Fuzzy Controller Design for Fuel Saving in Sun Point Mode for KOMPSAT-2

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Abstract: The mission life of a satellite determines the amount of fuel required on-board, while the total mass requirement limits the fuel to be loaded. Hence, for the design of thruster control loop, not only the satellite pointing accuracy but the saving of fuel is to be considered. In this paper, a two-step fuzzy controller is proposed for the thruster control loop to save fuel consumption. This approach combines requirements for pointing control accuracy with minimum fuel consumption into a fuzzy controller design. To demonstrate this approach, we have designed a fuzzy controller for the Sun point Mode of KOMPSAT-2. The performance of this fuzzy controller design is compared with that of PD controller used for KOMPSAT-2.

Keywords: Attitude and Orbit Control Subsystem, Pulse Width Modulation, Fuzzy Logic, Membership Function, Sun Point Submode

1. INTRODUCTION

The complexity of nonlinear systems makes it difficult to ascertain their behavior using classical methods of analysis. Many efforts have been focused on the advanced algorithms and techniques that hold the promise of improving control while at the same time providing higher accuracy.

Since Zadeh[1] introduced fuzzy logic, it has been very successful especially when applied to nonlinear control systems. Most physical systems are nonlinear. These systems are difficult to control with conventional controllers. Fuzzy logic control systems have shown the capability of handling system nonlinearities along with modeling uncertainties and imprecision[2]. The success that fuzzy logic has shown with control systems and the nonlinear engineering world has motivated us to look at using it to analyze and better understand fuzzy control for satellite systems.

In order to successfully develop attitude and orbit control system(AOCS), AOCS engineer performs hardware selection, controller design and analysis, control logic and interface verification on electrical test bed, integrated system test, polarity test, and finally verification on orbit after launching. The sun point mode for KOMPSAT-2 is used for simulation, which is solar array normal to the sun to provide battery charge necessary for the spacecraft power. Four coarse sun sensor provides pitch and yaw axis attitude information for the solar array and three gyro provides angular rate as sensors. Four thruster is used as actuators to control the torque. During the eclipse the spacecraft maintains fixed attitude for ECI coordinate. The solar array is fixed at 0 degree and normal to the sun[3].

In this paper, a two-step fuzzy controller is proposed for the thruster control loop to save fuel consumption. This approach combines requirements for pointing control accuracy with minimum fuel consumption into a fuzzy controller design. To demonstrate this approach, we have applied a fuzzy controller for the sun point mode for KOMPSAT-2. The performance of this fuzzy controller design is compared with that of PD controller used for KOMPSAT-2.[4].

2. CONTROLLER DESIGN FOR SUN POINT MODE

The thruster control loop for sun point mode consists of single axis S/C dynamics, thruster controller, gyro model and PD controller.

2.1 Thruster Model

Fig. 1 shows thruster configuration for KOMPSAT-2.

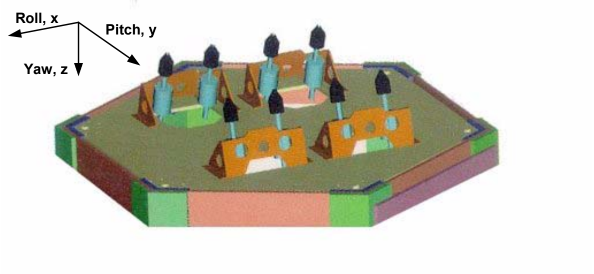

Fig. 1 Thruster Configuration for KOMPSAT

Thruster torques for each axis is

$$\vec{T} = (\vec{R} - \vec{G}) \times \vec{F} \tag{1}$$

where $\vec{R}$ is the thruster position from the separation plane of spacecraft, $\vec{G}$ is the center of gravity from the separation plane of spacecraft, $\vec{F}$ is thruster force. Thruster force levels at BOL and EOL are the function of fuel pressure levels. Thruster torque for each axis at BOL is as follows:

axis	Thruster torque
roll	1.10 N-m
pitch	1.48 N-m
yaw	0.37 N-m

Thruster torque for each axis at EOL is as follows:

axis	Thruster torque
roll	0.27 N-m
pitch	0.37 N-m
yaw	0.09 N-m

It is noticed that thruster torque at EOL is reduced since thruster force is reduced according to the consumption of fuel. The redundant thruster is designed to minimize the effect of thruster torque and the stretching gain exists to control the gain at EOL.

2.2 Dynamic Model with Flexible Mode

The spacecraft model is derived from finite element method using NASTRAN program[5]. The dynamic model is composed of 100 mode and each mode has a natural frequency calculated from physical characteristics and spacecraft configuration. Among them, 20 mode is selected to reduce the calculation time. The followings present the procedure derived ordinary differential equation from spacecraft dynamics in state space. Spacecraft with flexible mode acting on external force F(t), modal damping C can be described by Eq. (2)

$$M\underline{\ddot{q}}+C\underline{\dot{q}}+K\underline{q}=f(t)\underline{e}_i \tag{2}$$

Where M is the mass, K stiffness matrix, q state vector and $\underline{e}_i$ is the location of external force. In order to separate each mode , modal matrix is $\underline{P}$, principal axis is $\underline{p}$,

$$\underline{P}^T M\underline{P}\underline{\ddot{p}}+\underline{P}^T C\underline{P}\underline{\dot{p}}+\underline{P}^T K\underline{P}\underline{p}=\underline{P}^T f(t)\underline{e}_i \tag{3}$$

Where modal matrix is $\underline{P}=[P_1/\sqrt{M}\ P_2/\sqrt{M}\ P_3/\sqrt{M}\ \cdots]$. Therfore, if coupled modal damping is small enough, $\underline{P}^T C\underline{P}=diag\{2\xi_1\omega_{n1}, 2\xi_2\omega_{n2}, 2\xi_3\omega_{n3}, \cdots\}$ $\underline{P}^T K\underline{P}=diag[\omega_{n1}^2, \omega_{n2}^2, \omega_{n3}^2, \cdots]$, $\underline{P}^T\underline{e}_i=\Phi_{ij}$. Then, Eq.(4) is described by

$$\ddot{p}_i+2\xi_i\omega_{ni}\dot{p}_i+\omega_{ni}^2 p_i=\Phi_{ij}f(t) \tag{4}$$

Spacecraft with flexible model can be expressed for general coordinate in state space by the following Eq.(5)

$$\begin{aligned}\dot{X}&=AX+Bu\\ Y&=CX+Du\end{aligned} \tag{5}$$

Where matrix A, B, C, and D can be described by

$$A=\begin{bmatrix}0 & I\\ -\omega_n & -2\xi\omega_n\end{bmatrix},$$

$$B=\begin{bmatrix}0\\ \Phi_{thruster}^T\end{bmatrix},$$

$$C=\begin{bmatrix}\Phi_{CSSA} & 0\\ 0 & \Phi_{Gyro}\end{bmatrix},$$

$$D=\begin{bmatrix}0\\ 0\end{bmatrix}$$

Where ϖ_n is natural frequency, ξ is damping ratio, Φ_i is modal matrix at coarse sun sensor, gyro and thrusters and I is unit matrix.

3. FUZZY CONTROLLER DESIGN

In this paper, two step fuzzy controller is proposed. First step fuzzy controller is used for attitude control and determine the thruster and thruster fuel necessary for PWM. The phase plane is used for each axis including attitude and angular rate. The second fuzzy controller determine penalty based on the previous attitude and rate.[6].

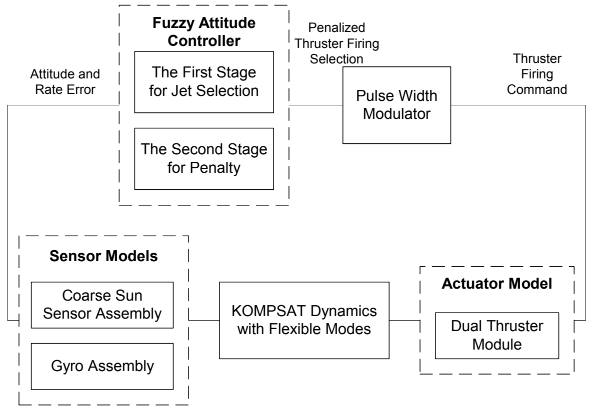

Fig. 2 Fuzzy Attitude Controller Block Diagram

3.1 Fuzzy Logic Controller

In general, fuzzy controller consists of fuzzifier, defuzzifier, fuzzy rule base and fuzzy inference system. Fuzzifier change to membership function from crisp data and defuzzifier change to crisp data from membership function. Fuzzy rule base generates the output using fuzzy data input. Fuzzy rule base is described by IF-THEN and is described

$$\begin{aligned}&R^{(l)}: IF\ x_1\ is\ F_1^l\ and\ x_n\ is\ F_n^l,\\ &\qquad THEN\ y^l\ is\ G^l\\ &\qquad\qquad l=1,2,\ldots,M\end{aligned} \tag{6}$$

where F_i^l and G^l is fuzzy membership function, M is the number of fuzzy rule base, IF-THEN. Also, x_i and y^l is the input and output of the fuzzy controller. Fuzzy controller output y *for* a certain real value x_i is described by

$$y=\frac{\sum_{l=1}^{u} y^l(w^l)}{\sum_{l=1}^{M} w^l} \tag{7}$$

where $y^{l'}$ is the center of mass and w^l is the membership fuction of input $\boldsymbol{R}^{(l)}$

3.2 Basic Rule Sets

The controller associated with the pointing accuracy performance is determined by the basic rule sets. The thruster torque is determined by the difference attitude error between present attitude and referenced attitude. The membership function has attitude error(Error) and angular rate error(CError) and the range of each membership function is [-π, π], [-π/200, π/200], respectively. Each membership function consists of Positive, Zero, Negative. In general, phase plane loolup table is applied to fuzzy rule. Output membership fuction consists of Positive Big, Positive Mid, Zero, Negative Mid, and Negative Big to determine attitude error and angular rate error. Fig. 3 shows rule surface of Basic Rule Sets.

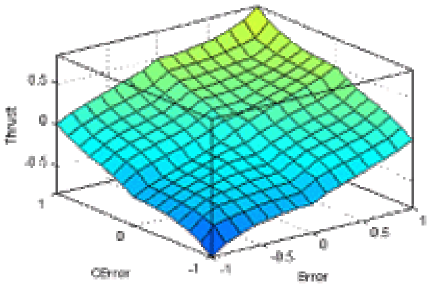

Fig. 3 Rule Surface of the Basic Rule Sets

3.3 Penalty Rule Sets

Fuzzy logic controller with penalty rule sets determines penalty for basic rule sets. Penalty Rule Sets has two inputs and uses 2-norm of attitude error and angular rate error. Input membership function has Small, Mid, Big. The range of output membership function has Bad, Normal, and Good. The output membership fuction is [0,1].

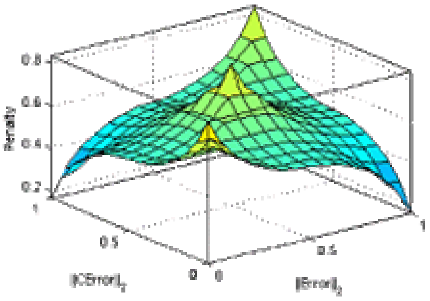

Fig. 4 Rule Surface of the Penalty Rule Sets

Table 1 shows the fuzzy rule base for Penalty Rule Sets.

Table 1. Fuzzy Rule Base for Penalty Rule Sets

No	Rule
1	If $\| \text{Error} \|_2$ is Small and $\| \text{CError} \|_2$ is Big, Then Jet Selection is Bad.
2	If $\| \text{Error} \|_2$ is Small and $\| \text{CError} \|_2$ is Mid, Then Jet Selection is Normal.
3	If $\| \text{Error} \|_2$ is Small and $\| \text{CError} \|_2$ is Small, Then Jet Selection is Good.
4	If $\| \text{Error} \|_2$ is Mid and $\| \text{CError} \|_2$ is Big, Then Jet Selection is Normal.
5	If $\| \text{Error} \|_2$ is Mid and $\| \text{CError} \|_2$ is Mid, Then Jet Selection is Good.
6	If $\| \text{Error} \|_2$ is Mid and $\| \text{CError} \|_2$ is Small, Then Jet Selection is Normal.
7	If $\| \text{Error} \|_2$ is Big and $\| \text{CError} \|_2$ is Big, Then Jet Selection is Good.
8	If $\| \text{Error} \|_2$ is Big and $\| \text{CError} \|_2$ is Mid, Then Jet Selection is Normal.
9	If $\| \text{Error} \|_2$ is Big and $\| \text{CError} \|_2$ is Small, Then Jet Selection is Bad.

4. SIMULATION RESULTS

The followings describe the simulation results from PD controller, pure fuzzy controller with basic rule sets, and proposed fuzzy controller with fuel saving penalty rule sets of sun point mode for KOMPSAT-2. The input angular command is fixed to 90 deg for roll axes.

Fig. 5 shows solar array sun point error of sun point mode for roll axis when initial angle starts from 0 degree to 90 degree. In sun point mode, the system successfully orients the solar array normal towards the sun from any initial orientation within 10 minutes in sunlight. The system acquires sun from any attitude with initial rates of 2.0 deg/sec per axis. The steady-state attitude pointing error with respect to the sun line is less than 8 degrees (3σ) to provide the required power of spacecraft. The steady-state roll rate control error is less than 0.2 deg/sec (3σ). It is satisfied under the all conditions. The settling time of the PD controller is around 50 sec faster than that of fuzzy logic controller. However, the attitude pointing error of the PD controller is better than that of fuzzy logic controller.

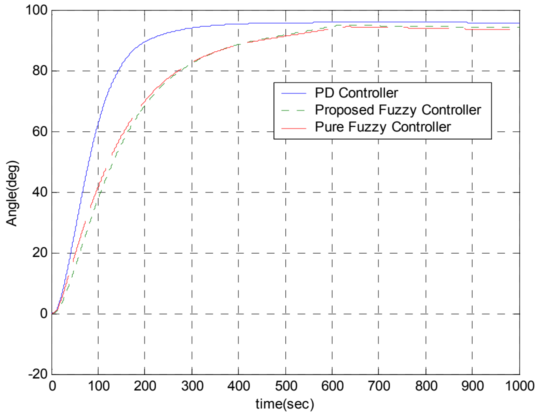

Fig. 5 Attitude Angle for Roll Axis

Fig. 6 shows the angular rate for sun point mode for roll. Solar array flexible effect is associated with roll axis. The maximum angular rate doesn't exceed the limit of angular rate.

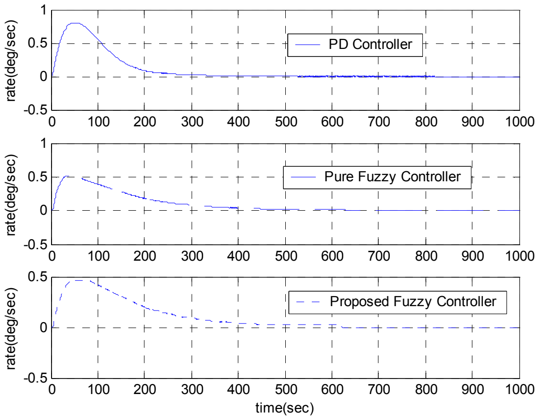

Fig. 6 Angular Rate for Roll Axis

Fig. 7 shows the pulse width for sun point mode in roll axis. The maximum pulse width is 0.25 s and the minimum pulse width is 0.03 s. The thruster is fired in transient and the thruster is fired to trigger the direction between the deadzone in steady state. It shows that fuzzy logic controller is more effective than PD controller to save fuel consumption.

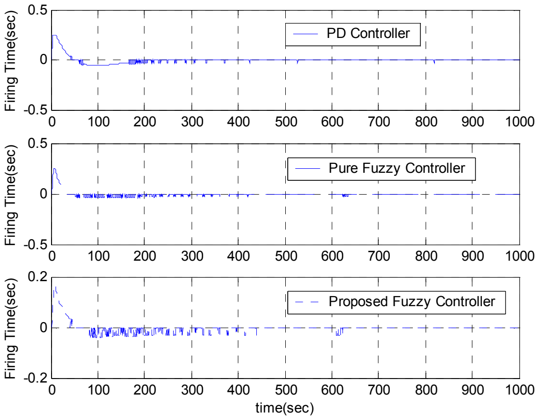

Fig. 7 PWM Output for Roll Axis

Table 2 summarizes total pulse width for roll axis during the operation of 1000sec. Compared to the PD controller, the fuzzy logic controller with proposed fuel saving penalty rule sets saves 39 % fuel consumption as well as the pointing accuracy.

Table 2. Total Firing Time and Fuel Saving Rate Comparison among PD, Pure Fuzzy, and Proposed Fuzzy Controller

Axes	Applied Controller	Total Firing Time [sec]	Percentage [%]
Roll	PD	47.3	100
	Pure Fuzzy	31.6	67
	Proposed Fuzzy	28.7	61

5. CONCLUSION

The mission life of a satellite determines the amount of fuel required on-board, while the total mass requirement limits the fuel to be loaded. Hence, for the design of thruster control loop, not only the satellite pointing accuracy but the saving of fuel is to be considered. In this paper, a two-step fuzzy controller is proposed for the thruster control loop to save fuel consumption. This approach combines requirements for pointing control accuracy with minimum fuel consumption into a fuzzy controller design. The proposed controller satisfied the requirement and saves about 39 % fuel consumption. KOMPSAT-2 has thruster loop controller which uses the thruster as an actuator. For further study, it is considered to design thruster loop controller to save the fuel consumption for the other modes.

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