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Fuzzy Sliding Mode for Spacecraft Formation Control in Eccentric Orbits

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The problem of relative motion control for spacecraft formation flying in eccentric orbits is considered in this paper. Due to the presence of nonlinear dynamics and external disturbances, a robust fuzzy sliding mode controller is developed. The slopes of sliding surfaces of the conventional sliding mode controller are tuned according to error states using a fuzzy logic and reach the pre-defined slopes. The controller is designed based on the nonlinear model of relative motion and J_2 perturbation and atmospheric drag are considered as external disturbances. Using the Lyapunov second method, the stability of the closed-loop system is guaranteed. The performance of the presented controller in tracking the desired reference trajectory is compared to a sliding mode controller in which simulation results confirm the superior performance of the proposed controller.

Keywords: Sliding mode, control, spacecraft formation flying, eccentric orbits, fuzzy

Nomencalture

$C_1 = \{X, Y, Z\}$	Inertial coordinate system
$C_2 = \{x, y, z\}$	Moving frame
C_D	Drag coefficient
$\boldsymbol{d}$	External disturbance vector
$\boldsymbol{D}$	Differential perturbation vector
J_2	Earth oblateness perturbation
$\boldsymbol{k} = diag(k_1, k_2, k_3)$	Gain matrix
m	Mass of spacecraft
$\boldsymbol{r}_f$	Position vectors of follower
$\boldsymbol{r}_l$	Position vectors of leader
R_e	Mean equatorial radius of the Earth
$\boldsymbol{s} = [s_1, s_2, s_3]^T$	Sliding surfaces
$sat(\boldsymbol{s},\varphi) = \begin{bmatrix} sat(s_1,\varphi), s \\ at(s_2,\varphi), \\ sat(s_3,\varphi) \end{bmatrix}^T$	Column matrix of saturation functions
$\mathrm{sgn}(\boldsymbol{s}) = \begin{bmatrix} \mathrm{sgn}(s_1), \\ \mathrm{sgn}(s_2), \\ \mathrm{sgn}(s_3) \end{bmatrix}^T$	Column matrix of sign functions
$\boldsymbol{u}$	Control input vector
$\boldsymbol{u}_{f_{eq}}$	Equivalent control input of the follower
$\lambda = diag(\lambda_1, \lambda_2, \lambda_3)$	Slopes of the sliding surfaces
$\mu = 398\,600\ \mathrm{km}^3/\mathrm{s}^2$	Constant of the Earth gravity
$\rho = [x \quad y \quad z]^T$	Relative position vector of the follower with respect to the leader
σ	Local atmosphere density
φ	Boundary layer thickness
ω_l	Angular velocity of the leader
S	Effective surface

Introduction

Spacecraft formation flying (SFF) has increasingly attracted attention in recent years. Using this approach, a large and expensive spacecraft is replaced with a number of smaller, less expensive and cooperative spacecrafts which work as an integrated unit and fulfill the purpose of the mission. Besides the simpler design and faster launch, the main advantage of this approach

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lies in its reliability and flexibility; so it is leading to novel and innovative applications in space and the Earth science missions including observation of the Earth and its atmosphere, geodesy, deep space imaging with high resolution, in-orbit servicing and spacecraft maintenance [1]. A common method for implementation of SFF is Leader/Follower approach. Based on this method, one spacecraft is controlled as a leader in a reference orbit while the other spacecrafts - as followers- adjust their positions relative to the leader and track the desired relative trajectory.

Practical implementation of SFF depends on accurate control of each spacecraft in formation. In general, the SFF design consists of two main parts: guidance and control. In guidance, the desired trajectory for each spacecraft is designed. Here, the trajectory should be close to the natural dynamics of the system to minimize the fuel cost. Furthermore, the reference trajectory can also be developed so as to include the external disturbances [2,3]. The purpose of the control part is to design an effective controller to track the predetermined desired trajectory in the presence of external disturbances. Dominant perturbation effects on satellite are due to non-spherical shape of the Earth, atmospheric drag, gravitational attractions from other celestial bodies, and solar radiation pressure [4]. Because of the presence of the nonlinear coupled dynamics and external disturbances, an exact robust controller is necessary for the spacecraft formation control.

Sliding mode controller (SMC) is a robust controller that has satisfactory performance for nonlinear systems subjected to uncertainties and disturbances. This controller has been used for spacecraft formation control in several studies. An effective robust method for satellite control using a sliding mode controller was presented by Yeh et al. [5]. They used Hill's equations and determined the equivalent damping ratio, bandwidth and thrust so that the fuel cost was minimized. Hui et al. [6] designed a low-level SMC for SFF based on nonlinear relative dynamics of circular reference orbit to control leader, follower and entire-formation maneuvering in low-Earth orbits. Bae and Kim [7] used SMC to control the relative position and attitude of the spacecraft in a formation. To improve the performance of the sliding mode controller, they designed an adaptive controller based on neural network to compensate for the modeling error, external disturbance and nonlinearities. Terminal SMC technique has also be applied to spacecraft formation control and reconfiguration in some researches [8,9]. Wang and Sun designed an adaptive terminal sliding mode control for spacecraft formation flying. They used Leader/Follower architecture and analytically proved the convergence of the desired trajectory to a neighborhood in finite time [10]. Recently a fuzzy sliding mode control with adaptive tuning technique has been presented for spacecraft formation control [11]. In this study a fuzzy logic inference mechanism is utilized to implement a fuzzy reaching control law to eliminate chattering phenomenon. An adaptive algorithm also considered to confront the uncertainties existing in the dynamic model of the agents.

Note that, most studies on spacecraft formation flying are about circular reference orbits. In the present work, a new fuzzy sliding mode controller has been designed for spacecraft formation flying in eccentric orbits. Herein, the slopes of sliding surfaces are tuned based on error states using a fuzzy algorithm. They move from a close distance to the system state to the pre-defined slopes. As a result, the required time for reaching to the sliding surface decreases and trajectory tracking will be accomplished more quickly. Then by increasing the slope, the final tracking error decreases. Sugeno-type fuzzy inference in form of singleton is applied. The design procedure of the controller is based on the nonlinear relative dynamics and J_2 perturbation and atmospheric drag are considered. To guarantee the stability of the closed-loop system, Lyapunov second method is employed and finally the performance of the proposed controller in tracking the desired trajectory is compared to a sliding mode controller.

System Model

In this section, a dynamic model of relative motion for SFF has been generated. It is assumed that each spacecraft is a point mass. A schematic view of an Earth-orbiting SFF is shown in Fig. 1; where $C_1 = \{X,Y,Z\}$ is the inertial coordinate system and $\boldsymbol{r}_l$ and $\boldsymbol{r}_f$ are the position vectors of the leader and follower, respectively. The coordinate system $C_2 = \{x, y, z\}$ is a moving frame located on the leader's center of mass. Herein, y axis is along the direction of $\boldsymbol{r}_l(t)$, x is along the direction of leader's velocity vector and normal to y, and z is perpendicular to the x and y axes, so that the moving frame C_2 forms a right-hand coordinate frame.

The dynamics of the leader and follower in the inertial reference frame can be written as

$$\ddot{\boldsymbol{r}}_l + \frac{\mu}{r_l^3}\boldsymbol{r}_l = \boldsymbol{d}_l + \boldsymbol{u}_l \tag{1}$$

$$\ddot{\boldsymbol{r}}_f + \frac{\mu}{r_f^3}\boldsymbol{r}_f = \boldsymbol{d}_f + \boldsymbol{u}_f \tag{2}$$

where $r = \|\boldsymbol{r}\|$, $\mu = 398\,600\ \mathrm{km^3/s^2}$ is the constant of the Earth gravity, $\boldsymbol{u}$ is control input vector and $\boldsymbol{d}$ is the vector of external disturbance. It is assumed that the leader spacecraft is subject to the perturbations and moves in an uncontrolled ballistic trajectory, and the follower spacecraft should be controlled; therefore

$\boldsymbol{u}_l = 0$. The relative position of the follower with respect to the leader is $\boldsymbol{\rho} = \boldsymbol{r}_f - \boldsymbol{r}_l$. Then relative dynamics is expressed as

$$\ddot{\boldsymbol{\rho}} = \ddot{\boldsymbol{r}}_f - \ddot{\boldsymbol{r}}_l = \mu\left(\frac{\boldsymbol{r}_l}{r_l^3} - \frac{\boldsymbol{r}_f}{r_f^3}\right) + \boldsymbol{D} + \boldsymbol{u}_f \tag{3}$$

where

$$\boldsymbol{D} = \boldsymbol{d}_f - \boldsymbol{d}_l \tag{4}$$

$\boldsymbol{D}$ is defined as differential perturbation imposed on the formation.

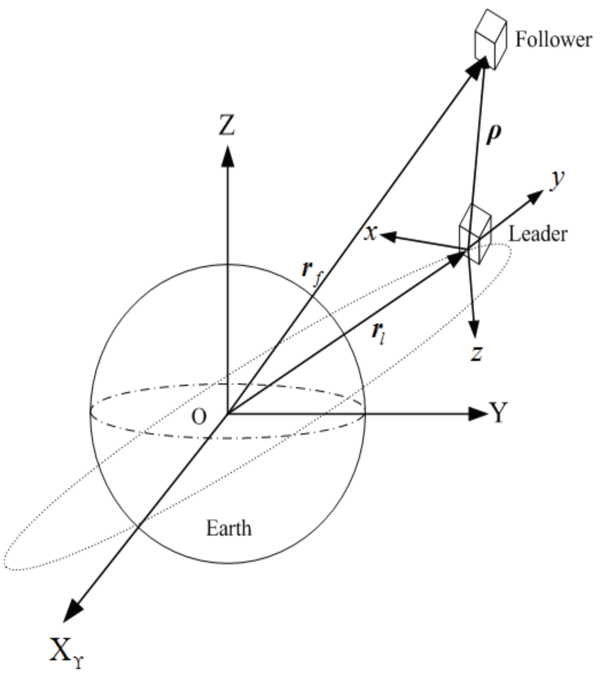

Fig. 1. Schematic view of an SFF system

According to the relation between relative velocity in the inertial and rotating frame, we may get

$$\ddot{\boldsymbol{\rho}}\big|_{C_1} = \ddot{\boldsymbol{\rho}}\big|_{C_2} + 2\boldsymbol{\omega}\times\dot{\boldsymbol{\rho}}\big|_{C_2} + \boldsymbol{\omega}\times(\boldsymbol{\omega}\times\boldsymbol{\rho}) + \dot{\boldsymbol{\omega}}\times\boldsymbol{\rho} \tag{5}$$

where $(\cdot)\big|_{C_1}$, $(\cdot)\big|_{C_2}$ represent the derivative under the Earth inertial and the moving coordinates, respectively. Relative dynamics equations must be expressed in the moving frame C_2, so $\boldsymbol{\omega} = \boldsymbol{\omega}_l = \begin{bmatrix}0 & 0 & -\omega_l\end{bmatrix}^T$, $\boldsymbol{\rho} = \begin{bmatrix}x & y & z\end{bmatrix}^T$, $\boldsymbol{r}_l = \begin{bmatrix}0 & r_l & 0\end{bmatrix}^T$ and $\boldsymbol{r}_f = \begin{bmatrix}x & r_l + y & z\end{bmatrix}^T$.

Therefore, the nonlinear relative dynamics of the follower with respect to the moving frame is described as

$$\ddot{\boldsymbol{\rho}} + \boldsymbol{C}(\omega_l)\dot{\boldsymbol{\rho}} + \boldsymbol{F}(\boldsymbol{\rho}, \omega_l, \dot{\omega}_l, \boldsymbol{r}_l, N, n) = \boldsymbol{D} + \boldsymbol{u}_f \tag{6}$$

where

$$\boldsymbol{C}(\omega_l) = 2\omega_l\begin{bmatrix}0 & 1 & 0\\ -1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},$$

$$\boldsymbol{F}(\boldsymbol{\rho}, \omega_l, \dot{\omega}_l, \boldsymbol{r}_l, N, n) = \begin{bmatrix}(N^2 - \omega_l^2)x + \dot{\omega}_l y\\ (N^2 - \omega_l^2)y + (N^2 - n^2)r_l - \dot{\omega}_l x\\ N^2 z\end{bmatrix} \tag{7}$$

$$\boldsymbol{F}(\boldsymbol{\rho}, \omega_l, \dot{\omega}_l, \boldsymbol{r}_l, N, n) = \begin{bmatrix}(N^2 - \omega_l^2)x + \dot{\omega}_l y\\ (N^2 - \omega_l^2)y + (N^2 - n^2)r_l - \dot{\omega}_l x\\ N^2 z\end{bmatrix}$$

and

$$\omega_l = \dot{\theta} = \frac{\sqrt{\mu a(1-e^2)}}{r_l^2},\quad \dot{\omega}_l = \frac{-2\mu e\sin\theta}{r_l^3},\quad n = \sqrt{\frac{\mu}{r_l^3}}$$
$$N = \sqrt{\frac{\mu}{\left[x^2 + (r_l + y)^2 + z^2\right]^{3/2}}},\quad r_l = \frac{a(1-e^2)}{1 + e\cos\theta} \tag{8}$$

in which ω_l, a, e, θ are the angular velocity, the orbital semi-major axis, the eccentricity and the true anomaly of the leader spacecraft orbit, respectively.

Controller Design

Sliding Mode Control

Sliding mode controller as a variable structured controller has a proper performance for nonlinear systems. The design procedure of SMC consists of two parts: first, a sliding surface is designed to fulfill the purposes of the system response, and then a control law is determined to slide system state on the surface.

Since in low-Earth orbits, J_2 perturbation and the atmospheric drag are dominant, they are considered as external disturbances in this study. They have bounded values based on the spacecraft altitude, so for D_i in (6)

$$|D_i| \le q_i \quad i = 1,2,3 \tag{9}$$

where the positive constant q_i is considered as [4,12]

$$q_i = 10^{-7}\ \text{km/s}^2 \tag{10}$$

The sliding surface is chosen as

$$\boldsymbol{s} = \dot{\boldsymbol{e}} + \boldsymbol{\lambda}\boldsymbol{e} \tag{11}$$

where $\boldsymbol{e} = \boldsymbol{\rho} - \boldsymbol{\rho}_d$ and $\dot{\boldsymbol{e}} = \dot{\boldsymbol{\rho}} - \dot{\boldsymbol{\rho}}_d$. $\boldsymbol{\rho}_d, \dot{\boldsymbol{\rho}}_d \in R^3$ are the relative position and velocity of the desired trajectory with respect to the leader. $\boldsymbol{s} = [s_1, s_2, s_3]^T$ and $\boldsymbol{\lambda} = diag(\lambda_1, \lambda_2, \lambda_3)$ are sliding surfaces and slopes of the sliding surfaces, respectively.

$$\dot{\boldsymbol{s}} = (\ddot{\boldsymbol{\rho}} - \ddot{\boldsymbol{\rho}}_d) + \boldsymbol{\lambda}(\dot{\boldsymbol{\rho}} - \dot{\boldsymbol{\rho}}_d) = 0 \tag{12}$$

substituting equation (6) into equation (12) and neglecting disturbance term, equivalent control $\boldsymbol{u}_{f_{eq}}$ is extracted as

$$\boldsymbol{u}_{f_{eq}} = \boldsymbol{C}(\cdot)\dot{\boldsymbol{\rho}} + \boldsymbol{F}(\cdot) + \ddot{\boldsymbol{\rho}}_d - \boldsymbol{\lambda}(\dot{\boldsymbol{\rho}} - \dot{\boldsymbol{\rho}}_d) \quad (13)$$

The system should be robust against uncertainties and disturbances, so the control input is complemented to

$$\boldsymbol{u}_f = \boldsymbol{C}(\cdot)\dot{\boldsymbol{\rho}} + \boldsymbol{F}(\cdot) + \ddot{\boldsymbol{\rho}}_d - \boldsymbol{\lambda}(\dot{\boldsymbol{\rho}} - \dot{\boldsymbol{\rho}}_d) - \boldsymbol{k}\,\mathrm{sgn}(\boldsymbol{s}) \quad (14)$$

where $\boldsymbol{k} = diag(k_1, k_2, k_3)$ is the gain matrix which is determined based on the amount of uncertainties, disturbance and the time for reaching the sliding surface. The vector of sign function $\mathrm{sgn}(\boldsymbol{s})$ is a column matrix of sign functions

$$\mathrm{sgn}(\boldsymbol{s}) = [\mathrm{sgn}(s_1), \mathrm{sgn}(s_2), \mathrm{sgn}(s_3)]^T \quad (15)$$

To guarantee stability, Lyapunov second method is used; wherein $V = \frac{1}{2}\boldsymbol{s}^T\boldsymbol{s}$ is considered as Lyapunov function and k_i is determined in such a way that $\dot{V} < 0$

$$, \dot{V} = \boldsymbol{s}^T\dot{\boldsymbol{s}} \quad (16)$$

so we have

$$\dot{V} = \boldsymbol{s}^T[\boldsymbol{D} - \boldsymbol{k}\,\mathrm{sgn}(\boldsymbol{s})] \le \sum_{i=1}^{3} |s_i|(q_i - k_i) \quad (17)$$

thus by choosing $k_i > q_i$, the closed-loop system will be globally asymptotically stable.

A common method for eliminating the chattering phenomenon is replacing the sign functions with saturation functions [13]. The controller then becomes

$$\boldsymbol{u}_f = \boldsymbol{C}(\cdot)\dot{\boldsymbol{\rho}} + \boldsymbol{F}(\cdot) + \ddot{\boldsymbol{\rho}}_d - \boldsymbol{\lambda}(\dot{\boldsymbol{\rho}} - \dot{\boldsymbol{\rho}}_d) - \boldsymbol{k}\,sat(\boldsymbol{s},\varphi) \quad (18)$$

where $sat(\boldsymbol{s},\varphi) = [sat(s_1,\varphi), sat(s_2,\varphi), sat(s_3,\varphi)]^T$ and the saturation function $sat(s_i,\varphi)$ is

$$sat(s_i,\varphi) = \begin{cases} s_i/\varphi & |s_i| \le \varphi \\ \mathrm{sgn}(s_i) & |s_i| > \varphi \end{cases} \quad i = 1,2,3 \quad (19)$$

where φ is the boundary layer thickness.

Fuzzy Sliding Mode Control

Constant sliding surface is replaced with variable one in the fuzzification process. The slope of the new sliding surface is increased based on error states from a close distance to the initial state to a predetermined surface. Therefore, the reaching phase to the sliding surface decreases and system response becomes faster. When the slope increases, the final tracking error diminishes . To select the final slope of the sliding surface, un-modeled natural frequency in the system, un-modeled system time delays and sampling rate should be considered [13]. In the fuzzification process, error e_i and its derivative $\dot{e}_i$ are considered as inputs and the slope $\lambda_i (i = 1,2,3)$ as output. Membership functions have been shown in Figure 2-4. These functions have been experimentally selected based on system states and system response. Triangular membership functions are considered for the inputs, and singleton type is used for the output.

The rule base for fuzzy logic is given in Table 1. where NB, NM, ZE, PM and PB stand for negative big, negative medium, zero, positive medium and positive big, respectively; while VS, S, M, B and VB stand for very small, small, medium, big and very big. Some of the rules are described below

If e_i : NB and $\dot{e}_i$: NB Then λ_i : VS

If e_i : NB and $\dot{e}_i$: ZE Then λ_i : M

If e_i : NB and $\dot{e}_i$: PB Then λ_i : VB

Based on the first rule, when error and its derivative are both negative big, the slope of sliding surface is considered as very small; i.e. the closest surface to the system state. Based on the second rule, when error is negative big and its derivative is approximately zero, the slope is considered as medium; and according to third rule, when error and its derivative are negative and positive big, respectively, the slope is considered as very big. Other rules have been demonstrated in table 1.

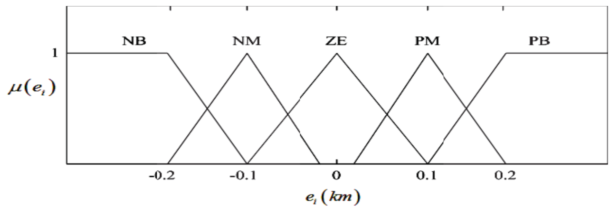

Fig. 2. Membership functions for input e_i

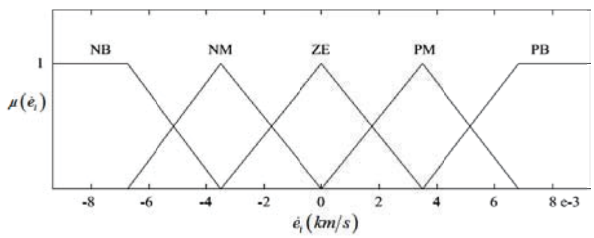

Fig. 3. Membership functions for input $\dot{e}_i$

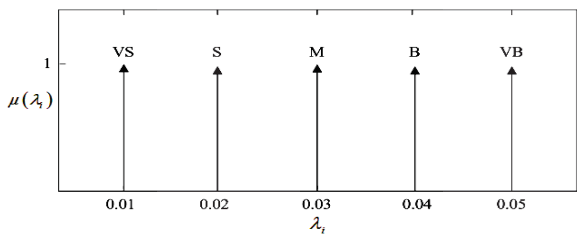

Fig. 4. Membership functions for output λ_i

Table 1. Fuzzy associative memory (FAM) table for λ_i

e_i	$\dot{e}_i$ NB	NM	ZE	PM	PB
NB	VS	S	M	B	VB
NM	S	M	B	VB	B
ZE	M	B	VB	B	M
PM	B	VB	B	M	S
PB	VB	B	M	S	VS

In the proposed fuzzy logic, the "and" operator is considered as the "product" and the defuzzification method is "weighted average".

Simulation Results

The nonlinear model (6) is used for simulation purposes. For the control part, it is assumed that $\boldsymbol{\rho}$ and $\dot{\boldsymbol{\rho}}$ are measurable and available. J_2 perturbation with respect to the inertial frame is given as [4]

$$\mathbf{D}_{J_2} = \frac{\mu J_2 R_e^{\,2}}{2}\begin{bmatrix} \frac{15Z^2X}{\|\boldsymbol{r}\|^7} - \frac{3X}{\|\boldsymbol{r}\|^5} \\ \frac{15Z^2Y}{\|\boldsymbol{r}\|^7} - \frac{3Y}{\|\boldsymbol{r}\|^5} \\ \frac{15Z^3}{\|\boldsymbol{r}\|^7} - \frac{9Z}{\|\boldsymbol{r}\|^5} \end{bmatrix} \tag{20}$$

where $J_2 = 0.0010826$, $R_e = 6378.137$ km is the mean equatorial radius of the Earth. Then, one can easily transform the disturbance to the moving frame by using coordinate transformation. Atmospheric drag is also given as [12]

$$\mathbf{D}_{drag} = -\frac{1}{2}\frac{C_D S}{m}\sigma v^2 \hat{\mathbf{v}} \tag{21}$$

where m is the mass of spacecraft, C_D is the drag coefficient, S is the effective surface, σ is the local atmosphere density, v is the velocity relative to the atmosphere and $\hat{\mathbf{v}}$ is the related unit vector. Constant coefficients are assumed as follows:

$m = 100\text{kg} \quad C_D = 2 \quad S = 0.5\text{m}^2 \quad \sigma = 10^{-12}\ \text{kg}/\text{m}^3$

The initial orbital elements of the leader are supposed as:

$a = 7378.137\text{km} \quad e = 0.1$

$i = 30^\circ \quad \omega = 45^\circ \quad \Omega = \theta = 0^\circ$

The desired relative trajectory of the follower is a circular formation with a radius of 1 km in x-y plane [14]. The center of the desired formation is located on (10000,0,0)m. The period of the follower movement lies entirely on the leader spacecraft angular velocity around the Earth and is obtained as $T \approx 6300\text{s}$. The initial relative position errors of the follower in the moving frame are chosen as

$$(e_x \quad e_y \quad e_z) = (-100 \quad 200 \quad 200)(\text{m}) \tag{22}$$

and the parameters of both controllers are considered below

$\boldsymbol{\lambda}_{\max} = 0.05 \times \text{diag}(1,1,1)$,

$\boldsymbol{k} = (1.5\text{e-}5) \times \text{diag}(1,1,1), \quad \varphi = 0.001$

Figure 5 shows a three-dimensional view of the follower relative motion using fuzzy sliding mode controller. Fuzzy variations of $\lambda_i (i = 1,2,3)$ are presented in Figure 6. Based on the fuzzy logic, λ_i converges to the pre-defined value appropriately. System response in reducing the tracking errors using both controllers are depicted in Figure 7 and Figure 8.

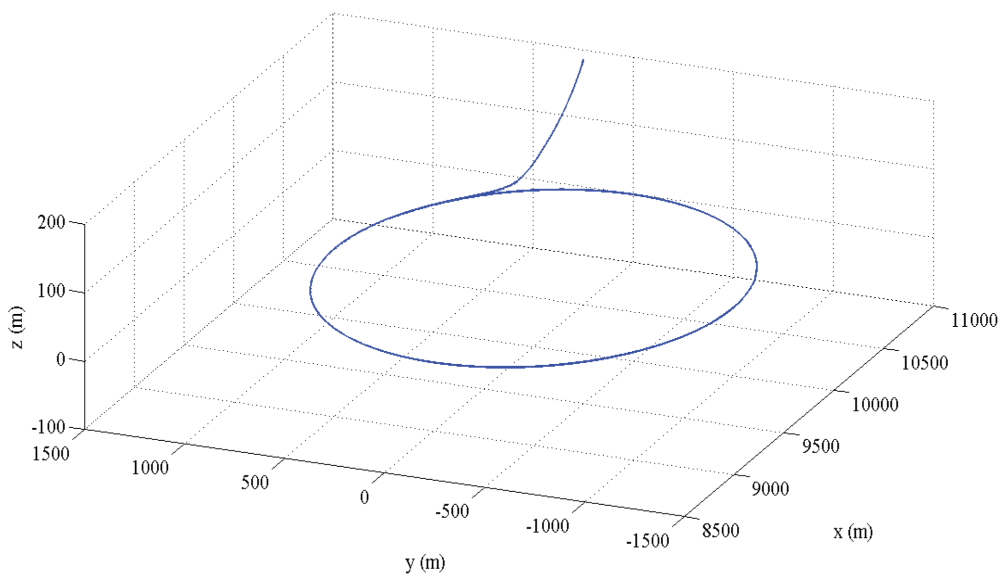

Fig. 5. Three-dimensional trajectory of the follower using FSMC

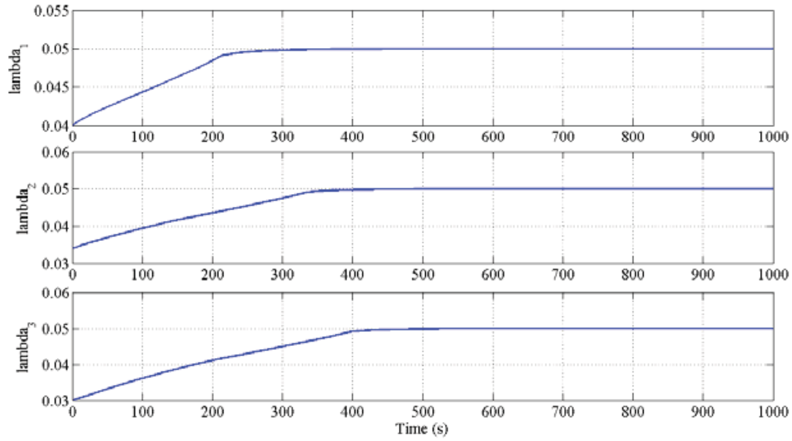

Fig. 6. Fuzzy variation of λ_i

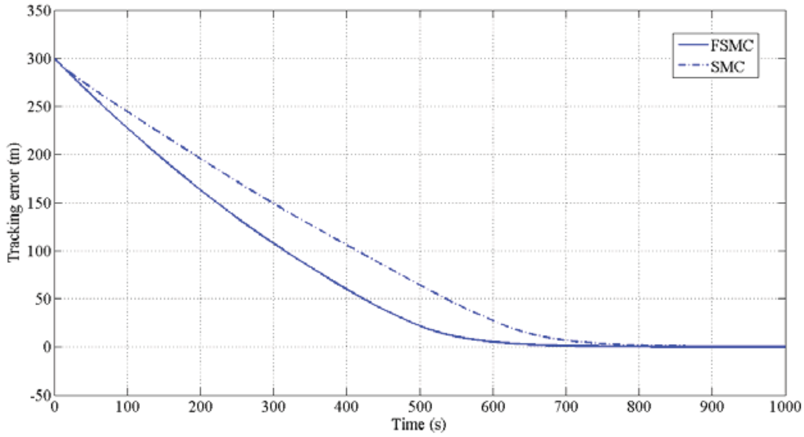

Fig. 7. Total tracking error using FSMC and SMC

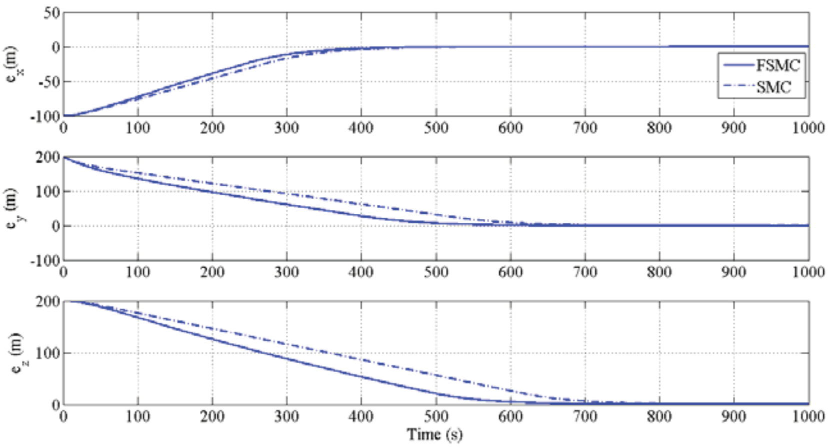

Fig. 8. Tracking error using FSMC and SMC

Figure 9 illustrates the differential external disturbance during one period. Control inputs of the follower for both controllers are presented in Figure 10.

Fuel cost is also demonstrated in Figiure 11. It can be obtained as

$$\Delta V = \int_0^t |u_x| + |u_y| + |u_z| dt \tag{23}$$

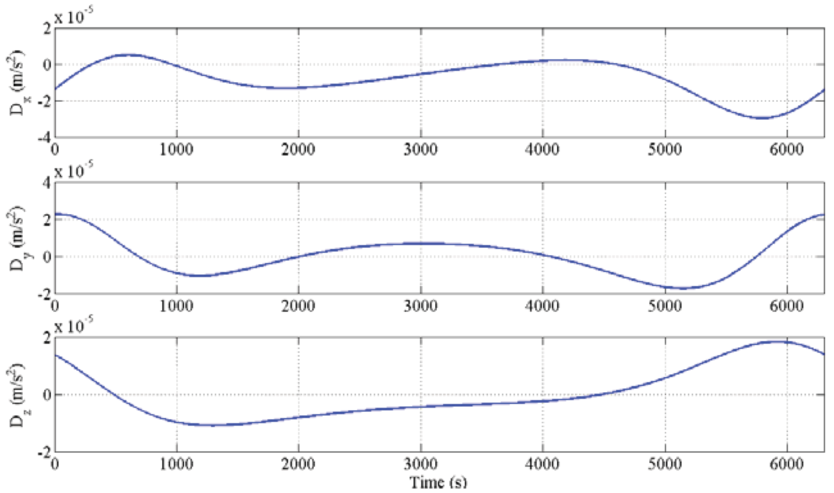

Fig. 9. Differential perturbation with respect to the moving frame

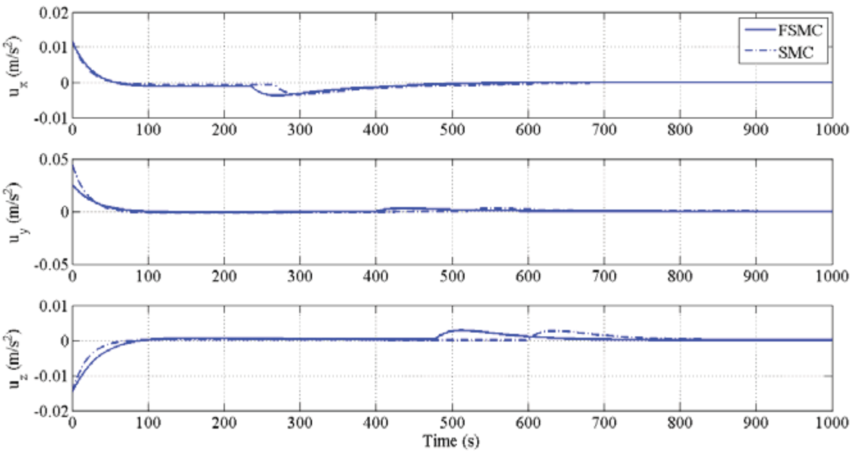

Fig. 10. Control inputs of the follower

using FSMC and SMC

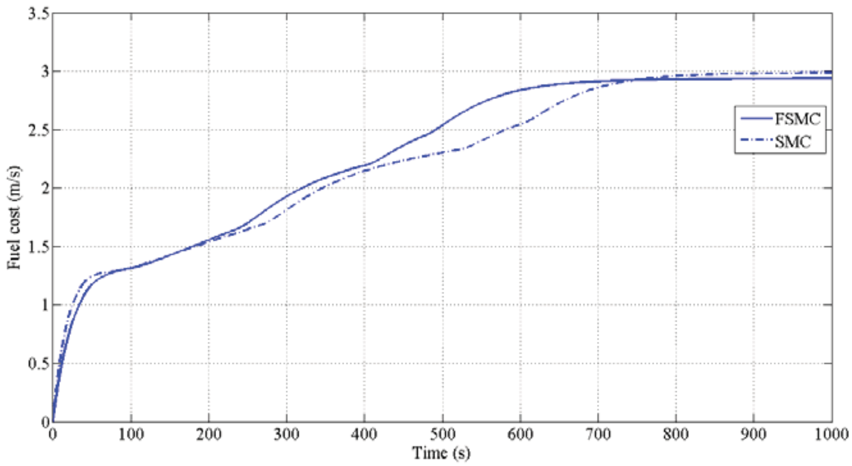

Fig. 11. Fuel cost for FSMC and SMC

Based on the results, although the controllers have identical parameters, the proposed fuzzy sliding mode controller has a superior performance in tracking the desired formation and fuel cost compared with traditional sliding mode controller.

Conclusion

In this study, a fuzzy sliding mode controller was presented for spacecraft formation control in eccentric orbits. To improve the performance of a traditional sliding mode controller, the slopes of sliding surfaces were changed based on error states using a fuzzy logic and reached the pre-defined slopes. The system response became faster, and the tracking action was improved. The controller was designed based on the nonlinear model of relative motion; while J_2 perturbation and atmospheric drag were considered as external disturbances. Stability of the closed-loop system was guaranteed using Lyapunov second method. In comparison between the performance of the proposed controller and a sliding mode controller, simulation results confirmed more efficient and superior performance of the proposed controller in tracking the desired formation and fuel cost.

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