

STK simulation design for satellite formation tracking mission with bidirectional communication

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Abstract: The problem of satellite formation tracking control is studied by using the tool, the satellite tool kit (STK) software. To fight against gravitational perturbation rejection, a sliding mode controller for each satellite is proposed to accomplish the orbit trace and is then verified by the STK. For the purpose of accomplishing the formation tracking mission with bidirectional communication in STK, a time-share orderly calling plug-in is designed by C++, which gives solutions to the problems of the monopolization of computing resource and no return of the satellite identifier in the calculation center. The effectiveness of the decoupling approach is tested and verified by the STK. The simulation results obtained by the STK are more meaningful than those obtained by Matlab.

Key words: satellite tool kit (STK); formation tracking control; decoupling approach

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Environmental issues are among the most important problems concerning the whole world. In order to understand and predict global climate, environmental experts use clusters of satellites to monitor settings such as animal habitats and river systems^[1-2]. To carry out these missions, a systematic method is required for dealing with the formation tracking control of multiple satellites.

In the literature, most results of satellite formation tracking control focus on the leader-following strategy^[3-6]. As we all know, the robustness of this strategy is weak due to no information translation from the follower to the leader and among the follower satellites. Beard et al.^[7] proposed a virtual structure to solve satellite forma-

tion flying along given orbits but with a formation that is rigid. Similar ideas can be found in Refs.[8-9]. For obtaining general formation, Aguiar et al.^[10] decoupled the control problem into the trajectory tracking control subproblem and formation control subproblem, which is called the decoupling approach. Similar methods are used for the decoupling-based cooperative control of underactuated vehicles^[11-12], simple full-actuated aircrafts^[13] and 3D nonholonomic vehicles^[14]. However, the effect of the decoupling approach is not verified in the field of satellite formation tracking yet.

Most current results^[3-11] about satellite formation tracking are validated by Matlab. Since Matlab simulations ignore the realistic features of satellite and the influences of realistic operating environment, the effects on the given control are difficult to assess. To deal with this limitation, STK software, a professional simulation tool for the satellite systems, is used in this paper. STK verification in this paper follows two steps: 1) A trajectory tracking control law derived from the sliding mode control method^[13] is given to each satellite for following its desired orbit, which is suitable to confront the gravitational perturbation; and then we use the COM interface supplied by the STK to add the gravitational perturbation and write the program to acquire the proposed trajectory tracking control in the STK. 2) According to the idea of the decoupling approach, we design the reference formation tracking input for each satellite in two parts. One is the trajectory tracking control input, which is the same as the controller given in step 1), the other is the consensus terms of the generalized arc-length computed by the reference motion along the given orbits and its deviation, which differs from the sliding mode formation fly protocol^[6] based on the leader-following strategy. In order to acquire the formation tracking control law in the STK, a time-share orderly calling plug-in is proposed by C++ to accomplish the bidirectional communication in the STK. Finally, we show the STK simulation results of formation tracking control from three satellites. In Refs.[15-16], some researchers used the STK to study satellite formation flying mission by using the solution of the classical C-W equations. This paper is different in that the C-W equations with the gravitation perturbation are considered and the decoupling-based formation tracking control is tested

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under bidirectional communication via STK.

1 Satellite's Dynamics

Consider the cooperative system composed of N satellites flying around a reference satellite (see Fig. 1). The reference satellite moves along a circular orbit in the inertial reference frame $W_1 = \{O_1, X_1, Y_1, Z_1\}$ and its angular velocity is ω_0 . Suppose that the distance between each satellite and the reference satellite is very small compared with the distance from the satellite to the earth. We define the satellite orbit frame $W_p = \{o_p, x_p, y_p, z_p\}$ such that the origin is located at the mass center of the reference satellite, x_p -axis of W_p is in the radial direction from the earth to the reference satellite, y_p -axis of W_p is in the tangential velocity direction of the primary satellite and z_p -axis completes a right-hand coordinate system. The dynamics of the i -th satellite in W_p can be written as

$$\begin{cases} \dot{\mathbf{p}}_i = \mathbf{v}_i \\ \dot{\mathbf{v}}_i = \mathbf{A}_p \mathbf{p}_i + \mathbf{A}_v \mathbf{v}_i + \mathbf{\Delta}_i + \mathbf{u}_i \end{cases} \quad (1)$$

where $\mathbf{p}_i = \{p_{x_i}, p_{y_i}, p_{z_i}\}^T$ is the position of the i -th satellite in W_p ; $\mathbf{v}_i = \{v_{x_i}, v_{y_i}, v_{z_i}\}^T$ is the velocity; $\mathbf{\Delta}_i = \{\Delta_{x_i}, \Delta_{y_i}, \Delta_{z_i}\}^T$ is the gravitational perturbation and satisfies that $\max\{\Delta_{x_i}, \Delta_{y_i}, \Delta_{z_i}\} \leq \Delta_{M_i} < +\infty$ and $\min\{\Delta_{x_i}, \Delta_{y_i}, \Delta_{z_i}\} \geq \Delta_{m_i} > -\infty$; $\mathbf{u}_i = \{u_{x_i}, u_{y_i}, u_{z_i}\}^T$ is the control input; $\mathbf{A}_p =$

$$\begin{bmatrix} 3\omega_0^2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\omega_0^2 \end{bmatrix} \text{ and } \mathbf{A}_v = \begin{bmatrix} 0 & 2\omega_0 & 0 \\ -2\omega_0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

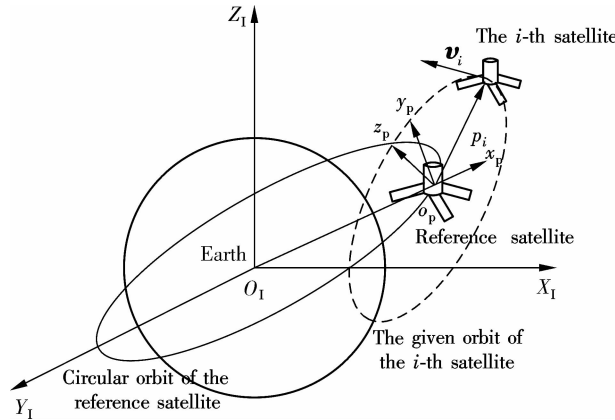


Fig. 1 Satellite's dynamics

Remark 1 When the gravitational perturbation $\mathbf{\Delta}_i$ is ignored, the dynamics (1) turns into classical C-W equations which are discussed in Refs. [15–16].

2 Trajectory Tracking Control Design

2.1 Sliding mode control for trajectory tracking

Let the desired motion dynamics with respect to the i -th satellite be

$$\begin{cases} \dot{\mathbf{p}}_i^* = \mathbf{v}_i^* \\ \dot{\mathbf{v}}_i^* = \mathbf{A}_p \mathbf{p}_i^* + \mathbf{A}_v \mathbf{v}_i^* + \mathbf{u}_{t_i}^* \end{cases} \quad (2)$$

where $\mathbf{p}_i^* = \{p_{x_i}^*, p_{y_i}^*, p_{z_i}^*\}^T$ and $\mathbf{v}_i^* = \{v_{x_i}^*, v_{y_i}^*, v_{z_i}^*\}^T$ are the reference position and velocity associated to the i -th satellite in W_p , respectively; $\mathbf{u}_{t_i}^* = \{u_{t_{x_i}}^*, u_{t_{y_i}}^*, u_{t_{z_i}}^*\}^T$ is designed according to the desired orbit. Define

$$\mathbf{p}_{e_i} = \mathbf{p}_i - \mathbf{p}_i^*, \quad \mathbf{v}_{e_i} = \mathbf{v}_i - \mathbf{v}_i^* \quad (3)$$

as the position error and the velocity error of trajectory tracking control with regard to the i -th satellite, respectively. From Eqs. (1) to (3), we can obtain

$$\begin{cases} \dot{\mathbf{p}}_{e_i} = \mathbf{v}_{e_i} \\ \dot{\mathbf{v}}_{e_i} = \mathbf{A}_p \mathbf{p}_{e_i} + \mathbf{A}_v \mathbf{v}_{e_i} + \mathbf{\Delta}_i + \mathbf{u}_i - \mathbf{u}_{t_i}^* \end{cases} \quad (4)$$

Also, let $\mathbf{e}_i = \{\mathbf{p}_{e_i}, \mathbf{v}_{e_i}\}^T$, and Eq. (4) can be rewritten as

$$\dot{\mathbf{e}}_i = \mathbf{A}_i \mathbf{e}_i + \mathbf{B}_i (\mathbf{u}_i - \mathbf{u}_{t_i}^*) + \mathbf{C}_i \mathbf{\Delta}_i \quad (5)$$

$$\text{where } \mathbf{A}_i = \begin{bmatrix} \mathbf{0}_{3 \times 3} & \mathbf{I}_{3 \times 3} \\ \mathbf{A}_p & \mathbf{A}_v \end{bmatrix}, \mathbf{B}_i = \mathbf{C}_i = \begin{bmatrix} \mathbf{0}_{3 \times 3} \\ \mathbf{I}_{3 \times 3} \end{bmatrix}.$$

In the following, a sliding mode control is designed according to Ref. [17], which drives \mathbf{e}_i to $\mathbf{0}$ asymptotically. Let $\mathbf{s}_i = \{s_{x_i}, s_{y_i}, s_{z_i}\}^T$ be the sliding quantity such that $\mathbf{s}_i = \mathbf{D}_{p_i} \mathbf{p}_{e_i} + \mathbf{v}_{e_i}$ and the exponent reaching law is $\dot{\mathbf{s}}_i = -\mathbf{K}_{\alpha_i} \text{sgn}(\mathbf{s}_i) + \mathbf{K}_{\beta_i} \mathbf{s}_i$, where $\mathbf{D}_{p_i} = \text{diag}(d_{x_i}^p, d_{y_i}^p, d_{z_i}^p)$, $d_{x_i}^p > 0$, $d_{y_i}^p > 0$, $d_{z_i}^p > 0$, $\mathbf{K}_{\alpha_i} = \text{diag}(k_{x_i}^\alpha, k_{y_i}^\alpha, k_{z_i}^\alpha)$, $k_{x_i}^\alpha > 0$, $k_{y_i}^\alpha > 0$, $k_{z_i}^\alpha > 0$, $\text{sgn}(\mathbf{s}_i) = \{\text{sgn}(s_{x_i}), \text{sgn}(s_{y_i}), \text{sgn}(s_{z_i})\}$, $\mathbf{K}_{\beta_i} = \text{diag}(k_{x_i}^\beta, k_{y_i}^\beta, k_{z_i}^\beta)$, $k_{x_i}^\beta > 0$, $k_{y_i}^\beta > 0$, $k_{z_i}^\beta > 0$. Due to the expression of \mathbf{B}_i , system (5) is simple because $\mathbf{B}_i = \mathbf{C}_i$, system (5) satisfies the perfect following condition. Owing to $\det[\mathbf{D}_{p_i}, \mathbf{I}_{3 \times 3}] \neq 0$, system (5) satisfies the variable structure controlled condition. Similar to Ref. [17], we denote

$$\begin{aligned} \mathbf{u}_i = \mathbf{u}_{t_i}^* - \mathbf{D}_{p_i}^{-1} \left[\left(\mathbf{K}_{\alpha_i} + \mathbf{D}_{p_i} \text{diag} \left(\frac{\Delta_{M_i} - \Delta_{m_i}}{2} \right) \right) \text{sgn}(\mathbf{s}_i) + \right. \\ \left. \mathbf{D}_{p_i} \text{diag} \left(\frac{\Delta_{M_i} + \Delta_{m_i}}{2} \right) + \mathbf{A}_p \mathbf{p}_{e_i} + (\mathbf{A}_v + \mathbf{D}_{p_i}) \mathbf{v}_{e_i} + \mathbf{K}_{\beta_i} \mathbf{s}_i \right] \end{aligned} \quad (6)$$

2.2 STK simulations of trajectory tracking

In this subsection, STK software is used to check the effect of the proposed trajectory tracking control (6). The HPOP orbit predictor in STK not only supplies orbit prediction in high precision and for the long term, but also gives the user a COM control interface to add perturbation acceleration. Here, we use HPOP to accomplish (6). The process is as follows.

Step 1 STK call. Since the HPOP orbit predictor gives a COM interface to the user's programs, the user is required to compile compliant programs and log them in to STK so that they are able to work.

Step 2 Coordinate translation. Since the call of satellite's states in STK is based on the inertial coordinate system but the trajectory tracking controller is designed for the primary satellite orbit frame, a frame translation is required before running the trajectory tracking algorithm

program.

Step 3 Working process of algorithm program. The working process of the trajectory tracking algorithm program includes the calculations of the sliding quantity, the exponent reaching law, the desired motion states of the satellite and the control input.

Step 4 Control input recalculation. In this step, the control input computed in the primary satellite orbit frame must be recalculated in the inertial coordinate system.

Step 5 Data record. The states of satellite are recorded and saved in the database, which is prepared for the mission of formation motion in the next section.

Step 6 STK Return.

Case 1 The desired orbit with respect to the satellite is an elliptical orbit where the center is located in $\{0 \text{ km}, 0 \text{ km}, 0 \text{ km}\}^T$. The semi-major axis length is 200 km, the semi-minor axis length is 100 km, and the period of flying around the primary satellite is 100 s. The control parameters are selected as $\mathbf{D}_{p_i} = \text{diag}(0.01, 0.01, 0.01)$, $\mathbf{K}_{\alpha_i} = \mathbf{K}_{\beta_i} = \text{diag}(0.1, 0.1, 0.1)$. We set the maximum degree of earth gravity as 10 in HPOP to represent the gravitational perturbation. The movements of the satellites are shown in Fig. 2. According to Fig. 2, we can conclude that the proposed controller is effective for trajectory tracking when gravitational perturbation exists.



(a)



(b)

Fig. 2 Trajectory tracking movement. (a) Global perspective; (b) Partial enlarged view

3 Formation Tracking Control Design

3.1 Decoupling design for formation tracking control

The key idea of the decoupling design is to decouple the trajectory tracking and formation motion. For the pur-

pose of applying the decoupling design to deal with the formation tracking control of satellites in STK, we first redesign the desired dynamics associated with each satellite (2) in two parts, that is

$$\left. \begin{aligned} \dot{\mathbf{p}}_i^* &= \mathbf{v}_i^* \\ \dot{\mathbf{v}}_i^* &= \mathbf{A}_{p_i} \mathbf{p}_i^* + \mathbf{A}_{v_i} \mathbf{v}_i^* + \mathbf{u}_{i_i}^* + \mathbf{u}_{f_i}^* \end{aligned} \right\} \quad (7)$$

where $\mathbf{u}_{i_i}^*$ is designed according to the reference orbit of the i -th satellite and the form of $\mathbf{u}_{i_i}^*$ is the same as Eq. (6); $\mathbf{u}_{f_i}^*$ contributes to the formation motion and is designed as

$$\mathbf{u}_{f_i}^* = \left[-k_1(\eta_i - \eta^*) - k_2 \sum_{j=1}^n a_{ij}(\xi_i - \xi_j) - k_3 \sum_{j=1}^n a_{ij}(\eta_i - \eta_j) \right] \boldsymbol{\tau}_{3_i} \quad (8)$$

where control parameters $k_1, k_2, k_3 > 0$; $\mathbf{A} = (a_{ij})$ is the adjacency matrix associated with bidirectional communication and is defined as: $a_{ii} = 0$, a_{ij} is 1 if the i -th satellite and the j -th satellite can transfer data each other and $a_{ij} = 0$, otherwise,

$$\boldsymbol{\Gamma}_i = \begin{bmatrix} \mathbf{N}_i^T \\ \mathbf{B}_i^T \\ \mathbf{T}_i^T \end{bmatrix}^{-1} = [\boldsymbol{\tau}_{1_i} \quad \boldsymbol{\tau}_{2_i} \quad \boldsymbol{\tau}_{3_i}]$$

where $\mathbf{N}_i, \mathbf{B}_i, \mathbf{T}_i$ are the normal vector, the binormal vector and tangent vector to the given orbit associated with the i -th satellite, respectively. In this paper, the communication topology under consideration is bidirectional and time-invariant. ξ_i is the general arc-length that is defined as Assumption 1 and $\eta_i(t) = (\partial \xi_i / \partial l_i) \mathbf{v}_i$; η^* is the desired orbit speed designed based on the period of the satellite flying motion. From Eq. (8), one can see that the last two terms are the consensus terms, which are widely used in the formation tracking control of 2D vehicles^[10–14] and aircrafts^[13–14]. Then $\mathbf{u}_{i_i}^*$ and $\mathbf{u}_{f_i}^*$ can achieve both trajectory tracking and formation flying around given orbits.

Assumption 1 $\xi_i(l_i)$ is a C^2 smooth function of the arc-length l_i such that all $\partial \xi_i / \partial l_i$ is bounded and greater than 0 and $\partial^2 \xi_i / \partial l_i^2$ is uniformly bounded.

3.2 STK simulations of formation tracking

To accomplish the formation tracking control protocol in STK, information translation among satellites is required due to the consensus terms such that $\sum_{j=1}^n a_{ij}(\xi_i - \xi_j)$

and $\sum_{j=1}^n a_{ij}(\eta_i - \eta_j)$ are used in Eq. (8). For this purpose, we use the connection module supplied by the STK. Although the connection module packages the TCP/IP protocol and supplies the user with a communication link to drive the STK by sending commands, the user cannot directly use it to translate the data between two

satellites in STK simulations. This is due to the following reasons:

1) Monopolization of computing resource. One precondition of data translation is that the motions of all satellites can be computed at the same time. However, one computing task of one satellite's motion uses the computing resource of the STK, which implies that the STK can only compute one satellite's motion at one time. Thus, the state data cannot be translated among satellites simultaneously.

2) Anonymous Information. The other precondition of data translation is that the owner of the data must be confirmed. However, the call of the plug-in in the STK is anonymous and thus the STK does not supply the user with the name of who owns the data, which is another obstacle to applying the communication link for transferring information in the STK.

To solve these two problems, we write a time-share orderly calling plug-in based on C++, which is used to send the data to STK for computing each satellite's motion in order. The operational principle of the time-share orderly calling plug-in is to cut the sampling time into pieces at first and then use each time fragment to compute the motion of its relative concomitant satellite. The other advantage of the time-share orderly calling method is that it can make the corresponding satellite compute one by one, which provides a solution to solving the problem of anonymous information. In the STK simulations, we output the calculation results into a log file with a special name at each end of the time fragments. The flow chart of a formation tracking STK simulation is shown in Fig. 3.

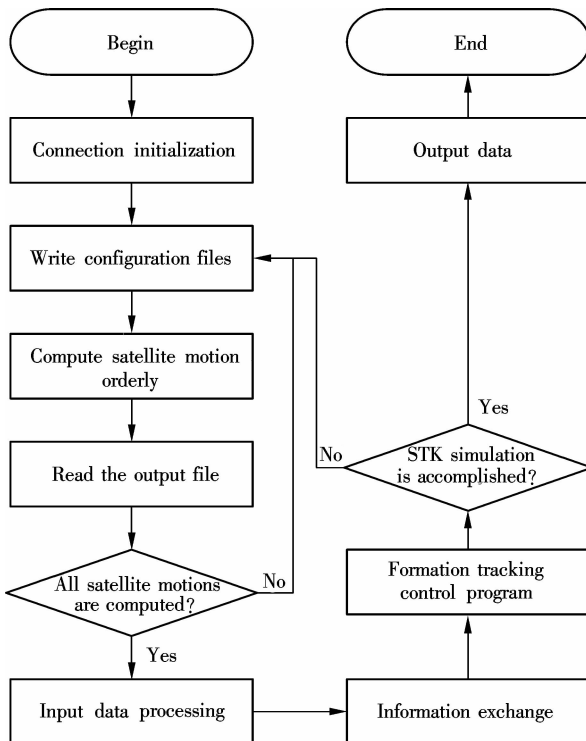
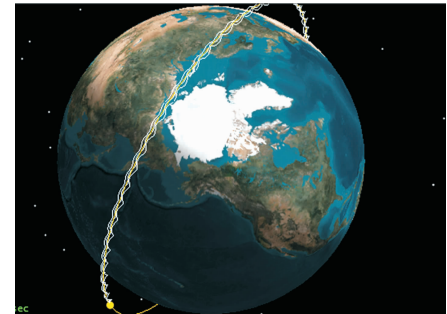


Fig. 3 Flow chart of formation tracking STK simulation

Case 2 A triangle formation fly is shown in this case. The communication among three satellites is that the 1st and the 2nd satellites, the 2nd and the 3rd satellites, the 1st and the 3rd satellites can exchange their information. The desired orbit with respect to the 1st satellite is an elliptical orbit where the center is located at $\{0 \text{ km}, 0 \text{ km}, 100 \text{ km}\}^T$ and the semi-major and semi-minor axis lengths are 100 and 50 km, respectively. The desired elliptical orbit with respect to the 2nd satellite is that the orbit's center is located at $\{0 \text{ km}, 100 \text{ km}, 0 \text{ km}\}^T$, the semi-major and semi-minor axis lengths are 75 and 37.5 km, respectively. The desired elliptical orbit with respect to the 3rd satellite is that the orbit's center is located at $\{0 \text{ km}, 0 \text{ km}, -100 \text{ km}\}^T$, the semi-major and semi-minor axis lengths are 100 and 50 km, respectively. The starting point for each orbit for computing arc length l_i is selected as the intersection of the orbit with the horizontal axis. The ξ_i is selected as $\xi_1 = l_1$, $\xi_2 = l_2/0.75$ and $\xi_3 = l_3$. The control parameters are $D_{p_i} = \text{diag}(0.01, 0.01, 0.01)$, $K_{\alpha_i} = K_{\beta_i} = \text{diag}(0.1, 0.1, 0.1)$. The maximum degree of earth gravity is set as the same as Case 1. The movements of the satellites are shown in Fig. 4. According to these pictures, we can conclude that the decoupling approach is effective in designing the formation tracking control for satellites.



(a)



(b)

Fig. 4 Formation tracking movement. (a) Global perspective; (b) Partial enlarged view

4 Conclusion

In this paper, STK is used to study the formation tracking control of satellites. For single trajectory tracking control, a robust control law is proposed by using the

sliding model design, which is useful for resisting the gravitational perturbation. To achieve the simulation of formation tracking control in STK, we present the time-share orderly calling plug-in to accomplish the unity of the simulation, algorithm programs and communication. In the future, we will devote ourselves to the field of the finite-time formation tracking control of satellites.

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基于双向通信的卫星寻迹编队任务的 STK 仿真设计

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摘要: 基于 STK 仿真软件研究了多卫星寻迹编队控制问题. 利用滑模控制方法设计单颗卫星轨迹跟踪控制律用以对抗引力摄动, 同时在 STK 仿真环境中验证了该算法的有效性. 为了在 STK 中实现基于双向通信的卫星寻迹编队任务, 利用 C++ 语言设计了一个分时有序调用插件解决了 STK 仿真中的计算独占的问题和仿真计算中心不返回当前卫星标识符的问题. 在此基础上, 利用 STK 仿真验证了解耦法设计的寻迹编队算法的有效性, STK 仿真结果比 Matlab 仿真结果更有实用意义.

关键词: 卫星工具包; 寻迹编队控制; 解耦法

中图分类号: TP24