Inter-satellite Link Topology Design and Relative Navigation for Satellite Clusters

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Abstract: A distributed relative navigation approach via inter-satellite sensing and communication for satellite clusters is proposed. The inter-satellite link (ISL) is used for ranging and exchanging data for the relative navigation, which can improve the autonomy of the satellite cluster. The ISL topology design problem is formulated as a multi-objective optimization problem where the energy consumption and the navigation performance are considered. Further, the relative navigation is performed in a distributed fashion, where each satellite in the cluster makes observations and communicates with its neighbors via the ISL locally such that the transmission consumption and the computational complexity for the navigation are reduced. The ISL topology optimization problem is solved via the NSGA-Ⅱ algorithm, and the consensus Kalman filter is used for the distributed relative navigation. The proposed approach is flexible to varying tasks, with satellites joining or leaving the cluster anytime, and is robust to the failure of an individual satellite. Numerical simulations are presented to verify the feasibility of the proposed approach.

Key words: satellite cluster; relative navigation; inter-satellite link; network topology; multi-objective optimization

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0 Introduction

Satellite clusters which consist of multiple cooperative satellites have received increasing attentions in recent years. Multi-satellite system has several advantages over the traditional monolithic satellite, such as lower price, increased flexibility and robustness to the failure of an individual satellite, and hence, it has great potential in distributed aperture telescopes, deep space exploration and other space missions[1-2].

For the satellite cluster in deep space, navigation is a challenging problem[3]. There are a significant number of satellites in the cluster, so the computational cost for navigation is expensive. Further, in many tasks, the satellites in the cluster are not required to track specified relative motion in contrast to the formation, so the relative states between satellites vary frequently, which poses extra challenge for real-time navigation with high accuracy. Moreover, for deep space missions, there are scenarios when the global navigation satellite system (GNSS) is not available or the satellites cannot contact with the ground frequently[4-5]. Therefore, to improve the autonomy of the multi-satellite system, a lot of work has been carried out on the relative navigation via inter-satellite links with limited on-board measurements[6].

An inter-satellite link (ISL) is a link used for communication between satellites and has a function of sensing[7]. Both radio-frequency (RF) links[8] and laser links[9] can be used for the relative navigation. The laser links can achieve high ranging accuracy while require higher power consumption. Thus, for small satellites with limited resources, relative navigation using RF links with high frequency is playing an important role at present.

The inter-satellite relative range or angle measurements are taken when the links are established, and the data are transmitted between neighbors via

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ISLs, thus designing the ISL network topology becomes important for both communication and navigation[10]. For example, the energy consumption for transmitting or receiving data is related to the distance between satellites, which is changing in time, and hence, there has considerable work been done on optimizing the ISL topology to reduce the total energy consumption[11-12]. Moreover, massive data packets are transmitted between satellites, which may cause the network congestion, and affect the navigation performance. Therefore, ISL assignment approaches such as reinforcement learning based algorithm[13] have been proposed. Other research focuses on improving the navigation performance, and the position dilution of precision (PDOP) criterion is proposed for the ISL assignment problem[14-15].

Another important issue needs to be addressed for the relative navigation arises from the fact that the number of the satellites in the cluster is huge. Traditional centralized state estimation algorithms, such as extended Kalman filter (EKF)[16], require to transmit all the measurements to a center satellite. While the performance of the centralized algorithm is optimal, it might be infeasible since the transmission consumption and the computational cost are huge. Therefore, distributed state estimation algorithms have attracted a lot of attentions, and have been widely used in multi-agent systems[17] and sensor networks[18]. The main idea of the distributed algorithm is that for each agent in the network, the information is only exchanged between neighbors, and each agent makes a local estimation using the data. Distributed estimation with applications in spacecraft navigation has been studied recently[19-20]. For example, a distributed information fusion algorithm is proposed to estimate the orbit of a single spacecraft using information from ground stations in the network[21]. For the relative navigation of multiple spacecrafts, a consensus extended Kalman filter algorithm is proposed with the observability analysis[22]. Different consensus-based state estimation algorithms, including consensus on information (CI), consensus on measurement (CM) and hybrid methods have been presented with stability analysis[23]. Since the optimality of the CI algorithm can be guaranteed with appropriate assumptions, thus, in this paper we design a RF-based ISL topology to meet the assumptions made in CI algorithm, and propose a distributed relative navigation scheme for clusters, where satellites only exchange navigation informations and take inter-satellite measurements with satellites in neighbours via ISLs.

The main contributions of this paper are summarized as follows:

(1) A time-varying sensing and communication ISL topology network is designed, and it can adapt to complicated tasks, with satellites joining or leaving the network at any time.

(2) Both the energy consumption and the navigation accuracy are taken into account when designing the ISL topology, which makes it more feasible in practice.

(3) A consensus-based Kalman filter algorithm is used for estimating the states of the satellite cluster in a distributed fashion, and the computational load as well as the transmission consumption is reduced with guaranteed stability.

The rest of the paper is organized as follows. In Section 1, the system model including the relative motion model and the observation model is introduced. In Section 2, the ISL topology optimization problem is formulated and in Section 3, the distributed relative navigation algorithm is presented. In Section 4, numerical results for a cluster with 15 satellites are presented. Finally, Section 5 concludes the paper.

1 System Model

In this section, we briefly introduce the relative navigation scheme for satellite clusters, including the relative orbital dynamics and the observation model.

1.1 Relative orbital dynamics

For the satellite clusters system, the local-vertical-local-horizontial (LVLH) coordinate frame originates from the barycenter of the chief satellite is used, where x-axis lying along the orbital radius vector $\boldsymbol{r}_c$ from the Earth center to the chief satellite, z-axis coinciding with the satellite angular moment vector, and y-axis coinciding with the satellite velocity vector, shown as Fig.1.

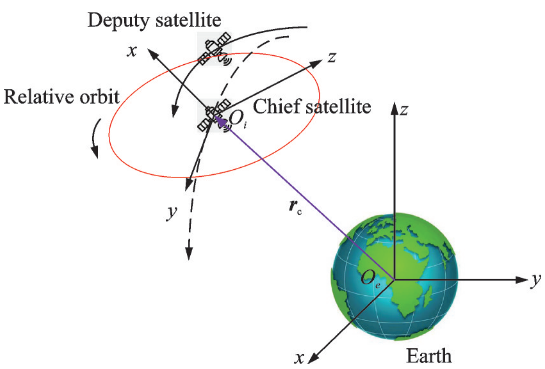

Fig.1 Satellite orbital coordinate system

Assuming that the orbit of chief satellite is circular and the relative distance between two satellites is not large, the relative orbital motion for any deputy satellite can be described by the Clohessy-Wiltshire equation as

$$\begin{cases} \ddot{x} = 3n^2 x + 2n\dot{y} \\ \ddot{y} = -2n\dot{x} \\ \ddot{z} = -n^2 z \end{cases} \tag{1}$$

where n is the orbit angular velocity of the circular reference orbit and $\boldsymbol{r}=\left[x, y, z\right]$ the triaxial components of the deputy satellite's relative positions in the LVLH frame.

Denote $\boldsymbol{x}^i(t)=\left[x^i, y^i, z^i, \dot{x}^i, \dot{y}^i, \dot{z}^i\right]^{\mathrm{T}}$, $i=1,2,\cdots,N$ as the state for the ith satellite, then the discrete-time state space model is given by

$$\boldsymbol{x}_{k+1} = \boldsymbol{A}\boldsymbol{x}_k + \boldsymbol{\omega}_k \tag{2}$$

where $\boldsymbol{A}=\mathrm{diag}(\boldsymbol{A}_1, \boldsymbol{A}_2, \cdots, \boldsymbol{A}_N)$ with $\boldsymbol{A}_i$ as the state transition matrix for the ith satellite, diag(·) represents the diagonal matrix with (·) as the diagonal entries, and

$$\boldsymbol{A}_i = \begin{bmatrix} 1 & 0 & 0 & \Delta t & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 1 & 0 & 0 & \Delta t \\ 3n^2\Delta t & 0 & 0 & 1 & 2n\Delta t & 0 \\ 0 & 0 & 0 & -2n\Delta t & 1 & 0 \\ 0 & 0 & -n^2\Delta t & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Denote $\boldsymbol{x}_k=\boldsymbol{x}(k\Delta t)[\boldsymbol{x}^1(k\Delta t)^{\mathrm{T}}, \cdots, \boldsymbol{x}^N(k\Delta t)^{\mathrm{T}}]^{\mathrm{T}} \in \mathrm{R}^{n_x}$ as the system state at time $k\Delta t$, with Δt as the sampling time and $n_x=6N$ as the dimension of the system state of the cluster; $\boldsymbol{\omega}_k \sim N(0, \boldsymbol{Q}_k)$ is the process noise and is assumed to be Gaussian white noise with zero mean and covariance $\boldsymbol{Q}_k$.

1.2 Multi-satellite relative navigation scheme

In this paper, the sensing and communication are conducted via inter-satellite RF links. Relative navigation based on angles-only, range-only and mixed measurements has been studied well. Although angles-only relative navigation[24-25] and range-only relative navigation[26] require fewer measurement devices to complete the relative orbit determination, the observability problem still exists. Therefore, in order to improve the navigation accuracy and reduce the total number of measurements, the multi-satellite navigation scheme is adopted[8].

Suppose all satellites in the cluster can measure the range and angle information and be divided into two groups, $\{C_i\}_{i=1}^{p}$ and $\{D_j\}_{i=1}^{N-p}$. At each time step, both inter-satellite angle and range measurements are taken between satellites $\{C_i\}_{i=1}^{p}$, while only range measurements can be taken between other satellites. The multi-satellite relative navigation scheme with $\{C_1, C_2, C_3\}$ and $\{D_1, D_2, \cdots, D_6\}$ is shown in Fig.2.

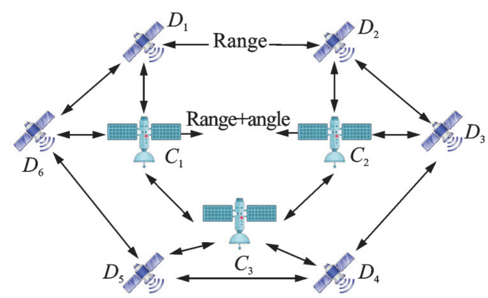

Fig.2 Multi-satellite relative navigation example

For each satellite i, the observation model is given as

$$\boldsymbol{z}_k^i = \boldsymbol{h}_k^i(\boldsymbol{x}_k) + \boldsymbol{v}_k^i \quad i=1,2,\cdots,N \tag{4}$$

where $\boldsymbol{h}_k^i(\boldsymbol{x}_k)$ is the measurement of satellite i at time step k, and $\boldsymbol{v}_k^i \sim N(0, R_k^i)$ the measurement noise and assumed to be Gaussian white noise with zero mean and covariance R_k^i.

2 Inter-satellite Link Topology Optimization Problem Formulation

In this section, we design a time-varying ISL topology for clusters with a large number of satellites. The energy consumption as well as the navigation performance is considered, with the ability to switch the satellites taking both range and angle measurements in an event-triggered fashion to extend the average working time of the whole cluster. The ISL topology optimization problem is formulated as a multi-constraint multi-objective problem and is described in detail below.

2.1 Network topology

Satellite clusters perform inter-satellite sensing and communication through a time-varying network topology $\mathcal{G}=(\mathcal{V},\mathcal{E},\mathcal{A})$, where $\mathcal{V}=[v_1,v_2,\cdots,v_N]$ represents the satellite nodes in the network, and $\mathcal{E}$ represents the connections between the satellite nodes, with $(v_i,v_j)\in\mathcal{E}$ indicating that the ISL is established between satellite i and j. Denote the neighbors of v_i as $\mathcal{N}_i\triangleq\{v_j\in\mathcal{V},|(v_i,v_j)\in\mathcal{E}\}$, and hence, $\mathcal{N}_i$ includes satellites that establish ISL with v_i. Moreover, the adjacency matrix $\mathcal{A}(\mathcal{G})$ is defined as

$$[\mathcal{A}(\mathcal{G})]_{ij}=\begin{cases}1 & (v_i,v_j)\in\mathcal{E}\\ 0 & \text{Otherwise}\end{cases}\tag{5}$$

and the Laplacian matrix $\mathcal{L}(\mathcal{G})$ is defined as

$$[\mathcal{L}(\mathcal{G})]_{ij}=\begin{cases}\sum\limits_{i\neq j}[\mathcal{A}(\mathcal{G})]_{ij} & i=j\\ -[\mathcal{A}(\mathcal{G})]_{ij} & i\neq j\end{cases}\tag{6}$$

Notice that the topology $\mathcal{G}(k)$ changes in time, and we design the optimal topology as follows.

2.2 Constraint formulation

In this paper, the following constraints are considered.

(1) Number of ISL

Since each satellite can carry limited number of RF equipments, limited number of ISLs can be established. We suppose for each satellite, at least one link and at most $l_{\max}$ links are established.

(2) Connectivity of the topology

The communication topology is connected if there exists a path connecting any two satellites. The connectivity of the topology could be satisfied when the second smallest eigenvalue of the Laplacian matrix $\mathcal{L}(\mathcal{G})$ is positive, i.e.

$$\mu_2(\mathcal{L}(\mathcal{G}))>0\tag{7}$$

where $\mu_2(\cdot)$ denotes the second smallest eigenvalue of $(\cdot)$.

(3) Symmetry of ISL assignment matrix

In this paper, we assume that when the ISL between two satellite is established, sensing and communication between two satellites are possible in both directions, and hence, the network topology is an undirected graph.

The ISL assignment matrix can be described as a two-dimensional symmetric matrix, shown as

$$\boldsymbol{L}=\begin{bmatrix}l_{11} & l_{12} & \cdots & l_{1N}\\ l_{21} & l_{22} & \cdots & l_{2N}\\ \vdots & \vdots & \ddots & \vdots\\ l_{N1} & l_{N2} & \cdots & l_{NN}\end{bmatrix}\tag{8}$$

where l_{ij} is a binary number, and $l_{ij}=1$ indicates that there exists a link between satellite i and j, when $i\neq j$. l_{ii} indicates that the satellite i can establish a link with the chief satellite. We require that $\boldsymbol{L}$ is symmetry, i.e.

$$l_{ij}=l_{ji}\tag{9}$$

Remark 1 Constraint (1) is proposed to meet the requirements in real applications. Constraints (2) and (3) are proposed such that the ISL topology is an undirected and connective graph.

2.3 Performance metrics

2.3.1 Navigation accuracy

PDOP can reflect both the number of inter-satellite observations and the geometric distribution of inter-satellite observations, and hence, PDOP criterion is taken as a measure of navigation accuracy performance, which is calculated as

$$\mathrm{PDOP}_i=\mathrm{tr}[(\boldsymbol{F}_i^{\mathrm{T}}\boldsymbol{F}_i)^{-1}]_i\tag{10}$$

where $\boldsymbol{F}_i$ is an observation matrix for satellite i with s ISL links, shown as

$$\boldsymbol{F}_i=\begin{bmatrix}\dfrac{\hat{x}_i-x_1}{R_{i1}} & \dfrac{\hat{y}_i-y_1}{R_{i1}} & \dfrac{\hat{z}_i-z_1}{R_{i1}}\\ \dfrac{\hat{x}_i-x_2}{R_{i2}} & \dfrac{\hat{y}_i-y_2}{R_{i2}} & \dfrac{\hat{z}_i-z_2}{R_{i2}}\\ \vdots & \vdots & \vdots\\ \dfrac{\hat{x}_i-x_s}{R_{is}} & \dfrac{\hat{y}_i-y_s}{R_{is}} & \dfrac{\hat{z}_i-z_s}{R_{is}}\end{bmatrix}\tag{11}$$

where R_{ij} is the range between satellite i and satellite j, $(\hat{x}_i,\hat{y}_i,\hat{z}_i)$ the position of satellite i, and (x_j,y_j,z_j) the position of satellite j, for $j=1,2,\cdots,s$.

2.3.2 Energy consumption

Suppose the distance between transmitting and receiving modules is d, then the energy consumption of the transmitting modules when transmitting a bit of data is expressed as

$$E_{tx}(a,d)=E_{elec}\cdot a+\varepsilon_{amp}\cdot ad^2 \tag{12}$$

The energy consumption of the satellite when receiving a bit of data is

$$E_{re}(a,d)=E_{elec}\cdot a \tag{13}$$

Therefore, the energy consumption in a satellite cluster network is given as

$$E(a,d)=\sum_{i=1}^{\phi}\left(E_{elec}\cdot a+\varepsilon_{amp}\cdot ad^2\right)+\sum_{j=1}^{\Psi}\left(E_{elec}\cdot a\right) \tag{14}$$

where E_{elec} denotes the energy consumption of the transmitter and receiver modules when transmitting or receiving 1 bit of data, $\mathcal{E}_{amp}$ is the energy consumption per square meter, and Φ and Ψ are the total numbers of links for the satellite to send and receive data, respectively.

2.4 Optimization problem

We consider scenarios when the inter-satellite distance is changing, and satellites can join or leave the cluster anytime during missions. The dynamically varying ISL topology optimization problem is formulated as: At each time step, finding the optimal adjacency matrix L, such that

$$\begin{cases}\text{Minimize}\left(\dfrac{1}{N}\sum\limits_{i=1}^{N}\text{PDOP}_i\right)\\ \text{Minimize}(E(a,d))\end{cases} \tag{15}$$

with constraints

$$\begin{cases}\mu_2(L(\mathcal{G}))>0\\ 1\leqslant\sum\limits_{j}^{N}l_{ij}\leqslant l_{max} \quad i=1,2,\cdots,N\\ l_{ij}=l_{ji}\end{cases} \tag{16}$$

Further, to avoid excessive energy consumption for satellites taking both range and angle measurements, we set a threshold U for the total energy consumption. And once the total energy consumption exceeds the threshold, the satellite taking both range and angle measurements is switched to the satellite with the smallest energy consumption in the cluster.

3 Relative Navigation Algorithm Based on Inter-satellite Link Topology Optimization

In this section, we propose a relative navigation algorithm for the satellite cluster, which solves the inter-satellite link topology optimization problem at each time step via NSGA-Ⅱ algorithm for the optimal sensing and communication topology, and then performs a distributed state estimation for relative navigation via the consensus Kalman filter algorithm.

3.1 NSGA-Ⅱ algorithm

The multi-objective optimization problem can be solved via many approaches, and in this paper, a modified genetic algorithm, NSGA-Ⅱ algorithm, is used[27]. The flowchart of NSGA-Ⅱ algorithm is shown in Fig.3, where gen is the nmber of generation.

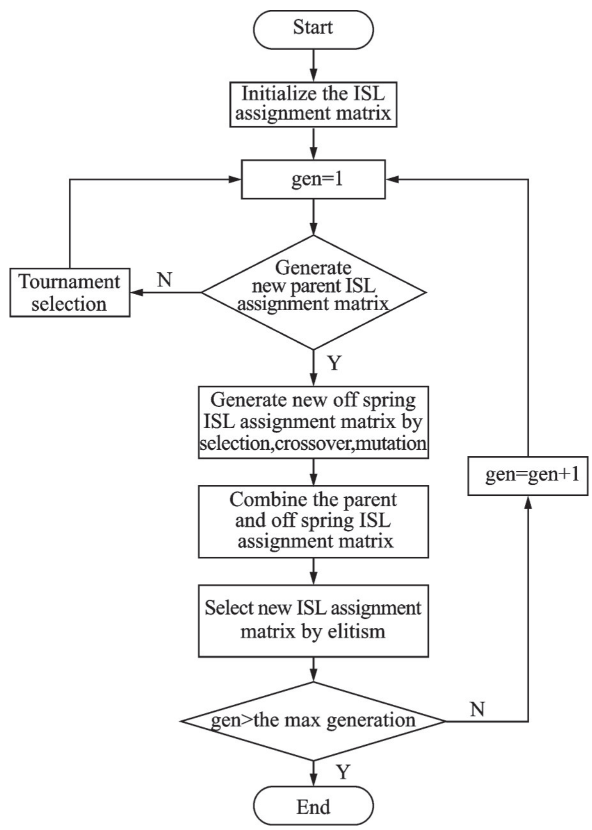

Fig.3 Flowchart of NSGA-Ⅱ algorithm

When initializing the ISL assignment matrix, all the constraints in Section 2 need to be satisfied. After establishing the initial population, selection, crossover, mutation, and elite retention are performed iteratively for solving the optimal link assignment matrix.

3.2 CI Kalman filter algorithm

For cluster with a large number of satellites, information filter is more computationally efficient than the traditional Kalman filter when the size of the measurement vector is large. Therefore, in this paper, a distributed consensus Kalman in information form is used. At each time step, satellite v_i performs information filter locally with its own measurements, communicates with neighbors, and then performs the consensus step for M iterations. The CI Kalman filter algorithm is shown in Algorithm 1.

Algorithm 1 CI Kalman filter algorithm

Step 1 Prediction. For each satellite $v_i \in \mathcal{V}$, estimate $\boldsymbol{x}^i_{k|k-1}$ and covariances $\boldsymbol{P}^i_{k|k-1}$ as

$$\boldsymbol{x}^i_{k|k-1} = \boldsymbol{A}\hat{\boldsymbol{x}}^i_{k-1}$$
$$\boldsymbol{P}^i_{k|k-1} = \boldsymbol{A}\boldsymbol{P}^i_{k-1}\boldsymbol{A}^{\mathrm{T}} + \boldsymbol{Q}_{k-1}$$

Step 2 Correction. For each satellite $v_i \in \mathcal{V}$, given the local measurement z^i_k, update the information vector $\boldsymbol{q}^i_k(0)$ and information matrix $\boldsymbol{\Omega}^i_k(0)$ as

$$\boldsymbol{H}^i_k = \left.\frac{\partial \boldsymbol{h}^i_k}{\partial \boldsymbol{x}}\right|_{x = x^i_{k|(k-1)}}$$

$$\boldsymbol{y}^i_k = \boldsymbol{z}^i_k - \boldsymbol{h}^i_k(\boldsymbol{x}^i_{k|(k-1)}) + \boldsymbol{H}^i_k \boldsymbol{x}^i_{k|(k-1)}$$

$$\boldsymbol{\Omega}^i_k(0) = \left(\boldsymbol{P}^i_{k|(k-1)}\right)^{-1} + (\boldsymbol{H}^i_k)^{\mathrm{T}}(\boldsymbol{R}^i_k)^{-1}\boldsymbol{H}^i_k$$

$$\boldsymbol{q}^i_k(0) = \left(\boldsymbol{P}^i_{k|(k-1)}\right)^{-1}\boldsymbol{x}^i_{k|(k-1)} + (\boldsymbol{H}^i_k)^{\mathrm{T}}(\boldsymbol{R}^i_k)^{-1}\boldsymbol{y}^i_k$$

Step 3 Consensus. For $m = 0, 1, \cdots, M-1$, perform M steps of fusion as

$$\boldsymbol{\Omega}^i_k(m+1) = \sum_{j \in N_i} \pi_{i,j}\boldsymbol{\Omega}^j_k(m)$$

$$\boldsymbol{q}^i_k(m+1) = \sum_{j \in N_i} \pi_{i,j}\boldsymbol{q}^j_k(m)$$

where $\pi_{i,j} \geqslant 0$ denotes the consensus weights, and $\sum_{j \in N_i} \pi_{i,j} = 1$, $\forall v_i \in \mathcal{V}$.

Step 4 Update. The posterior state estimation $\hat{\boldsymbol{x}}^i_k$ and error covariance $\boldsymbol{P}^i_k$ and state are calculated as

$$\boldsymbol{P}^i_k = \left[\boldsymbol{\Omega}^i_k(M)\right]^{-1}$$

$$\hat{\boldsymbol{x}}^i_k = \left[\boldsymbol{\Omega}^i_k(M)\right]^{-1}\boldsymbol{q}^i_k(M)$$

Remark 2 Since the system is stable, and the undirected graph is connected, it has been shown that the estimation error using CI filter designed in this paper is bounded for any number of consensus iterations M[23].

4 Numerical Simulation

In this section, a satellite cluster with 15 satellites is used to verify the proposed relative navigation approach.

The orbit elements are set as follows. The semi-major axis of all satellites is 7 100 km. The eccentrincity, inclination, right ascension of the ascending node, argument of perigee and mean anomaly of the chief satellite are 0, 30°, 120°, 60° and 45°, respectively. The eccentrincity of the 14 deputy satellites is 0.000 3, and the inclination, right ascension of the ascending node, argument of perigee and mean anomaly of 14 deputy satellites are randomly chosen between 29.9°—30.1°, 119.9°—120.1°, 59.9°—60.1°, and 44.9°—45.1°, respectively.

There are three satellites taking range and angle measurements, and the other satellites only take range measurements. The simulation is run for [0, 12 000] s, with the sampling time $\Delta t = 60$ s. Each satellite can establish at most three links. The parameters in energy consumption metrics are chosen as $E_{\mathrm{elec}} = 100$ nJ/b, $\varepsilon_{\mathrm{amp}} = 50$ pJ/(b·m^2). $a = 6$ b when data is transmitted or received by inter-satellite communication, $a = 3$ b when taking inter-satellite range and angle measurement, and $a = 1$ b when taking inter-satellite range measurements only.

The NSGA-Ⅱ algorithm is used for ISL topology optimization, with 50 iterations, chromosome crossover rate 0.9 and gene mutation rate 0.1. Metropolis weights[28] are used for the consensus step.

In the following, two different simulation scenarios are considered.

4.1 Relative navigation with dynamically varying ISL topology

Fig.4 shows the Pareto frontier of NSGA-Ⅱ algorithm. The non-dominated solutions (marked by the red stars) obtained by NSGA-Ⅱ algorithm converge after 50 generations approximately.

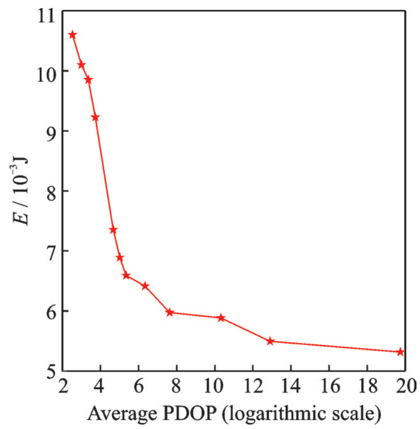

Fig.4 Pareto frontier of NSGA-Ⅱ algorithm

Fig.5 shows the ISL topologies at two consecutive sampling moments. The total energy consumption of Satellite 14 exceeds the threshold at 2 400 s, and is replaced by Satellite 1. From Fig.5(a) and Fig.5(b), it can be seen that the ISL topology is redesigned with Satellite 1 taking range and angle measurements.

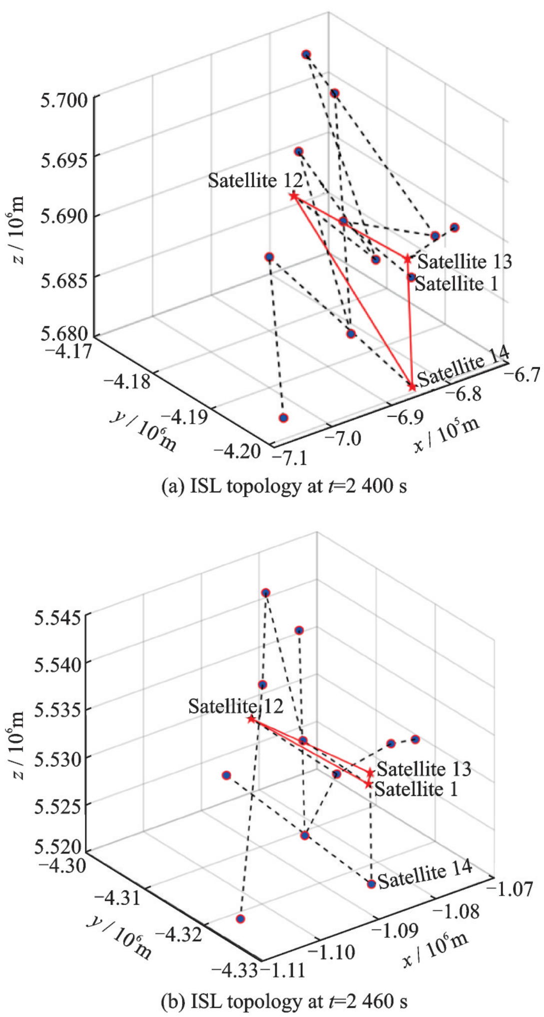

Fig.5 ISL topologies with satellite taking range and angle measurements replaced

Fig.6 shows the energy reduction with the proposed approach. In Fig.6(a), we compare the total energy consumption of the entire satellite cluster using the optimal ISL topology with the one using a fixed topology. The fixed topology is chosen to be the optimal topology designed at the first sampling time. It can be seen that the total energy consumption is reduced about 22.2% at the end of the simulation. In Fig.6(b), we show the energy consumption of Satellite 14. Satellite 14 is used for taking the range and angle measurements before t =2 400 s, and after that, it is replaced by Satellite 1. It can be seen that the energy consumption of Satellite 14 is significantly reduced compared with the case if it is not replaced. Thus, it can be verified that the dynamically adjustments of ISLs can extend both the average working time of an individual satellite and the entire cluster.

Fig.7 shows the state estimation errors for one satellite using the proposed distributed algorithm. The centralized EKF algorithm is used as a bench-

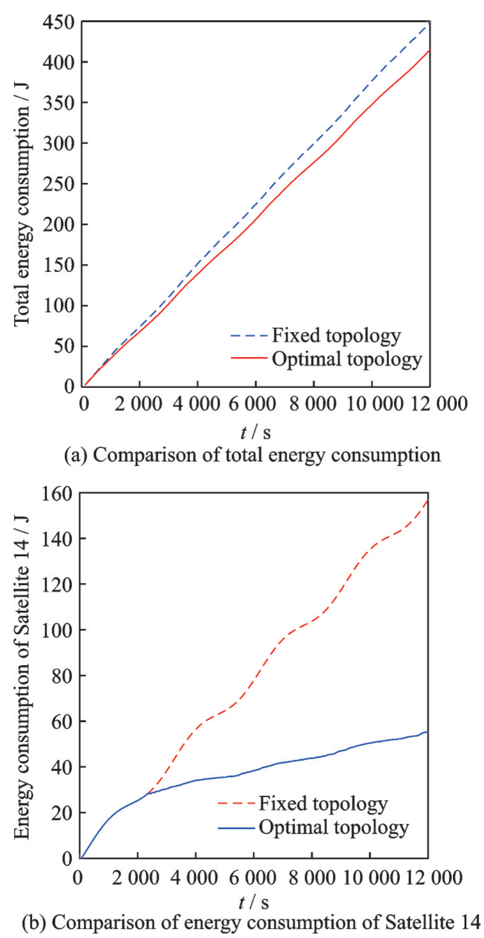

Fig.6 Comparison of energy consumption

mark. The errors and 3σ bounds using both algorithms are shown. It can be seen that albeit the error covariance of the consensus Kalman filter is larger than the centralized one initially, the error covariance converges, and the estimation errors and the converged error covariance of the consensus Kalman filter are quite close to the centralized one.

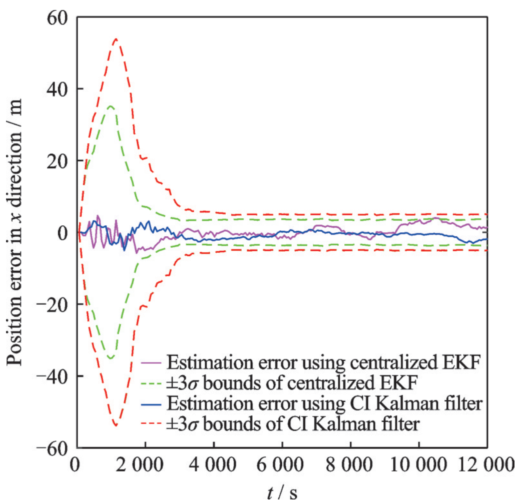

Fig.7 Comparison of navigation performance

4.2 Relative navigation with satellite leaving cluster randomly

Next, we consider the situation when a satellite leaves the cluster randomly. Fig.8 shows the ISL topology at two consecutive sampling moments, before and after Satellite 11 leaves the cluster. From Fig.8(a), it can be seen that if Satellite 11 leaves the cluster, Satellite 9 would be disconnected from the entire network, therefore Satellite 9 has to be reconnected to the cluster or the state estimation of Satellite 9 would become inaccurate. In Fig.8(b), it can be seen that Satellite 9 is reconnected to the cluster with new ISL topology designed at the next sampling time.

Fig.9 shows the local estimation from Satellite 1. It can be seen that with the connective ISL topology, the state of Satellite 9 could be estimated accurately by any other satellites.

Therefore, it can be seen that the proposed relative navigation scheme can optimize the ISL topologies in different scenarios, and the total energy consumption of the cluster is reduced. Further, the proposed distributed consensus Kalman filter algorithm can be used for the relative navigation effectively.

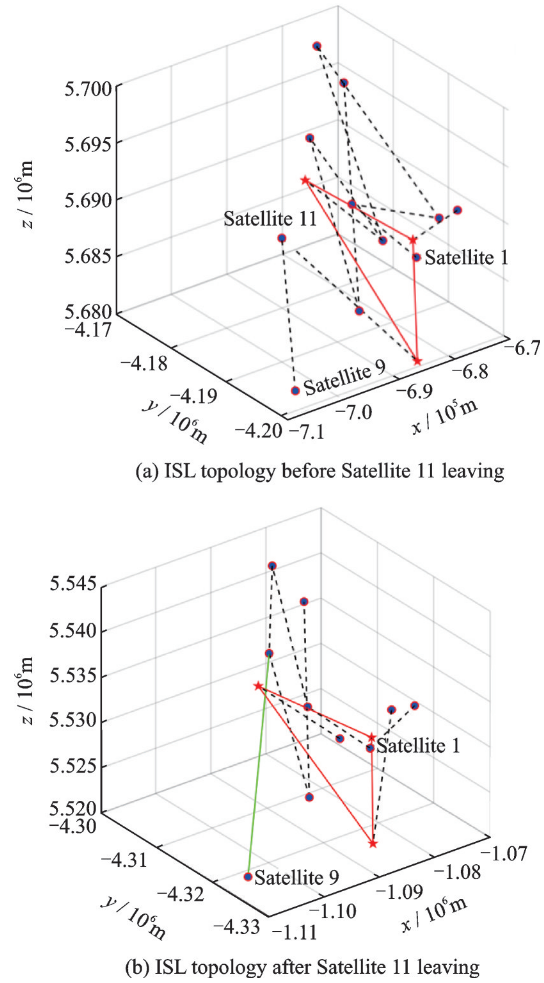

Fig.8 ISL topologies before and after Satellite 11 leaving cluster

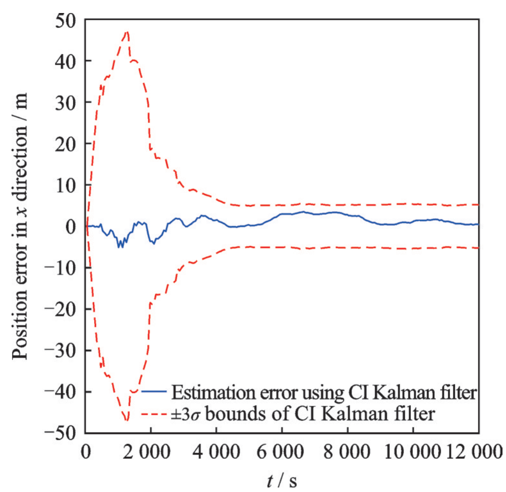

Fig.9 Estimation error for Satellite 9

5 Conclusions

We consider the relative navigation problem for satellite clusters using inter-satellite sensing and communication. The time-varying ISL topology is optimized to reduce the energy consumption and improve the navigation performance. Then a CI Kalman filter is used for the state estimation in a distributed fashion. The proposed approach is flexible and robust to different tasks. Simulation results show the effectiveness of the proposed approach.

Future work includes: (1) extending the time-triggered communication and navigation scheme to the event-triggered scheme for further reducing the communication consumption and (2) taking into account the transmission delay in designing the ISL topology as well as the distributed filtering algorithm.

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卫星集群星间链路拓扑设计与相对导航

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摘要:提出了一种基于星间测量与通信的卫星集群分布式相对导航方法,利用星间链路为相对导航提供星间测量并进行数据交换从而提高卫星集群系统的自主性。首先,考虑能量消耗和导航性能,将星间链路拓扑设计问题表述为一个多目标优化问题;此外,卫星集群以分布式方式进行相对导航,每颗卫星对相邻卫星进行测量并通过星间链路与相邻卫星通信,从而降低了导航的能耗和计算复杂度。采用NSGA-Ⅱ算法求解星间链路拓扑优化问题并基于一致性卡尔曼滤波进行分布式相对导航。本文提出的方法可适应不同的任务,卫星可以随时加入和离开集群并且对单个卫星失效具有鲁棒性。最后,通过数值仿真验证了本文方法的可行性。

关键词:卫星集群;相对导航;星间链路;网络拓扑;多目标优化