Fuzzy Logic Attitude Control for Cassini Spacecraft *

Richard Y. Chiang

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr
Pasadena, CA 91109-8099

Jyh-Shing Roger Jang

The MathWorks, Inc.
Cochituate Place
24 Prime Park Way
Natick, Mass. 01760

Abstract

A fuzzy logic attitude controller has been developed for Cassini spacecraft. Feedback control issues such as tracking capability, thruster on/off time and cycle have been investigated and compared with conventional bang/bang control. A discrete nonlinear simulation was set up to assess the system performance with different controllers.

1 Introduction

Saturn, one of the most interesting planet in our solar system, will be visited by Cassini spacecraft in 2004. Cassini spacecraft will be launched in 1997 and arrive Saturn orbit in 2004 for a four-year mission of orbiting Saturn and flying by its largest moon Titan, which scientists believe containing materials just like earth at its primitive stage millions years ago.

Spacecraft attitude control system plays a crucial role in this mission. It has to stabilize the spacecraft attitude and track a set of complicated maneuver command profiles to within ±2 mrad pointing accuracy in the presence of external disturbance and internal plant uncertainty. Cassini spacecraft dynamics, disturbance and model have been introduced in [1], where a modern $\mathbf{H}^\infty$ controller was designed and compared to bang/bang control. In this paper, a fuzzy logic controller is developed for Cassini and compare to the same bang/bang controller.

*Presented at *1994 IEEE World Congress on Computational Intelligence, June 26 — July 2, 1994, Orlando, Florida*

0-7803-1896-X/94 $4.00 ©1994 IEEE

Fuzzy logic has become one of the most active and fruitful areas of research and applications ([?],[2] and the references therein). MathWorks is currently developing a MATLAB^{TM} toolbox that works with Simulink^{TM} for designing fuzzy logic control system [3]. Design algorithm and simulation are presented here in detailed.

2 Conventional Bang/Bang Attitude Control

The conventional spacrcraft controller using on/off thrusters consists of a bang/bang relay, a deadband and a set of thruster mapping logics. It is called Reaction Control Subsystem (RCS). Basically, it takes both position and rate error signals and processes through these three components. In general, both position and rate signals are computed from the spacecraft attitude estimator. The additional rate feedback (in Cassini, rate gain = 3) can provide damping to the overall system. Figure 1 shows a block diagram of the RCS controller.

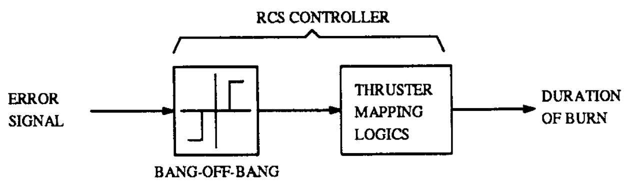

Figure 1: RCS Attitude Controller (Relay/Deadband + Thruster Logic).

A small deadband is also assigned to the controller so that the sensor noise can not trigger additional thruster activities. The minimum impulse bit defined in valve specification is about 7 mNs ± 35 %. Overall, the system will limit cycle with a peak-to-peak value approximately equal to the preset deadband. For Cassini spacecraft, the peak-to-peak deadband is currently set as 4 mrad to accommodate the pointing requirement.

Thruster Mapping Logic

Thruster mapping logic is an essential part of the RCS attitude controller. As shown in Figure 2, there are two sets of thrusters: Y-facing and Z-facing, where Y-facing thrusters control Z-axis motion and Z-facing thrusters control X,Y-axes turns. Each thruster has a backup module to be used in case the primary one fails. When RCS is functioning, eight thrusters are available to stabilize spacecraft 3-axis dynamics and provide precise control of its commanded attitude.

Based on the above concept, a set of logics has been developed:

- If X Torque ¡ 0, then thruster 1 and 2 are on
- If X Torque ¿ 0, then thruster 3 and 4 are on
- If Y Torque ¡ 0, then thruster 2 and 3 are on
- If Y Torque ¿ 0, then thruster 1 and 4 are on
- If Z Torque ¡ 0, then thruster 5 and 7 are on
- If Z Torque ¿ 0, tehn thruster 6 and 8 are on

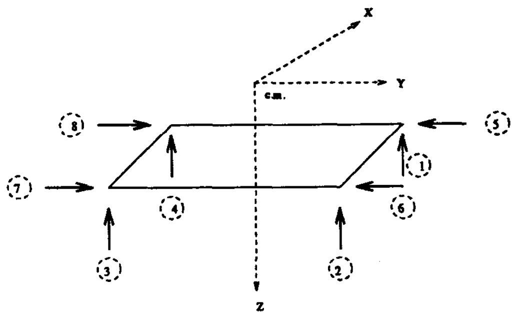

Figure 2: Thruster Locations and Firing Directions.

This set of simple logics seems very efficient to accomplish all of the Cassini spacecraft RCS maneuvers such as Titan flyby, sprint turn, probe release, reaction wheel momentum unload, and sun acquisitions, etc. The duration of burn for each thruster, Δt sec, is defined by the control designer to set an upper bound on the overall RCS duty cycle. It is also directly related to the fuel consumption. Currently, the thruster on time Δt is set to be fully open for the 125 msec rate group to reduce thruster cycles, which may end up using more fuel than it could have.

3 Fuzzy Attitude Control

One can substitute the regular thruster mapping logics with a set of fuzzy if-then rules. For instance, the fuzzy rules for thruster 4 would be

$$\begin{cases} \text{rule 1: } if\ tx \tilde{>} center,\ then\ out4 = 1, \\ \text{rule 2: } if\ ty \tilde{>} center,\ then\ out4 = 1, \\ \text{rule 3: } if\ tx \tilde{<} center\ and\ ty \tilde{<} center,\ then\ out4 = 0, \end{cases}$$

where $\tilde{>}$ and $\tilde{<}$ are the fuzzy versions for $>$ and $<$, respectively. However, the above rules do not take into consideration the constraint of no simultaneous diagonal fires. To accommodate this restriction, we obtain the following set of rules for thruster 4:

$$\begin{cases} \text{rule 1: } if\ tx \tilde{>} center\ and\ ty \tilde{>} -center,\ then\ out4 = 1, \\ \text{rule 2: } if\ tx \tilde{>} -center\ and\ ty \tilde{>} center,\ then\ out4 = 1, \\ \text{rule 3: } otherwise,\ out4 = 0. \end{cases}$$

This set of fuzzy rules are demonstrated in Figure 3, where (a) is rule 1, (b) is rule 2, and (c) is rule 3. The overall output of this fuzzy rule set is

$$output = \frac{w_1 f_1 + w_2 f_2 + w_3 f_3}{w_1 + w_2 + w_3},$$

where w_i and f_i are the firing strength and output, respectively, for rule i. If we choose the product as our T-norm operator, then

$$w_3 = (1 - w_1)(1 - w_2).$$

Also remember that $f_1 = f_2 = 1$ and $f_3 = 0$, therefore we have

$$output = \frac{w_1 + w_2}{1 + w_1 w_2}.$$

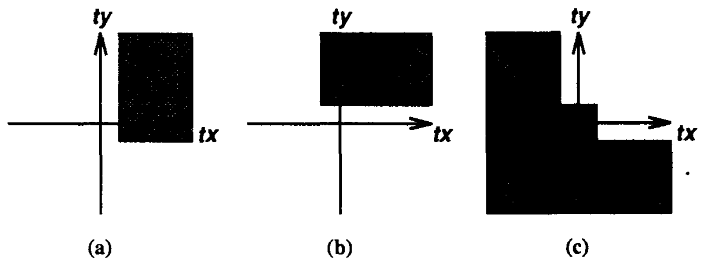

Figure 3: *Fuzzy rules for thruster 4: (a) rule 1; (b) rule 2; and (c) rule 3.*

The membership function (MF) we use to characterize $x \tilde{>} c$ is a generalized version of the common s membership function with three parameters c, s and k:

$$\mu_{x \tilde{>} c}(x) = \begin{cases} 0 & \text{if } x \leq c - s, \\ \frac{1}{2}[\frac{x-(c-s)}{s}]^{2k} & \text{if } c - s < x \leq c, \\ 1 - \frac{1}{2}[\frac{c+s-x}{s}]^{2k} & \text{if } c < x \leq c + s, \\ 1 & \text{if } c + s < x, \end{cases}$$

where c determines the cross-over point ($\mu_{x \tilde{>} c}(c) = 0.5$); s determines the spread of this MF ($0 < \mu_{x \tilde{>} c}(x) < 1$ whenever $c - s < x < c + s$); and k (together with s) control the slope of the entire curve (for instance, the slope at the cross-over point is $\mu'_{x \tilde{>} c}(x)|_{x=c} = k/s$). Figure 4 shows the physical meanings of these parameters. Figure 5 (a) and (b) demonstrate the effects of changing parameter s and k, respectively.

The MF for $x \tilde{<} -c$ is just an image of the MF for $x \tilde{>} c$ w.r.t Y-axis.

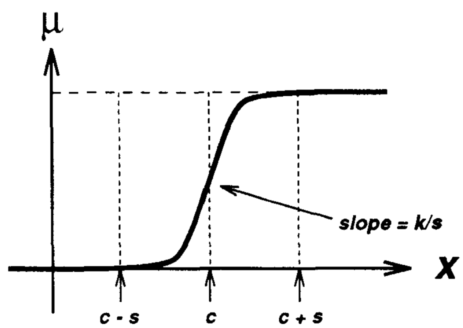

Figure 4: *Physical meanings of MF's parameters.*

4 Simulation and Result

A discrete nonlinear simulation was set up to evaluate both conventional and fuzzy attitude controllers (A & B). The sampling time is 125 msec. The spacecraft model consists only the rigid body Euler equations.

Figure 6 shows a comparison of a two degree step response in Y-axis for different RCS controller.

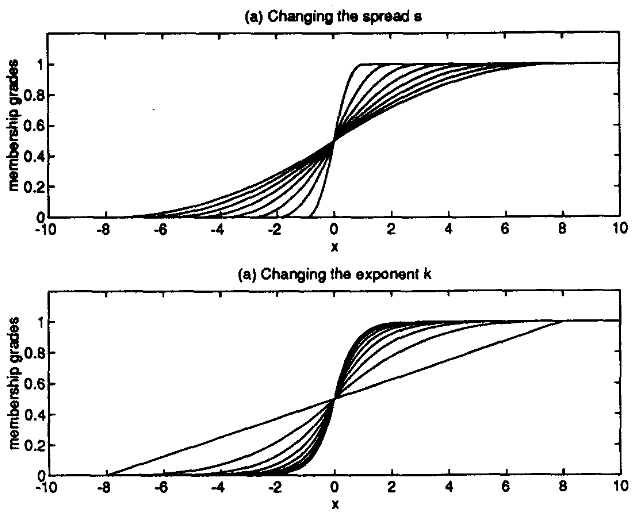

Figure 5: *The effects of changing MF's parameters: (a) change parameter s; (b) change parameter k.*

Table 1: Total Thruster On-time and Cycles

Controller	Total On-time	Cycle
Bang/Bang	77 Sec	30
Fuzzy A (Slope=1)	70 Sec	419
Fuzzy B (Slope=500)	75 Sec	46

Some observations:

- Both fuzzy controllers can track better than the conventional bang/bang controller
- By approximating the relay/deadzone with a continuous membership function, fuzzy controller A can save about 10 % fuel but ends up higher thruster on/off cycles
- By increasing the membership function slope (from 1 to 500), fuzzy controller B approaches bang/bang structure with much less thruster cycle

5 Conclusion

Spacecraft attitude control problem has been well known for decades. In this paper, a modern fuzzy logic controller has been developed to compare with the conventional bang/bang control on the issues involving tracking capability, thruster on-time/cycle trade-offs etc.

It has been shown that the fuzzy logic controller can track the system command better but ends up higher thruster on/off cycles. The design process of such a fuzzy logic controller is straightforward and systematic as shown in Section 3. The theory of fuzzy logic control is interesting and easy-to-use.

Future study will focus on comparing other fundamental feedback issues such as robustness, disturbance rejection, and sensor noise, etc. with a more complicated spacecraft model with fuel slosh mode and flexible body.

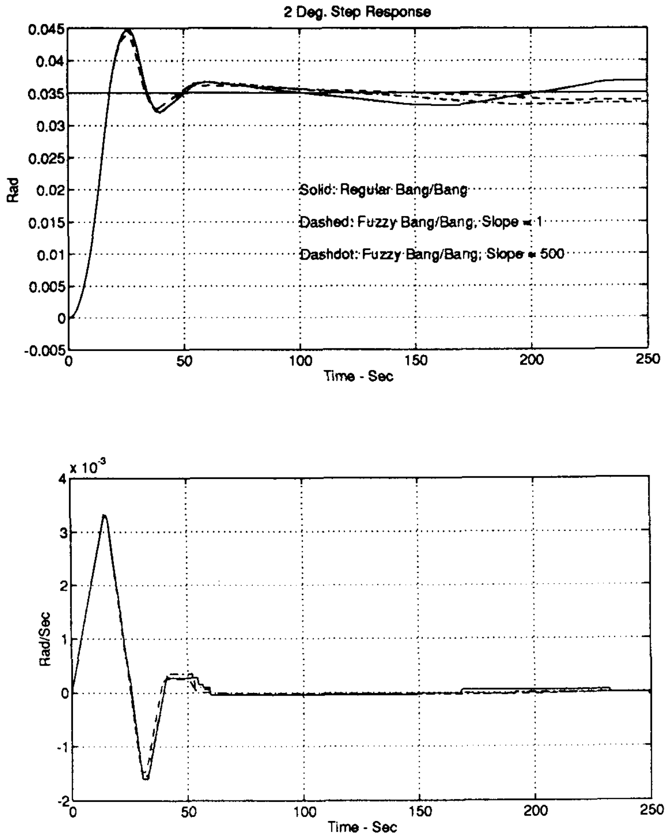

Figure 6: 2 Degree Step Response (Bang/Bang vs. Fuzzy).

6 Acknowledgement

The research described in this paper was partially carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Asronautics and Space Administration.

References

[1] R. Y. Chiang, S. Lisman, E. Wong, P. Enright, W. Breckenridge, M. Jahan, "Robust Attitude Control for Cassini Spacecraft Flying By Titan," *Proc. of AIAA Guidance and Control Conf.*, Monterey, CA., Aug. 1993.

[2] L. A. Zadeh, "Fuzzy Sets," *Information and Control*, 8:338-353, 1965.

[3] J. S. Roger Jang, "Self-Learning Fuzzy Controller Based on Temporal Back-Propagation," *IEEE Trans. on Neural Networks*, vol. 3, no. 5, pp 714-723, Sept. 1992.

[4] J. S. Roger Jang and N. Gulley, *Fuzzy Logic Toolbox*, The MathWorks, Inc., to be released 1994.