates by using the transformation matrix **A** given by [7]:

$$\boldsymbol{\omega}_{B}^{O} = \boldsymbol{\omega}_{B}^{I} - \mathbf{A}\,\boldsymbol{\omega}_{0} \tag{6}$$

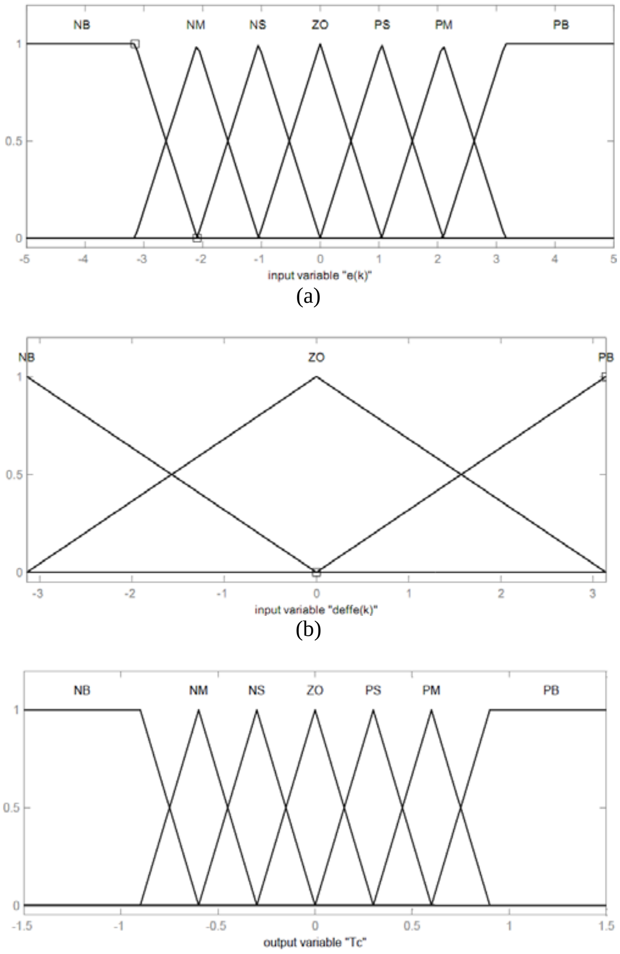
III. DESIGN OF PREDICTIVE FUZZY LOGIC CONTROLLER

A. Fuzzy logic controller

Fuzzy logic control is introduced by Mamdani based on Lofti Zadeh's [8] earlier development of linguistic approach and system analysis on fuzzy sets [9]. A fuzzy logic attitude controller has been developed where seven fuzzy labels: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZO),...., Positive Big (PB) have been defined for the input-output variables. The FLC system has two inputs, Angle error **e**(k) and its first difference Δ**e**(k) and one output, **T**c(k), the torque control to the satellite, as shown in Fig. 1. Also, 21 control rules were used which are shown in Table I.

TABLE I
FUZZY CONTOL RULLES

e(k) / Δ**e**(k)	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	Z	PS	PM	PB
Z	NB	NM	NS	Z	PS	PM	PB
PB	NB	NM	NS	Z	PB	PB	PB



(a)

(b)

(c)

Fig. 1 Membership functions used in FLC for (a) error e(k), (b) change of error Δe(k) , and (c) command Tc

B. Predictive Fuzzy Logic Controller

Since we assume a one-step delay in the satellite system, the predictive FLC needs a one-step ahead predictor. This predictor predicts the error values at (k+1) as $\mathbf{e}_p(k+1)$ and the change of error as $\Delta\mathbf{e}_p(k+1)$. Control signal at current instant k is computed as $\mathbf{T}c_p(k+1)$ as one-step ahead control and derived through the FLC. Fig. 2 shows the Predictive FLC system.

The control input to the satellite is one step ahead and this reduces the effect of inherent delay within the satellite system.

The predictive errors, $\mathbf{e}_p(k+1)$ and $\Delta\mathbf{e}_p(k+1)$, are computed by following equations [10]:

The error at the k instant is:

$$e(k) = \theta_r(k) - \theta(k) \tag{10}$$

The predicted attitude is

$$\theta_p(k+1) = \theta(k) + [\theta(k) - \theta(k-1)] \quad (11)$$

The predictor error and the change in predicted error can be written as:

$$e_p(k+1) = \theta(k+1) - \theta_p(k+1)$$

$$(12)$$

$$\Delta e_p(k+1) = e_p(k+1) - e(k)$$

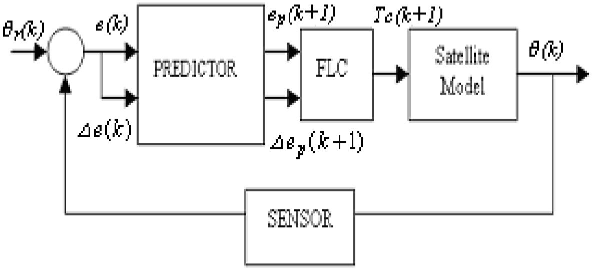


Fig. 2 Predictive FLC

IV. SIMULATION RESULT

The results presented in this section were obtained with a simulator that implements the dynamics of the satellite using C code, MATLAB and SIMULINK. A 98° inclination, circular orbit at an altitude of 650 km was used during the simulation tests, the following moment of inertia matrix is assumed.

$$\mathbf{I} = \begin{bmatrix} 33 & 0.0 & 0.0 \\ -0.25 & 34 & 0.0005 \\ 0.1 & 0 & 32 \end{bmatrix} \text{kgm}^2$$

The magnetic moment in the orthogonal X, Y and Z-axes was assumed to be equal to 10 Am^2 each. An IGRF model was used to obtain the geomagnetic field values.

We simulate 2 orbits and we compute the Euler angles root mean square error (RMSE) for the last orbit. Extended Kalman filter (EKF) quaternion version is used to estimate the full attitude from magnetometer and sun sensor measurement.

The estimated roll and pitch angle for two angle referenced are shown in Fig. 3 and 4, a 30° roll, 30° pitch and 0° yaw slew attitude maneuver is commanded, it can be seen that performance of the PFLC controller is better then the FLC in term of convergence .

Fig. 5 shows the roll angle error for a attitude reference [30 0 0]°, it can be seen from Table II that the magnitude of RMSE is approximately 0.42° using FLC and 0.19° using PFLC.

For a attitude reference [0 30 0]°, the pitch angle error is shown in Fig. 6 and from Table III, it can seen that the magnitude of RMSE is 0.43° using FLC and 0.23° using PFLC.

The system is subjected to an additional pseudorandom noise level of 2%. The roll angle error is shown in Fig. 7. Fig. 8 present the roll angle error in control phase damping of thruster disturbances for firing of 30 sec at 7000 sec. It can be observed that PFLC provides better tighter control over the conventional FLC. It also shows that APFLC is able of handling noise signals while minimizing the error and maintaining a stable responsive control rather than FLC.

TABLE II
ERROR COMPILATION (ATTITUDE REFERENCE [30 0 0] DEG)

	RMSE using FLC	RMSE using PFLC
Roll (°)	0.2008	0.1453
Pitch (°)	0.1950	0.0788
Yaw (°)	0.3189	0.0886
	Magnitude of error	Magnitude of error
Angles (°)	0.4241	0.1874

TABLE III
ERROR COMPILATION (ATTITUDE REFERENCE [0 30 0] DEG)

	RMSE using FLC	RMSE using PFLC
Roll (°)	0.2962	0.1272
Pitch (°)	0.1780	0.1563
Yaw (°)	0.2493	0.1071
	Magnitude of error	Magnitude of error
Angles (°)	0.4259	0.2282

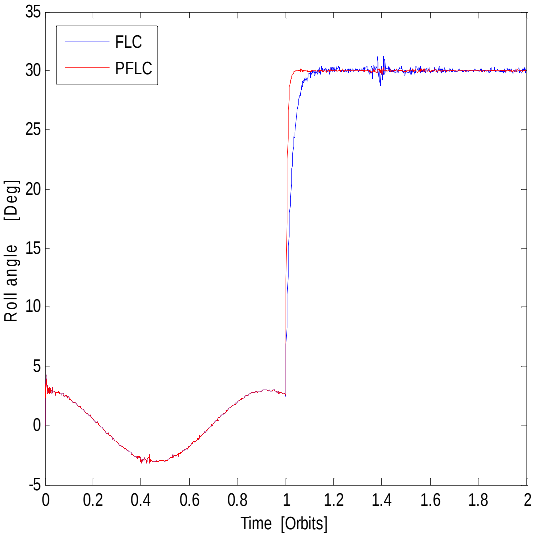


Fig. 3 Estimated roll angle during reaction wheel phase control

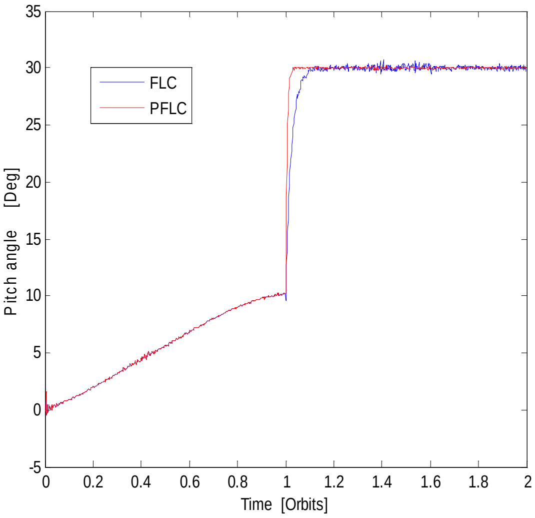


Fig. 4 Estimated pitch angle during reaction wheel phase control

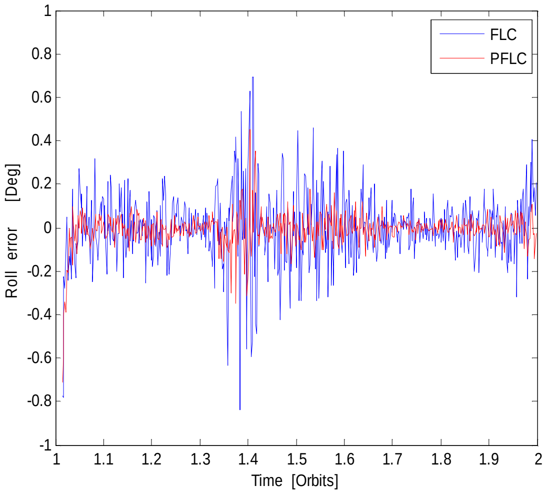


Fig. 5 Estimated roll angle error during reaction wheel phase control

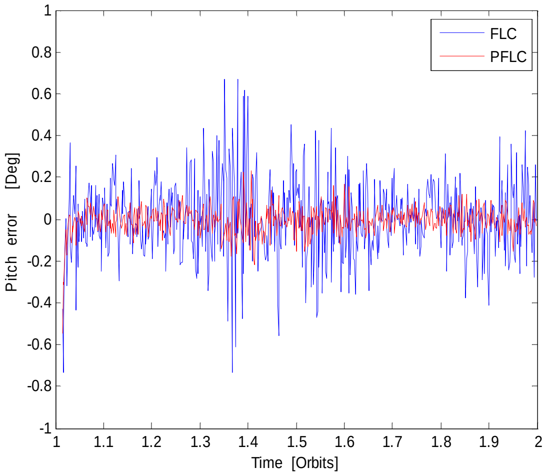


Fig. 6 Estimated pitch angle error during reaction wheel phase control

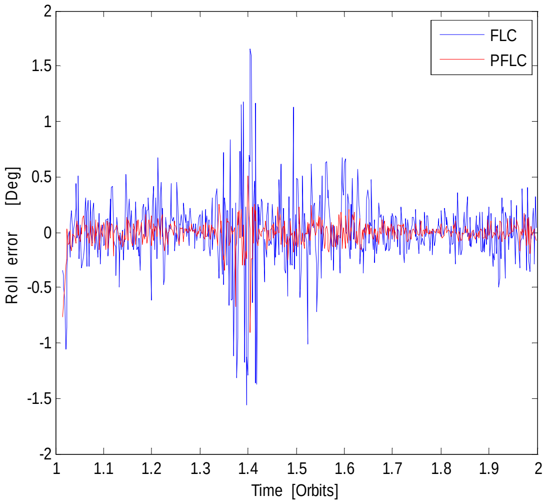


Fig. 7 Estimated roll angle error of PFLC and FLC controller with Pseudorandom Noise

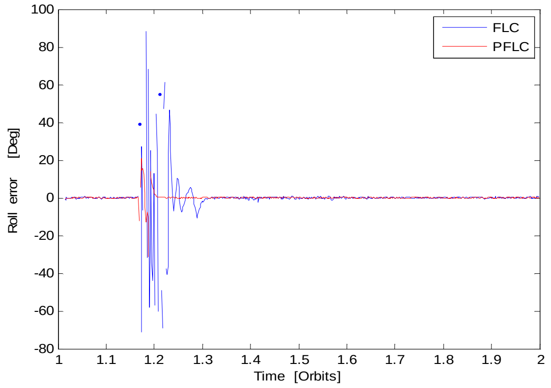


Fig. 8 Estimated roll angle error of PFLC and FLC controller during reaction wheel control dumping of thruster distrurbances

V. CONCLUSIONS

In this paper, a simple predictive fuzzy logic controller for attitude determination and control system of agile micro-satellite is developed and its performance is compared with the FLC. From the analysis it is clear that the performance of the PFLC has better performance in terms of convergence and attitude error pointing. It is, although observed that PFLC is controllable and more stable than FLC controller when the system is subject to noise and intermittent disturbance. The quality of FLC can be drastically affected by the choice of membership functions. Thus, methods for tuning fuzzy logic controllers are necessary.

In the future we hope to contribute of new systematic algorithm to design an optimal PFLC for a three-axis stabilized satellite. The optimization is performed by tuning the rules and membership function of FLC using the genetic algorithm.

REFERENCES

[1] Michael D.Griffin, James R.French,, “Space vehicle design”, AIAA education Series Second edition, Published by American Institute of Americans and Astronautics 2004.

[2] Marcel J. Sidi, “Spacecraft dynamics and control”, Cambridge Aerospace Series 7, Cambridge University Press, Cambridge, 1997.

[3] Robert A. Pazm, “The design of PID controller”, Klipsch School of Electrical and Computer Engineering, 2001.

[4] B. Wie, “space vehicule dynamics and control”, AIAA education Series, AIAA Inc. Reston, VA, 1998.

[5] Xianhua Jiang, Yuichi Motai, Xingquan Zhu, “Predictive fuzzy control for a mobile robot with nonholonomic constraints”, *12th International Conference, Advanced Robotics, 2005. ICAR '05. Proceedings*, 18-20 July 2005, pp. 58 – 63, ISBN 0-7803-9178-0.

[6] A.M. SI Mohammed, M. Benyettou, A. Boudjemai, Y. Hashida, “Seven state Kalman filtering for LEO microsatellite attitude determination”, *Proceeding of 9th WSEAS International conference on Signal Processing, Robotics and Automation*, pp. 151-157, Cambridge, UK, February 20-22, 2010.

[7] J. R. Wertz, “Space mission analysis and design”, Space Technology Library, Kluwer Academic Publishers, Dordrecht, Boston, London, 1991.

[8] Zadeh, L., “Knowledge representation in fuzzy logic”, *IEEE Trans. on Knowledge and Data Engineering*, vol. 1, pp. 89–100, 1989.

[9] Gene F. Franklin, J. David Powell and Abbas Emami-Naeini, “Feedback control of dynamic system”, Pearson Education Ltd., 2006.

[10] Sazali Yaacob, Nagarajan R, and Kenneth TTK., “Fuzzy logic predictive controller performance under variable time delay - A simulation study”, *Proceedings of IEEE Conference, NAFLIPS-FLINT on Fuzzy Information Processing*, pp. 99-104, Boston, USA. 2002.