Multi-Objective Control of Spacecraft Attitude Maneuver Based on Takagi-Sugeno Fuzzy Model

Xihai Zhang*†, Ming Zeng‡

*Space Control and Inertial Technology Research Centre, Harbin Institute of Technology, 150001, Harbin, China (e-mail: xhzhang1979@yahoo.com.cn).
†College of Electrical and Information, Northeast Agricultural University, 150030, Harbin, China (e-mail: xhzhang1979@yahoo.com.cn).
‡Space Control and Inertial Technology Research Centre, Harbin Institute of Technology, 150001, Harbin, China (Corresponding author Ming Zeng, e-mail: zengming@hit.edu.cn).

Abstract: The multi-objective control for a rigid spacecraft maneuver is designed in this paper, which contains disturbances rejection, decay rate, and input constraint. Firstly, the rigid spacecraft model consisting of the dynamic and kinematics equation are provided. This nonlinear system is converted into a Takagi-Sugeno fuzzy model. And based on the parallel distributed compensation (PDC) scheme, a fuzzy state feedback controller is designed, which guarantees the closed-loop system to meet the multi-objective design requirements. Furthermore, the problem is reduced to a convex optimization involving linear matrix inequalities (LMIs). The simulation results demonstrate that the proposed controller can guarantee the stability of control system and good disturbance attenuation.

Keywords: H_∞ control, T-S fuzzy model, multi-objective, attitude control, decay rate.

1. INTRODUCTION

The attitude maneuver control of spacecraft has important applications, such as the spacecraft surveillance and communication. This attitude maneuver often needs to achieve the highly accurate pointing and fast slewing in the presence of large environmental disturbances, large uncertainties and so on. Therefore, the attitude control of spacecraft is becoming more and more sophisticated and it is important to find new and more efficient ways to control the spacecraft attitude maneuver. It has attracted considerable attentions and many results have been reported in recent decades (Wen et al., 1991; Xu et al., 1991; Wang et al., 1996; Krstic et al., 1999; Marcu, 2011).

More recently, fuzzy control has been proposed as an alternative approach to conventional control techniques for the complex nonlinear systems (Tsai et al., 2008; Chen, 2009; Wang et al., 2009; Chen, 2010; Lee et al., 2010; Lendek et al., 2010). The primary advantage of the fuzzy controller is the ability to easily incorporate heuristic rule-based knowledge from experts in the control strategy. In aerospace engineering, fuzzy control has become one of the most favourable research topics. Wang (2009) proposes a novel fuzzy tracking control method, which is used for the attitude tracking problem of a reusable launch vehicle. Chiang and Jang (1991) develop a fuzzy logic attitude controller for Cassini spacecraft. They show that the fuzzy controller can track the reference command better than the conventional controller for the attitude control system. Pedrycz and Ramanna (1997) present a hierarchical architecture of fuzzy neural attitude control for the satellite based on fuzzy gain scheduling concept. They show that the nonlinear characteristics of the controllers contribute to better control characteristics of the overall system. Therefore, T-S fuzzy control has become powerful engineering tools for modelling and control of complex dynamic systems. Recent researches on fuzzy control have been devoted to model based fuzzy control systems that guarantee not only stability, but also performances of closed-loop fuzzy control systems (Song et al., 2006; Du et al., 2009).

Due to the limited power of actuator, the actual control input should be considered in practical attitude control system. At present, many researchers have paid great attention to the analysis and synthesis of control systems with input constraint (Park et al., 2004). The means utilized to treat with input constraint include designing low gain control laws, estimating the domain of attraction and so on (Cao et al., 2003). But, it is still a challenge to develop an appropriate control strategy for dealing with the highly nonlinear dynamics of spacecraft attitude. In addition, the asymptotically stable of closed-loop system under large environmental disturbances and rapid target retargeting maneuver should be considered at the same time. However, during the past decades, the most attentions for attitude control have been paid to many single objective control. Therefore, it seems that how to design a multi-objective control of the rigid spacecraft by the T-S fuzzy control, which motivates our research in this paper.

Following the above discussions, the problem of multi-objective control for a three-axis rigid spacecraft maneuver is investigated. Firstly, the rigid spacecraft model consisting of dynamic and kinematics equation are provided. This nonlinear model is converted into a Takagi-Sugeno fuzzy model. And based on the parallel distributed compensation scheme, a fuzzy state feedback controller is designed based on the obtained T-S fuzzy model, which guarantees the multi-objective design requirements of the closed-loop control system. The sufficient conditions for the existence of such a controller are derived in the form of linear matrix inequalities (LMIs) which can be solved efficiently via the Matlab Linear Matrix Inequalities Toolbox.

The rest of this paper is organized as follows. The T-S fuzzy modelling and problem formation are introduced in Section 2. The controller design is considered in Section 3. An illustrative example shows the effectiveness of the proposed control design method in Section 4 and the paper is concluded in Section 5.

Notations: The notation used throughout the paper is fairly standard. The superscript "T" stands for matrix transposition; R^n denotes the n-dimensional Euclidean space and $R^{n\times m}$ denotes the set of all $n\times m$ real matrices; In symmetric block matrices or complex matrix expressions, an asterisk (*) represents a term that is induced by symmetry. I and 0 denote the identity matrix and zero matrix with compatible dimensions, respectively. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations.

2. TAKAGI-SUGENO FUZZY MODELLING AND PROBLEM FORMULATION

In this section, a three-axis rigid spacecraft model is considered based on the T-S fuzzy model for spacecraft dynamics and kinematics. The spacecraft is assumed to be a rigid body by using the three reaction wheels that provide torques about three mutually perpendicular axes. The dynamics of rigid spacecraft (Park et al., 2001) can be written as

$$J\dot{\omega} + \Phi(\omega)J\omega = T_c + T_d\,, \tag{1}$$

where some physical parameters, $J \in R^{3\times 3}$ represents the positive definite, symmetric spacecraft inertia matrix and $J = J^{-1} > 0$, $\omega \in R^3$ represents the rigid body angular velocity, $T_c \in R^3$ is the control torque. T_d is an external disturbance torque (solar radiation, interaction with other bodies in space, etc.), $\Phi(\omega) \in R^{3\times 3}$ is a 3×3 skew-symmetric matrix:

$$\Phi(\omega) = \begin{bmatrix} 0 & \omega_z(t) & -\omega_y(t) \\ -\omega_z(t) & 0 & \omega_x(t) \\ \omega_y(t) & -\omega_x(t) & 0 \end{bmatrix}. \tag{2}$$

The kinematics equation of the rigid spacecraft expressed by the Cayley-Rodrigues parameters vector:

$$\dot{\rho} = H(\rho)\omega\,, \tag{3}$$

$\rho \in R^3$ is the Cayley-Rodrigues parameters vector describing the body attitude, the matrix-valued function H denotes the kinematics Jacobian matrix for the Cayley-Rodrigues parameters given by

$$H(\rho) = 1/2(I_3 - \Phi(\rho) + \rho\rho^T)\,. \tag{4}$$

It is known that the T-S fuzzy system is one of the most popular fuzzy systems in model-based fuzzy control. The fuzzy model proposed by Takagi and Sugeno is described by fuzzy IF-THEN rules which represent local linear input and output relations of a nonlinear system. The continuous T-S fuzzy system can be expressed as

If $Z_1(t) = M_{i1}$ and … and $Z_n(t) = M_{in}$, then

$$\begin{aligned} &\dot{x}(t) = A_i x(t) + B_i u(t) + D_i w(t), i = 1,\ldots,r \\ &y = Cx \end{aligned}\,, \tag{5}$$

where M_{ij} is the fuzzy set, $j=1\ldots n$, $Z_n(t)$ is the premise variable, $x(t)$ is the state vector, $u(t)$ is the control input, r is the number of model rules, n is the number of premise variable.

The T-S fuzzy model is then constructed according to the weighting of each linear model given as follows

$$\begin{aligned} &\dot{x}(t) = \sum_{i=1}^{r} h_i[z(t)]\{A_i(t)x(t) + B_i u(t) + D_i w(t)\} \\ &y = Cx(t) \end{aligned}\,, \tag{6}$$

where the membership functions i^{th} local model are

$$h_i[z(t)] = w_i[z(t)] / \sum_{i=1}^{r} w_i[z(t)], i = 1,\ldots,r\,, \tag{7}$$

where,

$$w_i[z(t)] = \prod_{j=1}^{n} M_{ij}[z_j(t)]\,\cdot \tag{8}$$

$M_{ij}[z_j(t)]$ is the grade of membership of $z_j(t)$ in the fuzzy set M_{ij} . The $h_i[z(t)], i = 1,\ldots,r$, hold a convex sum property:

$$\sum_{i=1}^{r} h_i[z(t)] = 1,\;\; h_i[z(t)] \geq 0, i = 1,\ldots,r\,, \tag{9}$$

To employ the model-based fuzzy control, a T-S fuzzy model is constructed according to the nonlinear equations (1), (3). In this study, the angular velocity and the Cayley-Rodrigues parameter are selected as the fuzzy premise variables. We are defining follows:

$x_1 = \omega_1$, $x_2 = \omega_2$, $x_3 = \omega_3$, $x_4 = \rho_4$, $x_5 = \rho_5$, $x_6 = \rho_6$, $x_\omega = [x_1 x_2 x_3]^T$, $x_\rho = [x_4 x_5 x_6]^T$, $x = [x_\omega^T x_\rho^T]^T$.

In order to reduce the complicacy of system, we try to use as few rules as possible and choose the nine operating points,

$[x_{\omega i} x_{\rho i}]$ = [0 0], [0 0.15], [0 -0.15], [0.1 0], [0.1 0.15], [0.1 -0.15], [-0.1 0], [-0.1 0.15], [-0.1 -0.15].

Therefore, the T-S fuzzy model in (6) can be written into the following form

$$\dot{x}(t) = \sum_{i=1}^{9} h_i(z(t)\{A_i x(t) + B_i u(t) + D_i w(t)\} \qquad (10)$$
$$y(t) = Cx(t),$$

where

$$A_i = \begin{bmatrix} -J^{-1}\Phi(\omega_i)J & 0_3 \\ \frac{1}{2}(I_3 + \rho_i\rho_i^T) & \frac{1}{2}\Phi(\omega_i) \end{bmatrix}, B_i = D_i = \begin{bmatrix} J^{-1} \\ 0_3 \end{bmatrix}, C = I_6,$$

$$h_i[z(t)] = \frac{\prod_{j=1}^{6} M_{ij}(z_j(t))}{\sum_{i=1}^{9}\prod_{j=1}^{6} M_{ij}(z_j(t))}.$$

The membership functions of fuzzy sets M_{ij} are defined as in Fig.1, 2.

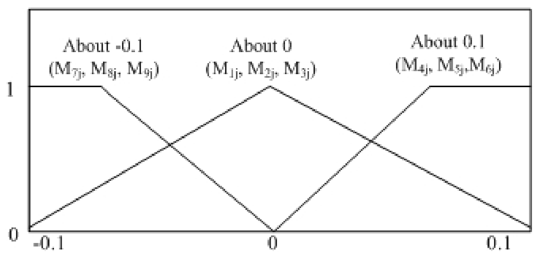

Fig. 1. Membership functions for fuzzy set M_{ij} , *j=1,2,3*

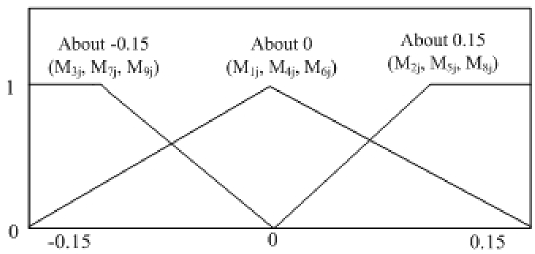

Fig. 2. Membership functions for fuzzy set M_{ij} , *j=4,5,6*

Remark 1. In this paper, the case of T-S fuzzy system with a common input matrix (B_1 = … = B_9 = B=D) is considered only.

The maneuver process can be described by the transformation of state vector $\omega(t), \rho(t)$ from nonzero initial state $\omega(0)$, $\rho(0)$ to the terminal state $\omega(t_r)$, $\rho(t_r)$ t_r is the maneuver time.

In this study, the following important aspects need be taken into consideration simultaneously:

(1) The closed-loop system is asymptotically stable and $\|T_{zw}\|_\infty < \gamma$.

(2) Decay rate. From a practical point of view, the spacecraft requires an attitude control system which provides rapid target retargeting maneuver.

(3) Input constraint. In view of the limited power of actuator, the actual control torque should be confined into a certain range, which means that

$$\|u(t)\|_2 \le u_{\max}, \qquad (11)$$

where $u_{\max}$ denotes the maximum input torque.

3. CONTROLLER DESIGN

In this section, the multi-objective state-feedback controller is investigated. The design requirements in Section 2 will be analyzed separately, and the obtained results will be utilized for the controller design.

The fuzzy controller for T-S model (10) is carried out based on the PDC scheme. For the T-S fuzzy model (10), the fuzzy state feedback controller is constructed as follows,

$$u(t) = -\sum_{i=1}^{9} h_i(z(t))K_i x(t), \qquad (12)$$

where K_i is the state feedback gain matrix to be designed.

Note that the T-S fuzzy controller shares the same fuzzy set with the T-S fuzzy model (10), where h_i is the same as the defined in (10). The parameters K_i in (12) should be designed to meet the stability and other performance requirements.

By substituting (12) into (10), the close-loop system is obtained as

$$\dot{x}(t) = \sum_{i=1}^{9}\sum_{j=1}^{9} h_i(z(t))h_j(z(t))\{A_i - B_i K_i\}x(t). \qquad (13)$$

The equation (13) can be rewritten as

$$\dot{x}(t) = \sum_{i=1}^{9} h_i(z(t))h_i(z(t))G_{ii}x(t) + 2\sum_{i=1}^{9}\sum_{i<j} h_i(z(t))h_j(z(t))\{\frac{G_{ij}+G_{ji}}{2}\}x(t), \qquad (14)$$

where, $G_{ji} = A_i - B_i K_j$.

Here, the angular velocitys and Cayley-Rodrigues parameters are chosen as the control output,

$$Z(t) = \sum_{i=1}^{9} h_i(Z(t))C_i x(t), i = 1, 2, \cdots, 9. \qquad (15)$$

The design requirements mentioned above will be analyzed separately, and the obtained results will be utilized for the controller design. First, we recall the following results which will be used in our later development, and their proofs can be found in (Tanaka et al., 2001, Du et al., 2009).

Lemma 1. Assume that the number of rules that fire for all t is less than or equal to s, where $1 < s \le r$. The equilibrium of continuous fuzzy control system described by (14) is globally asymptotically stable if there exists a common positive definite matrix P and a common positive semi-definite matrix Q such that.

$$G_{ii}^T P + PG_{ii} + (s-1)Q < 0, \tag{16}$$

$$\left(\frac{G_{ij}+G_{ji}}{2}\right)^T P + P\left(\frac{G_{ij}+G_{ji}}{2}\right) - Q \le 0, i<j \;\; s.t.\; h_i \cap h_j \ne \phi. \tag{17}$$

where s>1.

Furthermore, for practical engineering, the spacecraft requires the attitude control system can provide rapidly maneuver capabilities. Thus, besides the *Lemma 1*, the decay rate fuzzy controller is further considered at the same time.

Lemma 2. The condition for all trajectories is equivalent to

$$G_{ii}^T P + PG_{ii} + (s-1)Q + 2aP < 0, \tag{18}$$

$$\left(\frac{G_{ij}+G_{ji}}{2}\right)^T P + P\left(\frac{G_{ij}+G_{ji}}{2}\right) - Q + 2aP \le 0, i<j \;\; s.t.\; h_i \cap h_j \ne \phi \tag{19}$$

where $a > 0$. Therefore, the largest lower bound on the decay rate can be found by solving the following GEVP in X and a

$$\max_{X,Y,M_1,\dots,M_r} \alpha$$

subject to $X > 0, Y \ge 0$,

$$-XA_i^T - A_i X + M_i^T B_i^T + B_i M - (S-1)Y - 2aX > 0, \tag{20}$$

$$\begin{aligned}&2Y - XA_i^T - A_i X - XA_j^T - A_j X + M_j^T B_i^T + B_i M_j \\ &+ M_i^T B_j^T + B_j M_i - 2aX \ge 0, i<j \;\; s.t.\; h_i \cap h_j \ne \varphi,\end{aligned} \tag{21}$$

where $X=P^{-1}$, $M_i=K_iX$, $Y=XQX$. The feedback gains K_i, a common P and a common Q can be obtained as

$$P = X^{-1}, K_i = M_i X^{-1}, Q = PYP,$$

from the solution X, Y, M_i.

At last, in order to design attitude control system to perform adequately in external disturbance environments, the L_2 gain of the stable assumed system (10) with (15) is chosen as the performance measure, which is defined as

$$\|T_{zw}\|_\infty = \sup_{\|w\|_2 \ne 0} \frac{\|z\|_2}{\|w\|_2} \le \gamma. \tag{22}$$

Here, $\|z\|_2^2 = \int_0^\infty z^T(t)z(t)dt$, $\|w\|_2^2 = \int_0^\infty w^T(t)w(t)dt$, and the supremum is taken over all nonzero trajectories of the system (10) with $x(0)=0$. Our goal is to design a fuzzy controller (12) such that the fuzzy system (10) with controller (12) is quadratically stable and the L_2 gain (22) is minimized.

Lemma 3. The feedback gains K_i that stabilize the fuzzy model and minimize γ can be obtained by solving the following minimization problem based on LMIs.

$$\min_{x,M_1,\dots,M_r} \gamma^2$$

subject to $X > 0$,

$$\begin{bmatrix} \begin{pmatrix} -\frac{1}{2}\{XA_i^T - M_j^T B_i^T + A_i X - B_i M_j \\ + XA_j^T - M_i^T B_j^T + A_j X - B_j M_i\} \end{pmatrix} & -\frac{1}{2}(E_i+E_j) & \frac{1}{2}X(C_i+C_j)^T \\ -\frac{1}{2}(E_i+E_j)^T & \gamma^2 I & 0 \\ \frac{1}{2}(C_i+C_j)X & 0 & I \end{bmatrix} \ge 0, \tag{23}$$

$$i \le j \;\; s.t. h_i(z(t)) \cap h_j(z(t)) \ne \phi,$$

where $M_i = K_i X$.

Lemma 4. Assume that the initial condition $x(0)$ is known, the constraint $\|u(t)\|_2 \le \mu$ is enforced at all times $t \ge 0$, if the LMIs

$$\begin{bmatrix} 1 & x(0)^T \\ x(0) & X \end{bmatrix} \ge 0, \tag{24}$$

$$\begin{bmatrix} X & M_i^T \\ M_i & \mu^2 I \end{bmatrix} \ge 0, \tag{25}$$

hold, where $X=P^{-1}$, $M_i = K_iX$.

The lemmas 1-4 formulate the conditions under which the closed-loop system meets the multi-objectives. Based on these Lemmas, the following theorem presents a controller design method via convex optimization.

Theorem 1. For the spacecraft maneuver control system in (14), a given scalar γ and $a > 0$, $1 < s \le r$ under the constraint input in (11), the closed loop system is asymptotically stable with disturbance attenuation and the decay rate, if there exist s matrices X_i, Y_i, M_i satisfying

$$-XA_i^T - A_i X + M_i^T B_i^T + B_i M - (s-1)Y - 2aX > 0, \tag{26}$$

$$\begin{aligned}&2Y - XA_i^T - A_i X - XA_j^T - A_j X + M_j^T B_i^T + B_i M_j \\ &+ M_i^T B_j^T + B_j M_i - 2aX \ge 0, i<j \;\; s.t.\; h_i \cap h_j \ne \varphi,\end{aligned} \tag{27}$$

$$\begin{bmatrix} \begin{pmatrix} -\frac{1}{2}\{XA_i^T - M_j^T B_i^T + A_i X - B_i M_j \\ + XA_j^T - M_i^T B_j^T + A_j X - B_j M_i\} \end{pmatrix} & -\frac{1}{2}(E_i+E_j) & \frac{1}{2}X(C_i+C_j)^T \\ -\frac{1}{2}(E_i+E_j)^T & \gamma^2 I & 0 \\ \frac{1}{2}(C_i+C_j)X & 0 & I \end{bmatrix} \ge 0, \tag{28}$$

$$\begin{bmatrix} 1 & x(0)^T \\ x(0) & X \end{bmatrix} \geq 0, \quad (29)$$

$$\begin{bmatrix} X & M_i^T \\ M_i & \mu^2 I \end{bmatrix} \geq 0, \quad (30)$$

where, $X > 0, Y \geq 0, P = X^{-1}, K_i = M_i X^{-1}, Q = PYP$. Furthermore, the desired state feedback control law is given by $u(t) = \sum_{i=1}^{9} h_i(z(t)) K_i x(t)$.

Proof: we can see that all the conditions listed in Lemma 1-4 can be ensured by (26)-(30), which means that the controller design requirements can be guaranteed by these inequality constraints. And it is obvious that the desired controller can be calculated by $K_i = M_i X^{-1} (i = 1 \dots 9)$. The proof is completed. □

Remark 2. The scalar γ can be included as an optimization variable to obtain a reduction of the H_∞ disturbance attenuation level bound. Then, the minimum H_∞ disturbance attention level bound in terms of the feasibility of admissible controllers can be readily found by solving the following convex optimization problem:

Minimize γ subject to the LMIs in Theorem 1.

4. ILLUSTRATIVE EXAMPLE

In this section, an example to illustrate the effectiveness of the proposed multi-objective controller design method is provided.

Here, the maneuver of rigid spacecraft is considered. The initial condition is $\omega(0) = [0.08,-0.05,0.1,0.12,0.06,-0.08]^T$. The moment inertia I of spacecraft is [127 1.8 -3.4; 1.8 117 -2.3; -3.4 -2.3 210] $kg{\cdot}m^2$. Then purpose is to design a state feedback controller, such that the closed-loop system satisfies requirements in Section 2. Assume that the maximum input control torque is 0.01$N{\cdot}m$.

At first, the situation with external perturbations is considered. The disturbance is considered as follows,

$$T_{dx} = 1.2 \times 10^{-5}(3\cos \omega_0 t + 1)$$
$$T_{dx} = 1.5 \times 10^{-5}(1.5 \sin \omega_0 t + 3\cos \omega_0 t) N \cdot m,$$
$$T_{dx} = 1.2 \times 10^{-5}(3 \sin \omega_0 t + 1)$$

where $\omega_0 = 0.001 rad/s$ is the orbit angular velocity.

Applying the controller in Theorem 1 to the original system (1), (3), and then solving the convex optimization problem, we can obtain the minimum guaranteed closed-loop H_∞ performance $\gamma = 0.1338$. The time response of angular velocity and the Cayley-Rodrigues parameters are depicted respectively in Fig.3, 4. From the simulation results, it can be obtained that the design controller can make the system stable in a short time under the large disturbance. In practical design, due to the limited power of actuator, the actual control input torque should be considered. The variations of control input torque in three axes are depicted in Fig.5. From the Fig.5, it can be concluded that the input torque component in T_1 is the largest, which is obvious due to the initial state (the angular velocity ω_1 is the largest when $t=0$). At the same time, even the largest input torque of T_3 is too bellow the maximum allowed torque, which means that the input constraint can be guaranteed by the designed controller. Therefore, it can be concluded that the control strategy is reasonable and can effectively restrain the external disturbances.

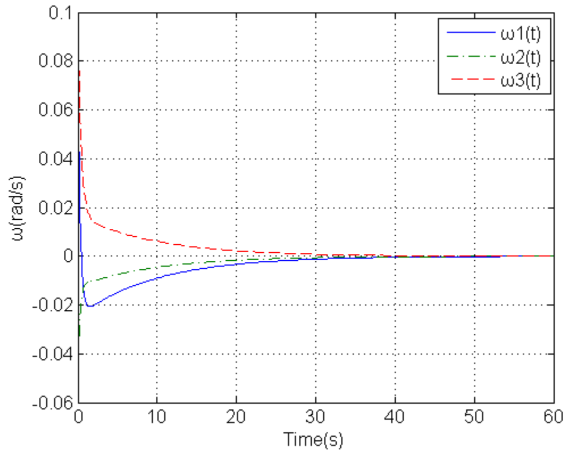

Fig. 3. Angular velocity response

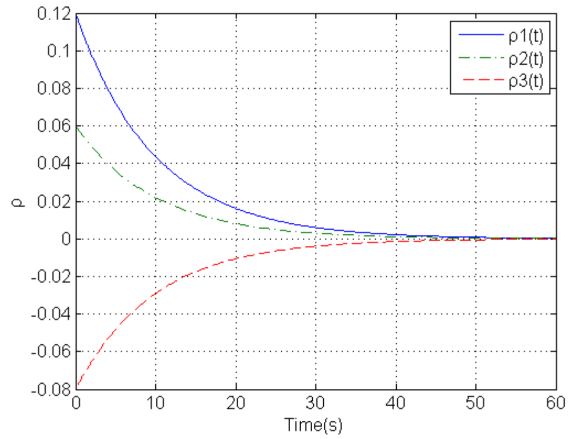

Fig. 4. Cayley-Rodrigues parameters response

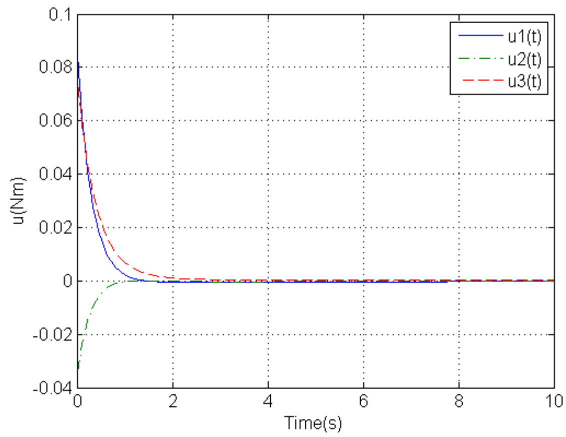

Fig. 5. Control input response

5. CONCLUSIONS

A new multi-objective state-feedback controller for spacecraft attitude control subject to external perturbation and input constraint has been proposed. Firstly, the nonlinear dynamic and kinematics of the three-axis rigid spacecraft have been represented as a T-S fuzzy model based on the parallel distributed compensation scheme. By using Lyapunov method and linear matrix inequality techniques, the controller design problem has been transformed into a convex optimization problem with linear matrix inequality constraint. An illustrative example has demonstrated that the proposed controller can guarantee the stability of control system and good disturbance attenuation. But, due to the measure errors or perturbations among the objects in space, the angular velocity ω can not be ascertained online accurately. On the other hand, there also exist inevitable inertia matrix uncertainties. Therefore, the future research direction is that the system model should be considered with these modelling uncertainties, so as to improve the robustness.

6. ACKNOWLEDGEMENTS

This work was supported in part by the National Natural Science Foundation of China (31101080), by Science and Technology Research Project of Heilongjiang Provincial Department of Education (12511040).

REFERENCES

Cao Y.Y. and Lin Z.L. (2003). Robust stability analysis and fuzzy-scheduling control for nonlinear systems subject to actuator saturation. *IEEE Transactions on Fuzzy System*, 11(1), 57-67.

Chen C.W. (2009). Adaptive fuzzy sliding mode control for seismically excited bridges with lead rubber bearing isolation. *International Journal Uncertain Fuzziness and Knowledge-Based Systems*, 17(5), 705-727.

Chen C.Y. (2010). Fuzzy control for an oceanic structure: A case study in time-delay TLP system. *Journal of Vibration and Control*, 16(1), 1651-1672.

Chiang R.Y. and Jang J.S.R. (1994). Fuzzy logic attitude control for cassini spacecraft. In *Proceeding of the 3rd IEEE World Congress on Computational Intelligence*, Orlando, FL, USA, 1532-1537.

Du H.P. and Zhang N. (2009). Fuzzy control for nonlinear uncertain electrohydraulic active suspensions with input constraint. *IEEE Transactions on Fuzzy System*, 17(2), 343-356.

Krstic M. and Tsiotras P. (1999). Inverse optimal stabilization of a rigid spacecraft. *IEEE Transactions on Automatic Control*, 44(5), 1042-1049.

Lee D.H., Park J.B. and Joo Y.H. (2010). Robust H∞ control for uncertain nonlinear active magnetic bearing systems via Takagi-Sugeno fuzzy models. *International Journal of Control, Automation, and Systems*, 8(3), 636-646.

Lendek Zs., Babusk R. and De Schutter B. (2010). Stability bounds for fuzzy estimation and control. *Control Engineering and Applied Informatics*, 12(3), 3-12.

Marcu E.(2011). Fuzzy logic approach in real-time UAV control. *Control Engineering and Applied Informatics*, 13(1), 12-17.

Park Y., Tahk M. J. and Park J.(2001). Optimal stabilization of Takagi-Sugeno fuzzy systems with application to spacecraft control. *Journal Guidance Control Dynamics*, 24(4), 767-777.

Park Y., Tahk M. J. and Bang H. (2004). Design and analysis of optimal controller for fuzzy systems with input constraint. *IEEE Transactions on Fuzzy System*, 12(6), 766-779.

Pedrycz W., Peters J.F. and Ramanna S. (1997). Hierarchical fuzzy neural attitude control for satellites. In *Proceeding of IEEE aerospace conference*, Snowmass at Aspen, CO, USA 385-400.

Song B., Ma G.F. and Li C.J.(2006). Robust fuzzy controller design for a rigid spacecraft attitude regulation system. In *Proceeding of the 1st International Symposium on Systems and Control in Aerospace and Astronautic*, Harbin, China, 424-429.

Tanaka K. and Wang H.O. (2001). *Fuzzy control systems design and analysis: A linear matrix inequality approach*. Wiley, New York.

Tsai C.H., Chen C.W., Chiang W.L. (2008). Application of geographic information system to the allocation of disaster shelters via fuzzy models. *Engineering Computations*, 25(1), 86-100.

Wang H., Ikeda T. and Griffin M. (1996). An approach to fuzzy control of nonlinear system: stability and design issues. *IEEE Transactions on Fuzzy System*, 4(1), 14-23.

Wang Y.H., Wu Q.X. and Jiang C.S. (2009). Reentry attitude tracking control based on fuzzy feed forward for reusable launch vehicle. *International Journal of Control, Automation, and Systems*, 7(4), 503-511.

Wen J.Y. and Kreutz-Delgado K. (1991). The attitude control problem. *IEEE Transactions on Automatic Control*, 36(10), 1148-1162.

Xu Y., Shum H.Y. ,Kanade T. and Lee J. J. (1991). Parameterization and adaptive control of space robot systems. *IEEE Transactions on Aerospace Electronic System*, 30(2), 435-451.