Fuel-Optimal Predictive Control of Satellite Formation Keeping Based on Genetic Algorithm

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***Abstract*—This paper addresses the keeping control problem of the leader-follower satellite formation by using an economic model predictive control method. The objective function in the designed economic model predictive control is comprised of two parts. One part is an adjustment term which is used to realize the trajectory tracking. The other part is an economic term l_e which achieves fuel optimization. In addition, genetic algorithm is used to solve the control law which realizes the keeping control of satellite formation. Simulation results show that the proposed control method can achieve fuel optimization control for satellite formation.**

***Index Terms*—satellite formation, fuel-optimal, economic model predictive control, genetic algorithm, penalty function method**

I. Introduction

Satellite formation keeping control is a hot research topic in the field of aerospace [1]. In order to achieve the long-term keeping control of satellite formation, the following two key factors need to be considered: 1) how to deal with the control constraints of the thruster; 2) how to reduce fuel consumption in control process. In the past decade, many kinds of control strategies have been developed for the keeping control of satellite formation. For example, adaptive control [2], [3], [4], sliding mode control [5], [6], [7] and optimal control [8]. However, these control methods cannot address the aforementioned factors simultaneously. For example, the literature [2] - [7] cannot deal with the constraints in the control process. Although the literature [8] can deal with the control constraint problem well, it is an off-line optimization method. It can not respond to the sudden disturbance in the control process in time, so that it can not achieve fuel optimization in real time.

Model predictive control (MPC) is an advanced control strategy on the basis of predictive model, rolling optimization and feedback correction [9]. Because it can directly deal with control constraints, model predictive control is used to deal with the constraint problem of actuator and realize the control of satellites [10], [11]. However, the fuel optimization problem is not taken into account.

In the past few years, economic model predictive control (EMPC) has attracted more and more attention because it can explicitly consider the economic factors which can help to realize the maximization of economic benefits [12], [13], [14], [15]. In this paper, a novel EMPC strategy is designed for the keeping control of the satellite formation. In order to realize the minimum fuel consumption in trajectory tracking, an economic term considering fuel consumption is added to the objective function of traditional predictive control [10], [11]. Moreover, due to the addition of the economic term and the penalty term, the objective function is non-convex, so the quadratic programming method used in traditional predictive control can not be used to solve the objective function. Compared with quadratic programming method, genetic algorithm calculates the fitness value according to the objective function. It does not need other derivation and additional information. Because of its lower requirements for the objective function, genetic algorithm is used to optimize the objective function in EMPC. The keeping control of satellite formation is realized by using EMPC strategy based on genetic algorithm.

The remainder part of this paper is organized as follows: The dynamic model of satellite formation and the design objective of the paper are introduced in section II. Section III presents the designed EMPC algorithm on the keeping control of satellite formation. Section IV verifies the effectiveness of the proposed algorithm through simulation and the final conclusion is given in Section V.

II. PROBLEM FORMULATION

A. Dynamic model of satellite formation

The leader-follower satellite formation and its orbital coordinate system are shown in Fig. 1. As can been seen from the picture, the orbital coordinate system is composed of an ECI coordinate system in which the earth's center is taken as its Origin and a LVLH coordinate system with centroid of leader satellite S_0 as its origin. Assuming that the leader satellite is in an ideal elliptical orbit around the earth, the relative dynamic model of the leader-follower satellite formation is described as follows [16]:

$$\begin{cases} \ddot{x} - 2\dot{\theta}\dot{y} - \dot{\theta}^2 x - \ddot{\theta} y + \frac{\mu_e (R_c + x)}{R^3} - \frac{\mu_e}{R_c^2} = u_x \\ \ddot{y} + 2\dot{\theta}\dot{x} - \dot{\theta}^2 y + \ddot{\theta} x + \frac{\mu_e y}{R^3} = u_y \\ \ddot{z} + \frac{\mu_e z}{R^3} = u_z \end{cases} \quad (1)$$

where u_x, u_y and u_z denote the control input in x, y and z direction, respectively. The orbit radius of the leader satellite

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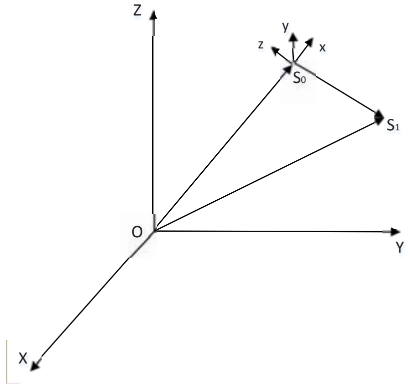

Fig. 1. The relative dynamic model of satellite formation

is $R_c = \frac{a_c(1-e_c^2)}{1+e_c \cos f}$. The geocentric distance of the follower satellite is $R = \sqrt{(R_c+x)^2+y^2+z^2}$. a_c, e_c and f are the major semiaxis, eccentricity and true anomaly of the leader satellite, respectively. The gravitational constant of the earth is μ_e=3.986 $\times$ 10^5. θ denotes the argument of latitude. Its first and second derivatives can be expressed as follows: $\dot{\theta} = \frac{\sqrt{\mu_e/a_c^3}*(1-e_c^2)}{(1-e_c^2)^{3/2}}$, $\ddot{\theta} = \frac{-2\mu_e(1+e_c\cos f)^3 e_c \sin f}{a_c^3(1-e_c^2)^3}$.

B. Design objective

The objective of this paper can be divided into the following two aspects: 1) realizing the tracking and keeping flight of the desired orbit $(x_{ref}, y_{ref}, z_{ref})$ by the follower satellite through the control strategy; 2) minimizing the fuel consumption in the control process.

III. DESIGN OF EMPC STRATEGY FOR SATELLITE FORMATION

In order to realize the real-time control of satellite formation, a linearized model is chosen as the research object because of its minor computation and short solution time. At the same time, the EMPC strategy is designed on the basis of the linearized model. The specific linearization process is described as follows.

Because the distance between the leader satellite and the follower satellite is far less than the orbit radius, the ratio of the relative state to the orbit radius (x/R_c ,y/R_c ,z/R_c) can be regarded as a very small number. By neglecting the second order small quantity of the ratio of relative state to orbit radius, the nonlinear term $\frac{\mu_e}{R^3}$ in (1) can be described as

$$\frac{\mu_e}{R_c^3}(1+\frac{2x}{R_c})^{\frac{-3}{2}} \ . \tag{2}$$

Expressing equation (2) in a Taylor's series and ignoring higher order terms, we can obtain that

$$\frac{\mu_e}{R_c^3}(1+\frac{2x}{R_c})^{\frac{-3}{2}} \approx \frac{\mu_e}{R_c^3}(1-\frac{3x}{R_c}) \ . \tag{3}$$

By substituting equation (3) into equation (1), the linearized model can be obtained as follows:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} \frac{2\mu_e}{R_c^3}+\dot{\theta}^2 & \ddot{\theta} & 0 \\ -\ddot{\theta} & \frac{-\mu_e}{R_c^3}+\dot{\theta}^2 & 0 \\ 0 & 0 & \frac{-\mu_e}{R_c^3} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} 0 & 2\dot{\theta} & 0 \\ -2\dot{\theta} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} + \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \ . \tag{4}$$

By introducing an augmented state vector $\bar{x} = \begin{bmatrix} x & y & z & \dot{x} & \dot{y} & \dot{z} \end{bmatrix}$ and the control vector $u = \begin{bmatrix} u_x & u_y & u_z \end{bmatrix}^T$, the above linearization equation is transformed into:

$$\dot{\bar{x}} = A\bar{x} + Bu \tag{5}$$

where $A = \begin{bmatrix} 0_{3\times3} & I_{3\times3} \\ A_1 & A_0 \end{bmatrix}$, $A_0 = \begin{bmatrix} 0 & 2\dot{\theta} & 0 \\ -2\dot{\theta} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, $A_1 = \begin{bmatrix} \frac{2\mu_e}{R_c^3}+\dot{\theta}^2 & \ddot{\theta} & 0 \\ -\ddot{\theta} & \frac{-\mu_e}{R_c^3}+\dot{\theta} & 0 \\ 0 & 0 & \frac{-\mu_e}{R_c^3} \end{bmatrix}$, $B = \begin{bmatrix} 0_{3\times3} \\ I_{3\times3} \end{bmatrix}$.

Since the model predictive control strategy is designed based on the discretization model, so the equation (5) can be discretized into the following equation by using the approximate discretization method:

$$\bar{x}(k+1) = A_k\bar{x}(k) + B_k u\,(k) \tag{6}$$

where $A_k = I + TA$, $B_k = TB$ and T is sampling period.

A. EMPC strategy design

In order to enable the satellite to track the reference trajectory quickly and smoothly and realize the fuel optimization, the optimal control problem 1 based on the satellite formation model (6) is defined as follows:

$$\begin{aligned} \min J = \lambda l_e + [Y(k) - Y_{ref}]^T Q\,[Y(k) - Y_{ref}] \\ + \Delta U^T\,(k)\,R\Delta U\,(k) \end{aligned} \tag{7}$$

s.t.

$$\bar{x}(k+1) = A_k\bar{x}(k) + B_k u\,(k)$$

$$-u_{\max} \le u(k+j) \le u_{\max}, j = 0,1,2,\cdots,N_c - 1$$

where λ is an adjustment coefficient. l_e is an economic term considering fuel consumption. By introducing the economic term into predictive control, the satellite can achieve fuel-optimal control in the process of tracking the reference trajectory. $Y\,(k) = \begin{bmatrix} y(k+1|k) \\ y(k+2|k) \\ \vdots \\ y(k+N_p|k) \end{bmatrix}$ denotes the predictive output within the predictive horizon N_p . $\Delta U\,(k) =$

$\begin{bmatrix} \Delta u(k|k) \\ \Delta u(k+1|k) \\ \vdots \\ \Delta u(k+N_c-1|k) \end{bmatrix}$ represents the control increment in the control horizon N_c . Q and R are the error weight matrix and the control weight matrix, respectively. $Y_{ref} = \begin{bmatrix} y_{ref}(k+1|k) \\ y_{ref}(k+2|k) \\ \vdots \\ y_{ref}(k+N_p|k) \end{bmatrix}$ is the reference trajectory of the system.

Specifically, the economic term l_e is defined as follows:

$$l_e = \sum_{i=1}^{W} \left(u(i)^T u(i)\right)^{0.5} T \tag{8}$$

where W and T are the number of sampling points and sampling period, respectively.

For the keeping control problem of satellite formation, minimizing the fuel consumption in the control process is very important [8]. The control input of the thruster directly determines the fuel consumption of the satellite. In this paper, the economic term l_e is described as equation (8) about the control input.

Defining the state variable $\tilde{x}(k) = \begin{bmatrix} \bar{x}(k) \\ u(k-1) \end{bmatrix}$, equation (6) can be transformed into a form of the control increment, which is described as follows:

$$\begin{gathered} \tilde{x}(k+1|k) = \tilde{A}_k \tilde{x}(k|k) + \tilde{B}_k \Delta u(k|k) \\ y(k) = \tilde{C}_k \tilde{x}(k|k) \end{gathered} \tag{9}$$

where $\tilde{A}_k = \begin{bmatrix} A_k & B_k \\ 0_{3\times6} & I_{3\times3} \end{bmatrix}$, $\tilde{B}_k = \begin{bmatrix} B_k \\ I_{3\times3} \end{bmatrix}$, $\tilde{C}_k = \begin{bmatrix} I_{6\times6} & 0_{6\times3} \end{bmatrix}$.

Correspondingly, the predicted output $Y(k)$ of the system can be expressed as follows:

$$Y(k) = \psi_k \tilde{x}(k|k) + \theta_k \Delta U(k) \tag{10}$$

where

$$\psi_k = \begin{bmatrix} \tilde{C}_k \tilde{A}_k \\ \tilde{C}_k \tilde{A}_k^2 \\ \vdots \\ \tilde{C}_k \tilde{A}_k^{N_c} \\ \tilde{C}_k \tilde{A}_k^{N_c+1} \\ \vdots \\ \tilde{C}_k \tilde{A}_k^{N_P} \end{bmatrix},$$

$$\theta_k = \begin{bmatrix} \tilde{C}_k \tilde{B}_k & 0 & 0 & 0 \\ \tilde{C}_k \tilde{A}_k \tilde{B}_k & \tilde{C}_k \tilde{B}_k & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{C}_k \tilde{A}_k^{N_c-1} \tilde{B}_k & \tilde{C}_k \tilde{A}_k^{N_c-2} \tilde{B}_k & \cdots & \tilde{C}_k \tilde{B}_k \\ \tilde{C}_k \tilde{A}_k^{N_c} \tilde{B}_k & \tilde{C}_k \tilde{A}_k^{N_c-1} \tilde{B}_k & \cdots & \tilde{C}_k \tilde{A}_k \tilde{B}_k \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{C}_k \tilde{A}_k^{N_p-1} \tilde{B}_k & \tilde{C}_k \tilde{A}_k^{N_p-2} \tilde{B}_k & \cdots & \tilde{C}_k \tilde{A}_k^{N_p-N_c} \tilde{B}_k \end{bmatrix}.$$

B. The handling of control constraint

As the power device of the satellite, the thruster realizes the orbit correction of the satellite. In practice, the power output of the thruster is limited. In this paper, the control constraint of the thruster in (7) can be redescribed as the following equation about the control increment:

$$\begin{bmatrix} L \\ -L \end{bmatrix} \Delta U(k) \le \begin{bmatrix} U_{\max} - U_t \\ U_{\max} + U_t \end{bmatrix} \tag{11}$$

where $L = \begin{bmatrix} 1 & 0 & \cdots & \cdots & 0 \\ 1 & 1 & 0 & \cdots & 0 \\ 1 & 1 & 1 & \ddots & 0 \\ \vdots & \vdots & \ddots & \ddots & 0 \\ 1 & 1 & \cdots & 1 & 1 \end{bmatrix}_{N_c\times N_c} \otimes I_{3\times3}$, $U_t = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}_{N_c\times1} \otimes u(k-1)$, $U_{\max} = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}_{N_c\times1} \otimes u_{\max}$ and $\otimes$ is kronecker product.

Defining $F = \begin{bmatrix} L \\ -L \end{bmatrix}$ and $H = \begin{bmatrix} U_{\max} - U_t \\ U_{\max} + U_t \end{bmatrix}$, then equation (11) can be represented as follows:

$$F\Delta U(k) \le H \ . \tag{12}$$

In this paper, problem 1 is a constrained optimization problem. In order to solve this optimization problem, penalty function method is used to transform the constrained optimization problem into the unconstrained optimization problem [17]. Correspondingly, the objective function (7) can be redefined as follows:

$$\tilde{J} = \begin{cases} J & F\Delta U(k) \le H \\ J + P & Otherwise \end{cases} \tag{13}$$

where $\tilde{J}$ represents a new objective function, J denotes the original objective function (7) and P is a penalty term.

In equation (13), when ΔU satisfies the constraint (12), $\tilde{J}$ equals J . On the contrary, when the constraint condition (12) is not satisfied, a penalty term is added to deal with it. The penalty term is defined as follows:

$$P = \sigma \max\{0, d\} \tag{14}$$

where σ is a very large positive number and d is a constant whose value is defined as follows:

$$d = \begin{cases} -1 & F\Delta U(k) \le H \\ 1 & Otherwise \end{cases} .$$

Compared with the standard model predictive control [10] and [11], the objective function (13) is composed of a trajectory tracking term and an additional economic term l_e . By optimizing the objective function (13), the trajectory tracking and fuel optimization can be achieved simultaneously. However, due to the addition of the economic term l_e and the penalty

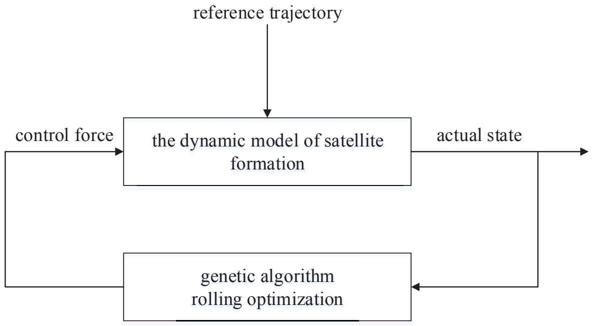

Fig. 2. EMPC strategy based on real-coded genetic algorithm

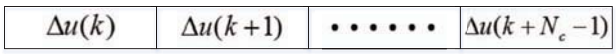

Fig. 3. The structure of chromosome

term P , the objective function (13) can not be directly solved by traditional optimization techniques. Motivated by [18] and [19], genetic algorithm is used to solve the optimization problem 1. The EMPC strategy based on genetic algorithm is shown in Fig. 2.

The specific EMPC strategy based on real-coded genetic algorithm is shown in Algorithm 1.

IV. NUMERICAL SIMULATION

A. Model parameters

In this paper, a leader-follower satellite formation is taken as the research object. The corresponding satellite parameters are shown in Table I and Table II. In addition, the key to the keeping control of the satellite formation is the tracking of the reference trajectory by the follower satellite. For this purpose, the reference trajectory is set as follows: $x_{ref} = -0.5\cos\dot{\theta}t$, $y_{ref} = \sin\dot{\theta}t$, $z_{ref} = -0.5\sqrt{3}\cos\dot{\theta}t$.

B. Controller parameters

In the designed EMPC strategy, firstly, the controller parameters are given as follows:predictive horizon $N_p = 10$, control horizon $N_c = 3$, error weight matrix $Q = 50I_{60\times 60}$,

TABLE I
ORBITAL PARAMETERS OF THE LEADER SATELLITE

semimajor axis a	$7000km$
eccentricity e	0.01
the argument of latitude θ	$0°$
true anomaly f	$0°$

TABLE II
THE INITIAL STATE OF THE FOLLOWER SATELLITE

$x\,(m)$	0
$y\,(m)$	500
$z\,(m)$	0
$v_x\,(m/s)$	0.2696
$v_y\,(m/s)$	0
$v_z\,(m/s)$	0.4668

Algorithm 1 EMPC strategy based on real-coded genetic algorithm

Set reference trajectory and sampling period
while The keeping control of satellite formation does not stop **do**
Step1: Collect real-time state of the satellite.
Step2: Use genetic algorithm to replace traditional optimization techniques to solve control laws.
(Initialization) Determine population size. The population consists of several chromosomes, each of which consists of a sequence of control increments as shown in Fig. 3. In addition, the maximum number of iterations, crossover and mutation probability are initialized.
(Determine the fitness function) In order to facilitate the implementation of GA algorithm, the objective function (13) is transformed into the fitness function in the form of the maximum value. The specific fitness function is:

$$f_k = \frac{1}{1+J_k}, k = 1, 2, ..., N \tag{15}$$

where N represents the number of individuals in the population, J_k is the objective function value of the k_{th} chromosome.
while The maximum number of iterations has not arrive **do**
(Selection) The following formula is used to calculate the probability that a chromosome is selected:

$$p = \frac{f_k}{\sum\limits_{k=1}^{N} f_k}, k = 1, 2, ..., N \ . \tag{16}$$

(Crossover) Generate a random number between 0 and 1 and compare it with the crossover probability. If the crossover condition is satisfied, the arithmetic crossover operation will be performed on any two selected individuals.
(Mutation) Real Mutation Method is used in mutation operation. Set the mutation probability P_m . If the mutation condition is satisfied, then the mutation operation will be performed on the members of the selected chromosome by the following formula:

$$X'(i,j) = X(i,j) + \Delta \tag{17}$$

where Δ is a very small number.
end while
Step3: Individuals with the largest fitness value are used as optimal control inputs for control.
Step4: Return to **Step1**.
end while

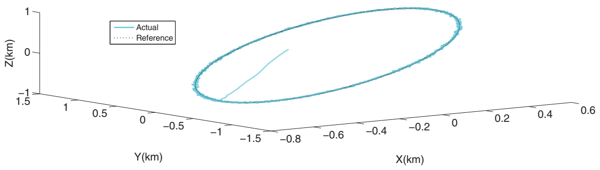

Fig. 4. Moving trajectory of the follower satellite in x , y and z directions

TABLE III
COMPARISON OF FUEL CONSUMPTION BETWEEN MPC AND EMPC

λ	Total fuel consumption
λ=0	92.5 m/s
λ=1	90.3425 m/s

control weight matrix $R = 80I_{9\times 9}$, adjustment coefficients $\lambda = 1$. Moreover, in the process of using genetic algorithm to optimize the solution of control law, the initial parameters of genetic algorithm are set as follows: Population size $Size = 50$, the number of variables $codel = 9$, the maximum number of iterations $G = 100$, the crossover probability $P_c = 0.9$ and the mutation probability $P_m = 0.01$. Finally, in the simulation, the sampling period and the number of sampling points are $T = 0.1s$ and $W = 60000$, respectively. The scope of control input of the actuator is $\left[\begin{array}{cc} -0.5 & 0.5 \end{array}\right]$.

C. Simulation results

The proposed algorithm is validated in SIMULINK/MATLAB environment and the simulation results are shown in Figs. 4-8. Fig. 4 and Fig. 5 describe the tracking of the reference trajectory by the follower satellite. In particular, Fig. 5 specifically depicts the tracking of the reference trajectory by the satellite in x , y and z directions. In Fig. 5, the satellite can track the reference trajectory in a short time. $u(x)$, $u(y)$ and $u(z)$ in Fig. 6 denote the control input of the thruster in x , y and z direction, respectively. Fig. 6 describes the change of the control input during the tracking of the reference trajectory by the follower satellite. It can be seen from the figure that the control input of the thruster is not only kept within the constraint range $\left[\begin{array}{cc} -0.5 & 0.5 \end{array}\right]$, but also relatively small. Fig. 7 displays the tracking error of the follower satellite. We can see from the picture that the control algorithm has a relatively high control accuracy. Fig. 8 reflects the fuel consumption of the follower satellite during trajectory tracking. In Table III, when λ=0 , the objective function (7) represents the traditional predictive control. When λ=1 , the objective function (7) denotes the economic predictive control considering fuel optimization. Table III depicts the total fuel consumption when these two control methods are used. As shown in Table III, economic predictive control achieves fuel saving compared to traditional predictive control. In summary, the proposed EMPC strategy based on genetic algorithm has been confirmed to be effective.

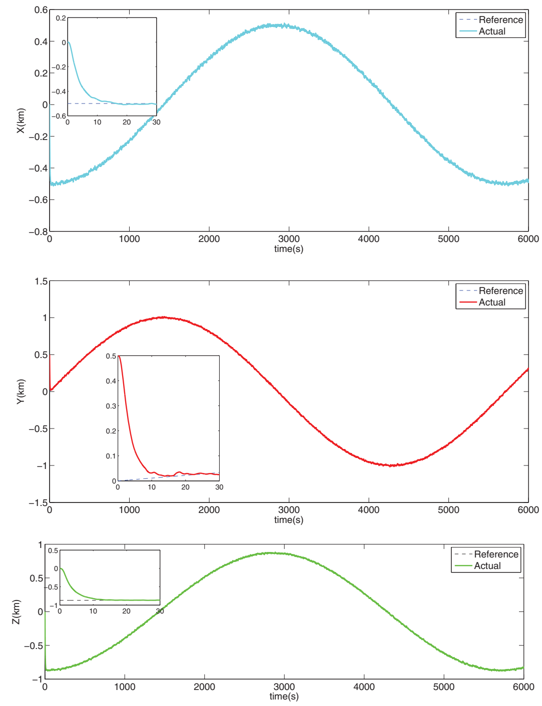

Fig. 5. Trajectory Tracking of the follower satellite in x , y and z directions

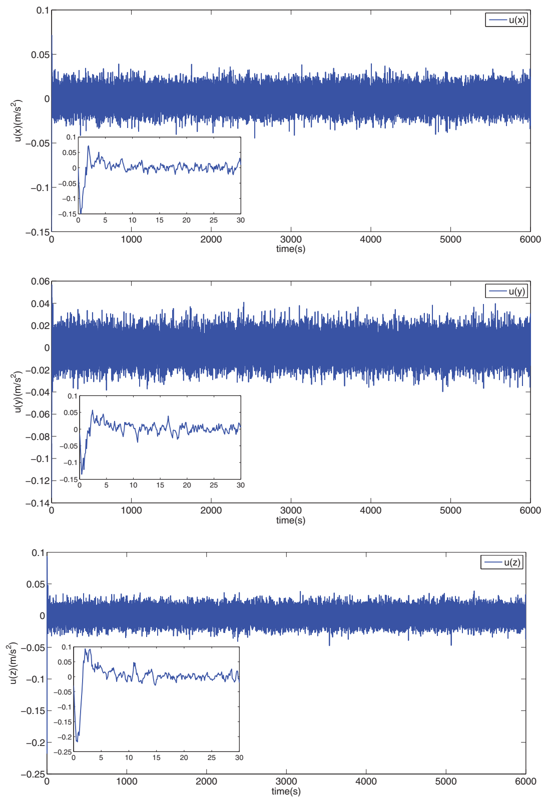

Fig. 6. Control input in x , y and z directions

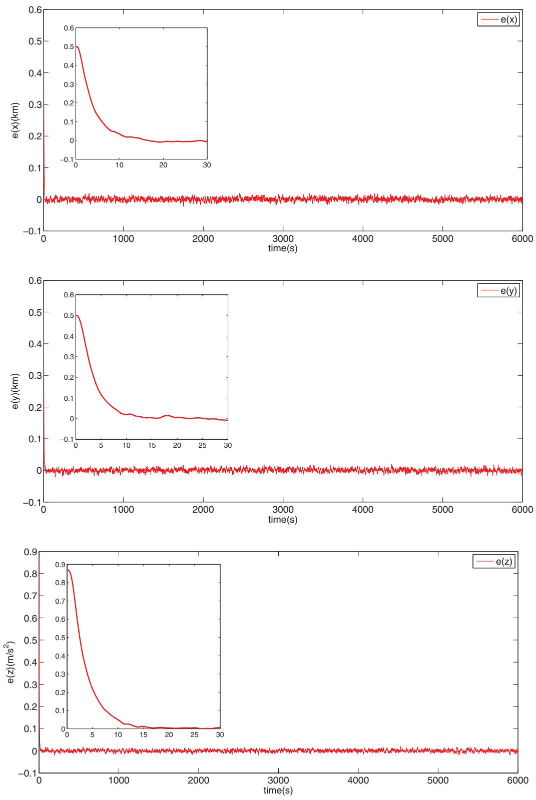

Fig. 7. Tracking errors in x , y and z directions

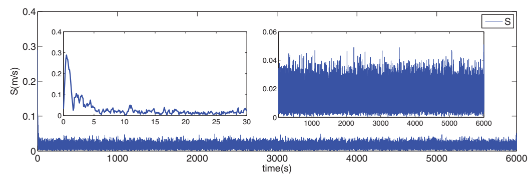

Fig. 8. Fuel consumption in trajectory tracking

V. CONCLUSION

In this paper, a novel fuel-optimal control strategy for the leader-follower satellite formation has been proposed. This control strategy is implemented by the EMPC algorithm in which the cost function is composed of a trajectory tracking term and an economic term on fuel consumption. Moreover, in order to solve the problem that traditional optimization techniques are difficult to solve the cost function, genetic algorithm is applied to solve the control law. The simulation results show that the designed EMPC strategy can achieve fuel optimization in the process of satellite formation keeping.

VI. ACKNOWLEDGMENT

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