

Controlling the micro satellites with adaptive and PID controllers and their function comparison

¹Saeed Balochian, ²Ali Asaee

*1 Department of Electrical Engineering, Gonabad Branch, Islamic Azad University, Gonabad, Iran

2 Department of Electrical Engineering, Gonabad Branch, Islamic Azad University, Gonabad, Iran

Email: saeed.balochian@gmail.com, ali.asaee@yahoo.com

Abstract – This study aims to design two kinds of controllers by satellite modeling on the basis of nonlinear rigid body in order to control the satellite position while maneuvering. Then the controller performance results are compared. PID control and model reference adaptive control are used. The comparison of these two controllers is simulated in MATLAB.

Keywords – Satellite attitude control; Adaptive Control; Euler Angel; Nonlinear behavior; PID controller

1. Introduction

The attitude of a satellite is its orientation towards different coordinate system in space. Systems of attitude determination and control are one of the fundamental subsystems which the accuracy of the satellite function always is depended on the accuracy of this systems function. This system plays a severe role in micro satellites. The size of small satellites limits us to use controlling system and algorithm as small and fast as possible that have low volume software's and hardware's. So, designing engineers try to use some kinds of techniques and segments which overcome this limitation and also improve accuracy and the rate of the system response. Importance points of the attitude controlling subsystems are as followed:

- a) It is essential that communication satellites have antennal carefully adjusted in order to focus on certain point on earth.
- b) For satellites with earth-observing mission the cameras are focused on certain point on earth. In

addition they have to record reliable videos coverage of the desired area.

- c) Desired attitudes must be provided for orbiter maneuvers.
- d) Keeping solar cells towards sun result in maximum usage of solar energy.

Satellite attitude investigations can to determine the attitude, controlling it and predicting the next move. The system overall attitude control block diagram is given in figure1.

Determination of satellite attitude can be done according to sun, stars and earth orientation, or magnetic field. The torque (i.e. magnetic coil) can also be used to change satellite attitude into desired one. This is done by different sensors and stimulants. Sensors send errors of satellite attitude to the control processor. Then it runs controlling algorithms and makes controlling rules. Finally it sends signals to stimulus. Stimulus product required torque to control satellite attitude. The aim of satellite attitude determination is to calculate the attitude of a fixed coordinate system on the body of satellite according to a desired coordinate system. Different coordinate systems are shown in figure 2.

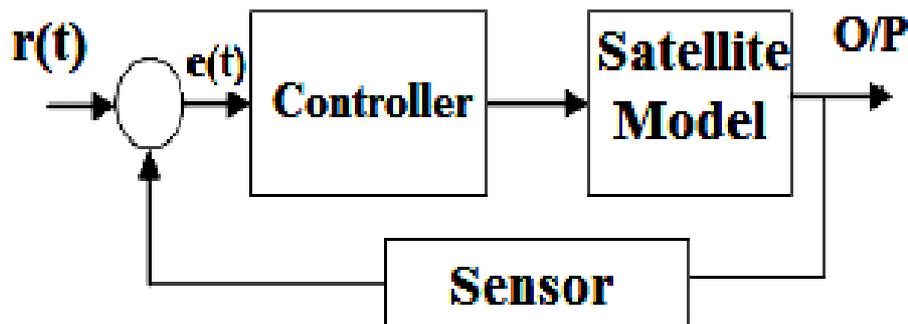


Fig.1. attitude control block diagram

In recent years, the enhancing robustness of I/O linearization controllers has been widely discussed in satellite control. In [7], robustness of linearization control system is obtained by the integral error feedback. Intelligent controls such as fuzzy logic and neural network controls have become one of the most favorable areas of research in aerospace engineering. In [9] developing intelligent controller for satellites attitude control aims at dealing with the large variation of system parameters and relevant uncertainties in the environment is presented. Chiang and Jang in [18] have developed a fuzzy logic attitude controller for the cassini spacecraft. In [19] a model reference adaptive neuro-controller using

feed-forward neural networks with momentum back-propagation (MBP) is proposed. In [20] two level Bang-bang controllers are generally used in conjunction with the thrust reaction actuator for spacecraft/satellite attitude control. This paper is organized in the following manner. In section 2, Attitude controlling actuators and methods and algorithms and satellite model which is used in the paper, are presented. In section 3, micro satellite PID controller is presented. In section 4, adaptive control of the micro satellite is presented. Finally, simulation results are shown comparison of two controls performance for satellite.

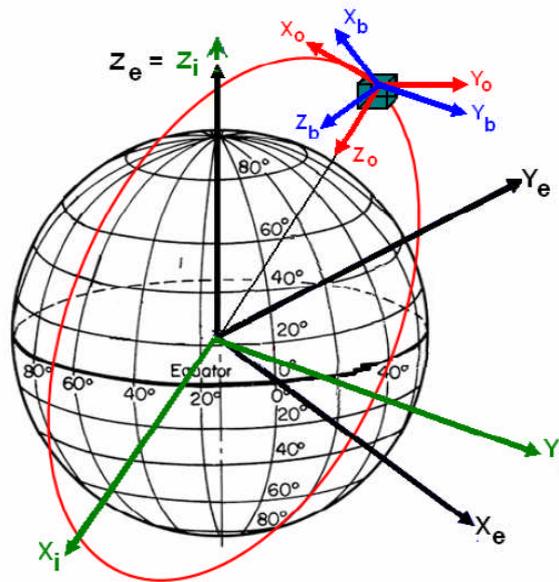


Fig.2. Different coordinate systems

2. Attitude Controlling Actuators

Attitude controlling actuators of the system are torque producing because control input is a torque. Attitude controlling actuators are divided in to two main categories, Active and inactive. Inactive actuators change the angular momentum of the satellite by interacting with environmental torque. Gravity gradient boom and

magnetic actuators are as an example. Magnetic torque producer and gravity gradient are used to product torque in reference [15] and [5], respectively. Active actuators are included: momentum wheels, momentum controlling gyroscope and reaction wheel needed electric power. The range of produced torque by each device is listed in table 1.

Tab.1. The range of produced torque

Momentum Control System	Momentum Range(N/m)
Reaction Wheel	0.1-1
Momentum Controlling Gyroscope	0.01-1000
Magnetic Torque Producer	0.01-0.1
Gravity Gradient	0.000001-0.001
Momentum Wheels	0.01-10

2.1. Attitude Determination Methods and Algorithms

There are two attitude determination methods:

- 1) Point to point

- 2) Recursive

Point to point method is on basis of two or more sensors measurements at any point and any time. While recursive method was point sequence information and knowledge of dynamic satellite attitude model [10].

2.2. Attitude Controlling Methods and Algorithms

Attitude controlling is directing satellite into a specific predetermined direction which includes two processes: attitude stabilization and controlling the maneuver attitude. Attitude stabilization means keeping the satellite in its current attitude, while controlling the maneuver attitude is changing its attitude from one to another one. In nano satellite attitude controlling system (include actuators and controlling algorithms), are selected so that have less power consumption which guarantees useful life of it in its mission.

2.3. Satellite Model

Although finding a right model describing real satellite change in its environment is hard, but improper model is not able to analyze, estimate and design the controllers successfully. Controlling torque resulted from control rules is easily affected by used model. Controlling torque are functions of attitude errors. Usually designing of controllers is done by tree methods as followed: model- independent design, model-depended design and adaptive controlling design [15]. For satellite modeling linear rigid body, non linear rigid body and elastic model has been used in some literatures [2].

In this study, our approach is to use nonlinear rigid body with tree translational degrees of freedom in inertia coordinate system. This motion can be described by translation of the center of mass and body rotation around its center of mass [4]. It is essential to use attitude dynamic and systematic to build a model. Assuming an hypothetical coordinate system and X,Y and Z as its vectors on fix body of a satellite so that center of this system is in accordance with satellite center of mass. In other words, Axes X_B , Y_B , and Z_B define the satellite's body axis frame, and the axis system is considered centered at the centre of gravity as shown in Figure3. Thrusters are available to produce torques about each of the three principal axes. The physical interpretation of the Euler angles [4] for a micro-satellite platform is shown in figure3. Using of this angles results in singularity, especially in sequential rotations [3, 6]. Thus it is preferred to use Euler parameters (Quaternion).

Micro satellite dynamic is shown in following equations:

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{M_x - qI_{zz}r + rI_{yy}q}{I_{xx}} \\ \frac{M_y - qI_{xx}r + rI_{zz}q}{I_{yy}} \\ \frac{M_z - qI_{yy}r + rI_{xx}q}{I_{zz}} \end{bmatrix} \quad (1)$$

$$\omega = [p, q, r]^T \quad (2)$$

$$u = [M_x \ M_y \ M_z]^T \quad (3)$$

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \quad (4)$$

In this equations ω is angular velocity vector towards three principal axes, u is torque vector applied on satellite (resulted from controlling rule) and I is inertia matrix around the body principal axes (X_B , Y_B and Z_B), These are given by equations (4). Relation between satellite body velocity and angular velocity is received by followed conversions [4].

$$\begin{bmatrix} \dot{\phi}_I \\ \dot{\theta}_I \\ \dot{\psi}_I \end{bmatrix} = \begin{bmatrix} 1 & \frac{\sin \Phi \sin \theta}{\cos \theta} & \frac{\sin \Phi \sin \theta}{\cos \theta} \\ 0 & \cos \Phi & -\sin \Phi \\ 0 & \sin \Phi & \cos \Phi \end{bmatrix} \cdot \begin{bmatrix} p_b \\ q_b \\ r_b \end{bmatrix} = \begin{bmatrix} p + \frac{(q \sin \Phi + r \cos \Phi) \sin \theta}{\cos \theta} \\ q \cos \Phi - r \sin \Phi \\ \frac{q \sin \Phi + r \cos \Phi}{\cos \theta} \end{bmatrix} \quad (5)$$

System states are assumed as

$$x = [p_b \ q_b \ r_b \ \phi_I \ \theta_I \ \psi_I]^T.$$

The nonlinear state model of the satellite shown in following equations

$$\dot{x} = A(x)x + B(x)u \quad (6)$$

where matrix $A(x)$ is a nonlinear function of state vector x and $B(x)$ is an input matrix of the input vector.

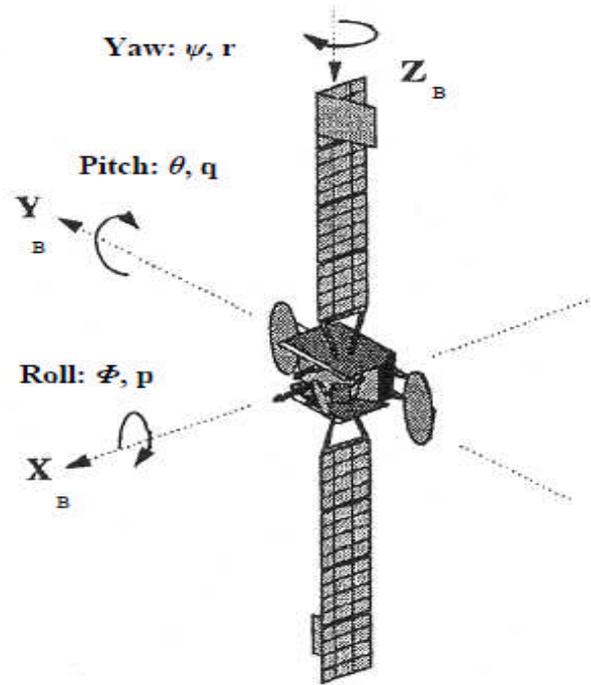


Fig.3. The roll (ϕ), pitch (θ), and yaw (ψ) angles are defined by successive rotations around the coordinate axes X_B , Y_B , and Z_B in the body fixed frame.

3. Micro Satellite PID Controlling

PID classic controlling is the control of engineering system which can be easily developed. PIDs can significantly act for one and two order systems. But for systems with large time delay, big uncertainty and distributed harmonics PID classic controlling is not desirable. Thus intelligent controls are necessary. PID controllers flexibility make them desirable for many cases. The problem of these controllers is to find maximum of proportional, integral and derivative parameters to have closed loop system outputs in reasonable region. It has been reported that PD control speeds up the output and turn it into a steady state quickly. PI control reduces steady state errors. And the PID includes both of them. So a combination of two methods (PID) is the best choice. The control signal is thus a sum of three terms: the P-term (which is proportional to the error), the I-term (which is proportional to the integral of the error) and the D-term (which is proportional to the derivative of the error). The controller parameters are proportional gain K_p , integral time T_i , and derivative time T_d . Selection of PID parameters (K_p , T_i , T_d) always has disagreement. Several methods have been presented for adjusting the PID controllers. Some of parameters adjusting algorithms have just developed but the problem is still unsolvable. PID control is as following:

$$\mathbf{u}(\mathbf{t}) = \mathbf{k}_P \left(\mathbf{e}(\mathbf{t}) + \frac{1}{T_i} \int_0^{\mathbf{t}} \mathbf{e}(\mathbf{s}) \, \mathbf{d}\mathbf{s} + T_D \frac{d\mathbf{e}}{d\mathbf{t}} \right) \quad (7)$$

u is the control signal and e is the control error ($e = Y_{SP} - y$), where y is the measured process variable, Y_{SP} is the reference variable, that is often called the set point.

The algorithm which is usually used for adjustments consists of several data. Usually it is preferred that

derivative and proportional parameters only act on output and referent value, respectively. Derivation is usually replaced by an approximation which decreases the gain in above frequency.

Integration is refined in a way that stops when the controlling parameter is saturated. It is essential to not have a transition state when manual mode switches into automatic mode. There are several methods for automatic adjustment of controlling parameters of PID control. In this investigation determination of controlling parameters is on the basis of zigler-Nichols closed loop method. It's an easy and accurate method used critical interest and alternative period to calculate controlling parameters.

Ziegler- Nichols method is based on a simple characterization of the frequency response of the process dynamics. The design is based on knowledge of only one point on the Nyquist curve of the process transfer function $G(s)$, namely the point where the Nyquist curve intersects the negative real axis. This point can be characterized by two parameters the frequency ω_{180} and the gain at that frequency $k_{180} = |P(i\omega_{180})|$. For historical reasons the point has been called the ultimate point and characterized by the parameters $K_u = 1/k_{180}$ and $T_u = 2\pi/\omega_{180}$, which are called the ultimate gain and the ultimate period. These parameters can be determined in the following way. To adjust the controller coefficients first control system is switched to automatic mode and the integrator and derivatives time are adjusted on maximum and minimum of their values, respectively. Increase the gain slowly until the process starts to oscillate. The gain when this occurs is k_u and the period of the oscillation is T_u . The parameters of the controller are then given by Table2 [16].

In this paper for design PID control, we linearized (and normalized) equation of motion of satellite around

the equilibrium point. To obtain this linearized model, the original variables are assumed to deviate only slightly about the operating point. To obtain the equilibrium

point, all the derivative terms in the governing equation are equated to zero.

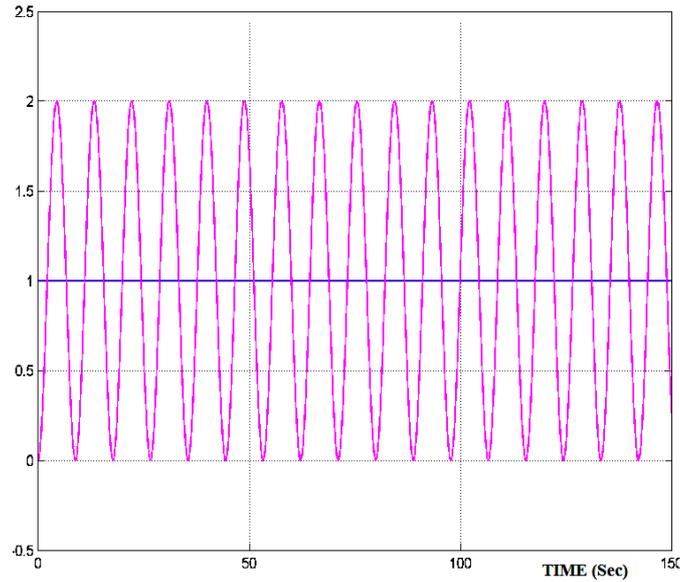


Fig.4 – closed loop system output, finding Critical interests and critical alternative period

Tab.2. controlling parameters calculated by zigler –Nicholes method.

Tuning Formula	
T_I	$T_I = 0.5 \times T_u$
T_D	$T_D = 0.125 \times T_u$
K_P	$K_P = 0.6 \times K_u$
K_I	$K_I = \frac{K_P}{T_I}$
K_D	$K_D = K_P \times T_D$

4. Adaptive Controlling

Model reference adaptive control is used for micro-satellite control system in this study, too. It is one of the most important adaptive controllers used to adjusted satellite attitude. In model reference adaptive control (MRAC), a reference model is chosen to generate the desired output trajectory, and the main task of MRAC is to ensure the output of the controlled system to follow the output of the reference model, in addition to closed-loop stability. Adaptive laws are used to update the controller parameters to achieve desired system performance in the sense of closed-loop stability and output tracking of a desired reference output [12, 13]. Unlike the conventional adaptive control schemes, the control scheme in Figure5 does not estimate the plant parameters but directly estimate the controller parameters [6].

The MRAC objective is met if $u(t)$ is chosen so that the close loop transfer function from $r(t)$ to $y(t)$ have stable response and is equal to $Y_m(t)$, the transfer function of the reference model. A stable linear continuous-time reference model is specified by the following difference equation [6].

$$Y_m(t) = a_{m1}Y_m(t-1) - a_{m2}Y_m(t-2) + b_{m0}r(t-1) + b_{m1}r(t-2) \tag{8}$$

where $r(t)$ is bounded reference input and $Y_m(t)$ is reference model output; a_m and b_m are fixed model parameters and their values are chosen for any desired stable response, which the process system is expected to acquire. Thus, the MRAC desired to design a controller that computes a control action signal, such that the overall control system responds dynamically as the specified reference model. Model reference adaptive control block diagram is given in figure5.

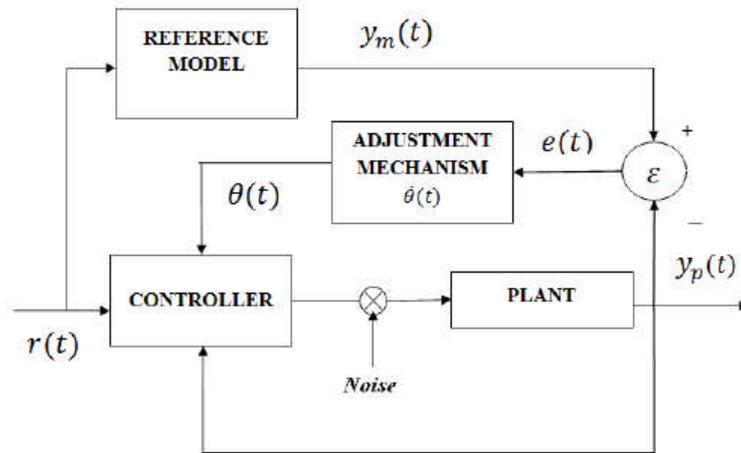


Fig.5 .Model Reference block diagram

Model reference was selected as

$$y_m(t) = y_m(t-1) - 0.15y_m(t-2) + 0.15r(t-1) \quad (9)$$

Where $r(t)$ is a square wave reference input signal. Parameter $a_{m1} = 1$, $a_{m2} = -0.15$ and $b_{m0} = 0.15$ have been chosen such that a desired trajectory $y_m(t)$ is obtained for the plant output $y(t)$ to follow.

Controller parameter varies on the basis of error output which is on error between system output and model reference output. The equations can be converted into state equations format

$$dx/dt = Ax + Bu$$

$$y = Cx. \quad (10)$$

where x is state variable u , control input and y is measurement output. we assume the reference model as follows.

$$dx_m/dt = A_m x_m + B_m u_c \quad (11)$$

Then the controller structure is determined, we assume a control law as equation (12).

$$u = \theta_1 u_c - \theta_2 y \quad (12)$$

Now the state equation of the closed loop system has been changed to the following equation.

$$\begin{aligned} dx/dt &= (A - B\theta_2)x + B\theta_1 u_c \\ &= A_c(\theta)x + B_c(\theta)u_c \end{aligned} \quad (13)$$

where the parameters in matrices θ_1 and θ_2 can be selected in any way, there can also exist some constraints between them. We suppose the closed loop system can be described with equation (13), where matrices A_c and B_c depend on the parameter θ , and θ is a certain combination of θ_1 and θ_2 . If equation (13) is equivalent

to equation (11) at any time, then the original system can follow the reference model completely.

In the study the parameters adjustment is on the basis of MIT rule. Controlling parameters are adjusted to minimize a cost function which is defined as followed:

$$j(\theta) = \frac{1}{2} e^2 \quad (14)$$

The MIT rule then gives the following adaptation law:

$$\frac{d\theta}{dt} = -\gamma \frac{\partial j}{\partial \theta} = -\gamma e \frac{\partial e}{\partial \theta} \quad (15)$$

$\frac{\partial e}{\partial \theta}$ is sensitivity derivative, γ is adaptation gain

and θ is adjustable parameters vector. Becoming e equal to zero doesn't necessarily converge control parameter to one certain value [1]. According to MIT rule, now the output error between real system and reference model will approximate to zero, and the whole system will be asymptotically stable.

5. Simulation Results

This paper has compared the performance of adaptive controller with conventional PID regulator. Micro satellite initial conditions are shown in Table 3. The three parameters of PID regulator are chosen as $k_p = 16.68$, $k_I = 2.952$, $k_D = 23.5$. The behavior of the system is now illustrated by simulation. Figure 6 give the updating process of parameters θ_1 and θ_2

of the adaptive control law when $\gamma = 0.5$. In figure 7 we see the relation between controller parameter. Figure 8 shows control signal which is obtained from the adaptation law. Figure 9 shows the comparison between PID with MRAS. This figure shows the MRAS has little deflection from the transient period with small magnitude of oscillation, but it is stabilized very soon. The command signal is square wave with amplitude 1, and $\gamma = 0.5$.

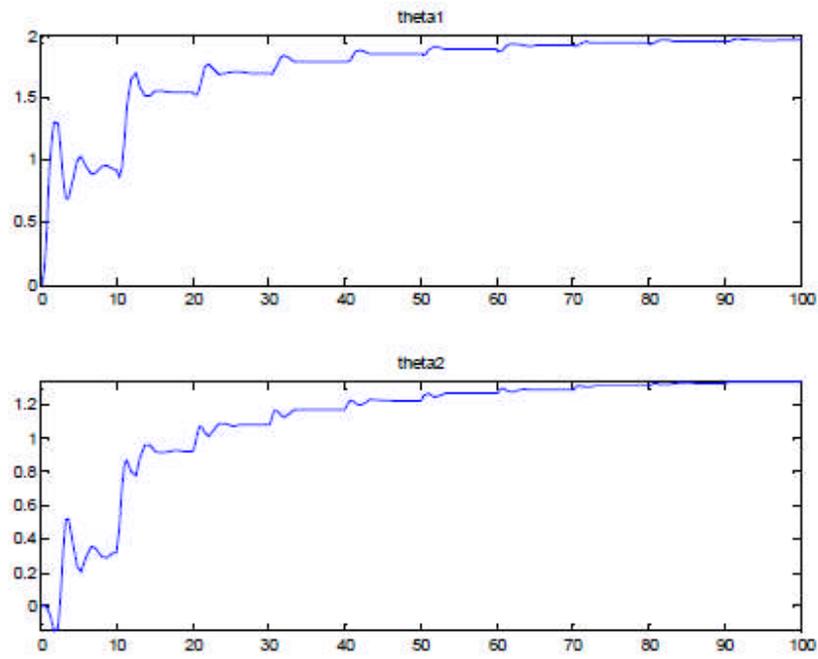


Fig.6 .Tuning of the parameter θ_1 and θ_2 of the adaptive control law when $\gamma = 0.5$

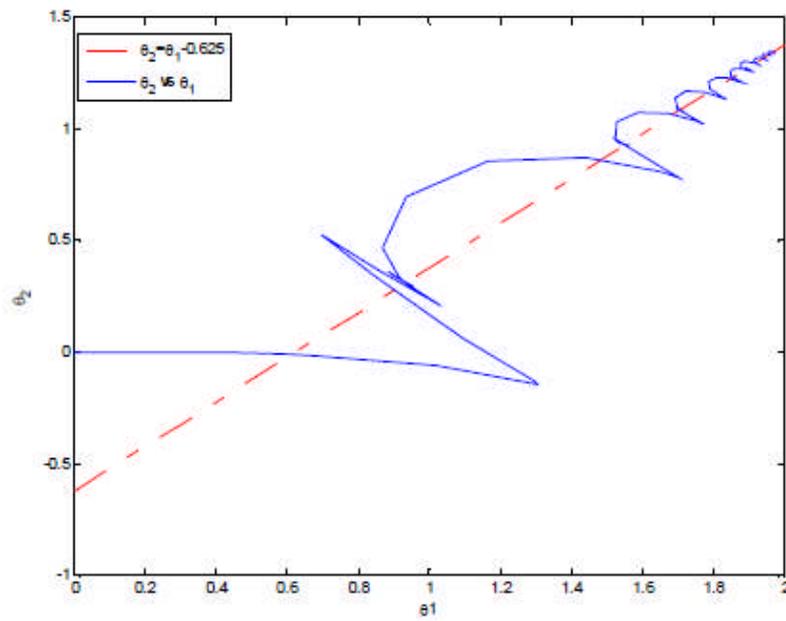


Fig.7 . Relation between controller parameter

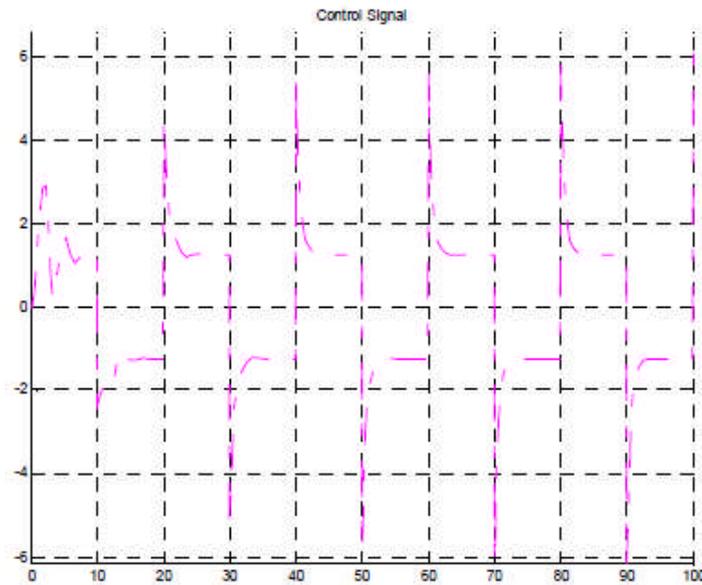


Fig.8 .control signal

Tab.3.Micro satellite Initial Conditions

parameter	value
I_{xx}	1.928 kg- m^2
I_{yy}	1.928 kg- m^2
I_{zz}	4.9 kg- m^2
Thruster	1 kg- m^2
Φ_o	0.36 kg- m^2
θ_o	0.52 kg- m^2
Ψ_o	-0.2 kg- m^2

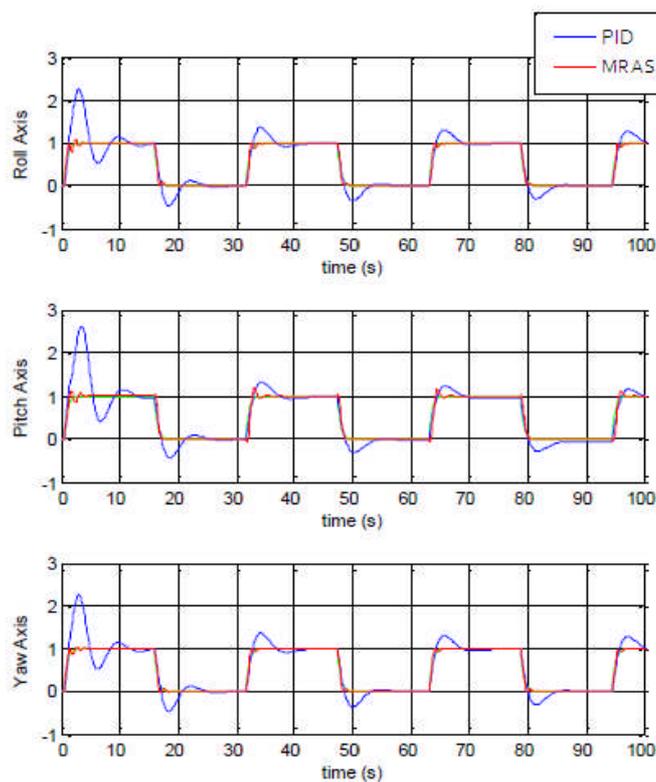


Fig. 9. the comparison between PID with MRAS when command signal amplitude is 1, red is MRAS output and blue is PID output

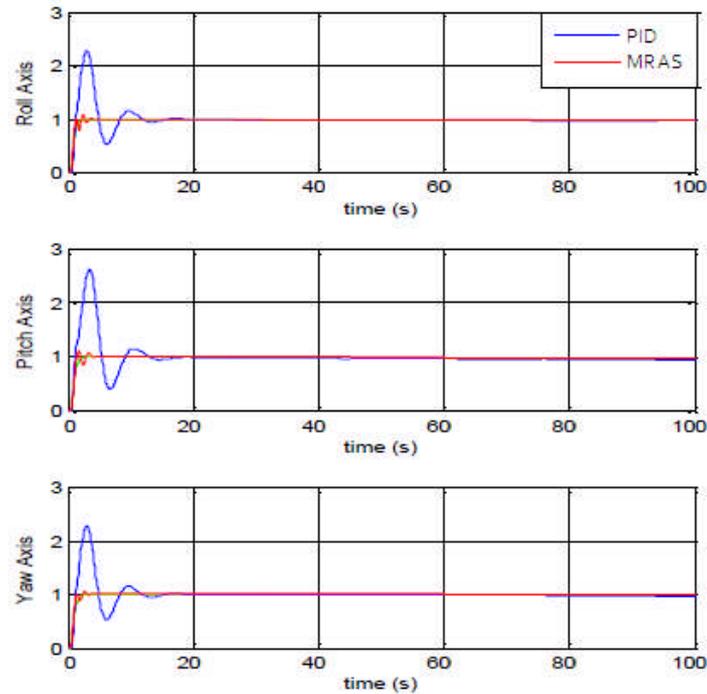


Fig.10.step response output for MRAS and PID controller

Fig.10 shows the step response output waveforms of reference model, MRAS and PID regulator system. In this figure, the dynamic performance of MRAS is much better than of PID regulator system owing to its shorter settle time. PID has severe oscillations with a very high peak overshoot which causes the damage in the system performance. As a comparative controller, the PID regulator system has more steady state error and its settle time is very long.

6. Conclusion

In this paper a model reference adaptive controller has been designed based on the MIT rule, and a comparative study on conventional PID regulator has been completed. Simulation results show that the model reference adaptive system is robust and stable, which has better dynamic performance and stronger disturbance rejecting ability than PID regulator system. The adaptive control law is independent of plant parameters and easy to implement. Therefore the proposed method is effective.

References

- [1] K.J. Astrom and B. Wittermark, Adaptive Control, 2nd Ed. Lund Institute of Technology, Sweden: Addison-Wesley Publishing Company, Inc.1995
- [2] Mc Farlane, D; Glover, k; Noto n, M, Robust stabilization of Flexible space platform: An H coprime Factor Approach"; in Proceedings of control 88, IEE conference, oxford UK (1998).
- [3] K. L. Makovec, "A Nonlinear Magnetic Controller for Three-Axis Stability of Nano-satellites," M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, July 2001.
- [4] Marcel J. Sidi, Spacecraft Dynamics and Control, Cambridge University Press, 2001.
- [5] F.Martel, k Parimal, and M.Psiaki," Active Magnetic control system for Gravity Gradient stabilized spacecraft", In Proc. : Annual AIAA /USU, conference on small satellite Sep.1988
- [6] M.Y. Mashor, "Indirect Model Reference Parametric Adaptive Controller", Proceeding of the International Conference on Control, Instrumentation and Mechatronics Engineering, Johor Bahru, Malaysia, 2007.
- [7] N. S. Sahjendra and Y. Woosoon, "Feedback linearization and solar pressure satellite attitude control," IEEE Trans. on aerospace and electronic systems, vol.32, no.2, pp.732-741, 1996.
- [8] Osburn.P.V., H.P.Whitaker, and A.Kezer,1961." New developments in the design of adaptive control system".PaperNo.6139, February1961, Inst. Aeroel Sciences.
- [9] J. Zhang et al.,"Application of Neuro-fuzzy Control for Satellite AOCS," Seventh International Conference on Control, Automation, Robotic and Vision, Singapore, Dec 2002.
- [10] S. M. Sharun, M. Y. Mashor, M. N. Norhayati, S. Yaacob, and W. N. W. Jaafar, "Adaptive neuro-controller for satellite attitude control," Proceeding of the 4th International Conference of Postgraduate Education, Kuala Lumpur, Malaysia, November 2010.
- [11] N. Sivaprakash and J. Shanmugam, "Neural Network Based Three Axis Satellite Attitudes Control Using Only Magnetic Torques," Proceeding of the 24th Digital Avionics Systems Conference, October 2005.
- [12] H.D. Patino and D. Liu, Neural Network-Based Model Reference Adaptive Control System," Systems, Man and Cybernetics, Part B, IEEE Transactions, 30, 198-204, 2000.
- [13] Q. Sang and G. Tao, "Gain Margin of Model Reference Adaptive Control Systems," Proceedings of the 7th World Congress on Intelligent Control and Automation , 2008.
- [14] Wang, P., Shtessel, Y.B; Wang, Y.Q., "satellite Attitude control using only Magnitorquers"; Proc. of American control conference, Philadelphia ,June1998; PP.222-226
- [15] Yung wen. J.T.;Kreutz Delgo,k,;"The attitude control Problem";IEEE Trans. Automatic control,vol.36,No.10, October 1992;PP.1148-116
- [16] K. Astrom and T.Hagglund "PID Controller :Theory; Design and Tuning "Instrument Society Of America,1999

- [17] Tao Yonghua, Yin Yixin, and Ge Lusheng, "New Type of PID Control and Its Application [M]," 2000, pp.101-142.
- [18] Chiang,R,Y and Jyh-shing Jang, "fuzzy logic attitude control for cassini spacecraft" IEEE word congress on computational Intelligence, Orlando, FL,1994
- [19] A.R. Mehrabian and M.B. Menhaj," A real-time neuro-adaptive controller with guaranteed stability," Applied Soft Computing, 8, 530-542, 2008.
- [20] F. Nagi, A.T. Zulkarnain, J. Nagi, Tuning fuzzy Bang-bang relay controller for satellite attitude control system, Aerospace Science and Technology, in press 2012, doi:10.1016/j.ast.2012.02.016.