Satellite SAR Antenna Deployable Structure Design and Kinematic Analysis

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Abstract. Satellite SAR antennas are widely applied in earth observation. Deployable support structures (DSS) are key components for supporting and spreading such antennas. Given the improvement in observation resolution requirements, designing high-rigidity, large-scale, and simple-motion DSS has increasingly become necessary. This study presents two kinds of DSS with a single-wing design that can support four antenna panels and proposes two kinds of synchronizing mechanisms. The geometric model is established for solving the design parameters that are related to each other. These mechanisms are parametrically optimized to improve the stability of deployment. Kinematic simulation is conducted on the DSS, and results indicate that the deploying movement is smooth when two driving sources are used. The proposed DSS can be applied to support more large-scale SAR antennas, which is of great importance to improve observation resolution.

Introduction

Satellite SAR antennas are widely applied in marine observation and in the disaster and environmental detection of earth observation [1]. Given the high demand for development of earth observation from space, large satellite SAR antennas with high observation resolution are required. Moreover, such antennas must have high stiffness, accuracy, and dimension. To realize high observation resolution, a deployable structure is adapted to support the classic satellite SAR antenna [2–6]. Aside from providing support, the deployable support structure (DSS) serves an important function in driving and coordinating the satellite SAR antenna [7–9]. Thus, DSS is a key technology of satellite SAR antennas, and whether its performance is good or poor, it directly influences the resolution of earth observation.

A few problems are commonly encountered in using DSS, for example, Seasat-SAR, ERS-1, and ALOS all need three times of movement in orbit and have complex deploying movements. Although both RADARSAT-1 and RADARSAT-2 need only one movement, their single-wing designs can support only two antenna panels, and their large-scale capacities are poor. Thus, DSS should be improved. Thus, the object of this study is to propose a novel DSS for large SAR antenna, and to investigate its deploying properties.

Deployable Support Structure Design

Design Scheme. The configuration of the rectangular pyramid scheme is shown in Fig. 1. A total of eight antenna panels are located on both sides of the bus and form two wings. The DSS supports the panels at the back; in this scheme, the DSS has the advantages of high stability and great stiffness. The stowed DSS is collapsed in the gaps between the two adjacent panels to form a compact structure; this scheme is suitable in deploying and supporting large SAR antennas.

The configuration of the rectangular prism scheme is shown in Fig. 2. Four panels of the single-wing antenna are supported by four rectangular prism mechanisms. To enhance stiffness and stability, cables are applied along the diagonals of the rectangular prisms. When the structure is fully deployed, tension cables are employed. The principle of the rectangular prism is similar to that of the parallelogram mechanism. This structure possesses the advantages of simple construction and easy deploying movement.

Fig. 1 Rectangular pyramid scheme

Fig. 2 Rectangular prism scheme

Both the bus and the connected type of the two schemes can simply be adopted using a single-wing design, which forms two wings when the satellite is in orbit. The antenna panels construct a large and high plane flatness. However, both DSS schemes of the SAR antenna have advantages and disadvantages, as summarized in Table 1.

Table 1 Comparison of the two schemes

	Mass	Stiffness	Simple	Folding and deployment ratio
Rectangular pyramid	Light	Very high	Simple	Very large
Rectangular prism	Light	High	Simple	Large

Given the high-resolution requirement of satellite SAR antennas, the scheme with the highest stiffness and largest folding and deployment ratio is the most suitable for DSS.

Geometric modeling. DSS has various correlative design variables. Unreasonable design variables may cause truss links to deviate from the designed lock dead positions and affect rigidity, thereby causing the antenna panels to deviate from the designed position and affect precision. The geometric model of DSS is shown in Fig. 3: the lower-case letters with numerical subscripts, such as a_1 , stand for nodes; letter E means; and letter F means.

Fig. 3 Geometric model of DSS

Based on the folded and deployed assembly conditions, the length of each support link is expressed as follow,

$$l_{d3-d4} = l_{a2-a3}^f + \text{Con} \quad (1)$$

Where l_{d3-d4} the distance between nodes d3 and d4 is l_{a2-a3}^f the distance between nodes a2 and a3 in folding, Con is constant quantity.

$$l_{a1-d3} = \sqrt{(Y_{d1} - Y_{a1}^d)^2 + [l_{a1-a2} - \frac{1}{2}(l_{d3-d4} - l_{a2-a3}^d)]^2} \quad (2)$$

Where l_{a1-d3} is the length of the oblique support link, l_{a1-a2} is the distance between nodes a1 and a2, l_{a2-a3}^d is the distance between nodes a2 and a3 during deployment, Y_{d1} is y-axis coordinate of node d1, Y_{a1}^d is y-axis coordinate of node d1 during deployment.

$$l_{d3-c1} = \frac{1}{2} \left\{ \sqrt{(Y_{d1} - Y_{a1}^d)^2 + \left[\frac{1}{2}(l_{d3-d4} - l_{a2-a3}^d) \right]^2} + (l_{d3-a1} - l_{a1-a2}) \right\} \quad (3a)$$

$$l_{c1-a2} = l_{d3-c1} - (l_{d3-a1} - l_{a1-a2}) \quad (3b)$$

where l_{d3-c1} is the length of the longer middle support link, l_{c1-a2} is the length of the shorter middle support link, l_{d3-a1} is the distance between nodes d3 and a1, l_{d3-c1} is the distance between nodes d3 and c1.

$$l_{d4-d5} = F + E - \frac{1}{2}l_{d3-d4} \quad (4)$$

Where l_{d4-d5} the distance between nodes d4 and d5, E is the distance between two adjacent deploying panels, F is the length of the antenna panel.

$$l_{d1-d2} = \frac{1}{2} \left[N - \sqrt{N^2 - \frac{(B^2 - N^2)^2 + B^2 M^2}{N^2 - B^2}} \right] \quad (5a)$$

$$l_{d2-d3} = \frac{1}{2} \left[N + \sqrt{N^2 - \frac{(B^2 - N^2)^2 + B^2 M^2}{N^2 - B^2}} \right] \quad (5b)$$

Where l_{d1-d2} the length of the shorter upper support link, and l_{d2-d3} is the length of the longer upper support link. The variables B , M , and N may be expressed as follows:

$$B = l_{a1-d3} + (X_{a1}^d - X_{b1}) - (Y_{d1} - Y_{b1}) \quad (6a)$$

$$M = X_{b1} + Y_{b1} - Y_{a1}^d - X_{d1} \quad (6b)$$

$$N = X_{b1} - X_{d1} + F + E - 0.5l_{d3-d4} \quad (6c)$$

Where X_{a1}^d , Y_{a1}^d is x -axis and y -axis coordinates of node a_1 during deployment, respectively X_{b1} , Y_{b1} is x -axis and y -axis coordinates of node b_1 , respectively, X_{d1} is x -axis coordinate of node d_1 .

Taking the scaled prototype as an example, the following are assumed $l_{a2-a3}^d = 82\text{mm}$, $\text{Con} = 2\text{mm}$, $Y_{d1} = 221.5\text{mm}$, $Y_{a1}^d = 16\text{mm}$, $l_{a1-a2} = 425\text{mm}$, $l_{a2-a3}^d = 10\text{mm}$, $F = 435\text{mm}$, $E = 2\text{mm}$, $X_{a1}^d = 58\text{mm}$, $X_{b1} = 53\text{mm}$, $Y_{b1} = 5\text{mm}$, and $X_{d1} = 20\text{mm}$. From these assumptions, the component size is derived as follows: $l_{d3-d4} = 84\text{mm}$, $l_{a1-d3} = 439.06\text{mm}$, $l_{d3-c1} = 111.43\text{mm}$, $l_{c1-a2} = 97.37\text{mm}$, $l_{d4-d5} = 395\text{mm}$, $l_{d1-d2} = 100.43\text{mm}$, and $l_{d2-d3} = 327.57\text{mm}$.

Design configuration. The single-wing DSS is composed of two modules that support four panels. The folded and deployed states of this design are shown in Fig. 4. DSS supports the antenna panels at the back and increases the antenna stiffness when the antenna is deployed. Four antenna panels lean parallel toward each other on the bus sides, and the DSS is stowed at the inner part of the antenna panels when the antenna is folded. In the deploying process of the antenna, the DSS delivers power and drives the four antenna panels for deployment.

(a) Folded state

(b) Deployable state

Fig. 4 Single-wing antenna prototype

The components of the single-wing antenna are shown in Fig. 5. This structure has the advantages of simple movement, light weight, high stability in deploying, and great stiffness in folding and deploying. The single-wing antenna can be divided into two modules, and each module is composed of two rectangular pyramid elements.

Fig. 5 Components of the single-wing antenna

Design and optimization of the synchronizing mechanism

The single-wing antenna has 4 DOF and needs more driving sources, which reduce the deploying stability and increase the difficulty of the control. Thus, synchronizing mechanisms are designed to lessen the DOF and decrease the driving sources.

Design of synchronizing mechanism I. Synchronizing mechanism I is composed of driving, linkage, and slave links (Figure 6). Bracket 1, driving links, linkage links, and panel 1 constitute a parallelogram mechanism. Driving links and panel 1 are synchronized. Linkage links, slave links, panel 1, and panel 2 constitute a parallelogram mechanism. Panel 2 travels twice as long as the linkage link travels. The movements of both the driving links actuating the linkage links and the linkage links driving panel 1 are rotated at 90° . The movements of both the linkage links driving slave link and the slave links driving panel 2 are rotated at 180° . Therefore, panels 1 and 2 simultaneously rotate at 90° and 180° , respectively. Synchronizing mechanism I introduces 3 components and increases 5 kinematic pairs, thereby resulting in 1 DOF. Therefore, the increased framework and kinematic pairs produce 1 DOF.

Fig. 6 synchronizing mechanism I

Design of synchronizing mechanism II. Synchronizing mechanism II is composed of a single-linkage link (Figure 7). Bracket 4, synchronizing mechanism II, bracket 5, and panel 3 constitute a parallelogram mechanism. Panel 3 drives synchronizing mechanism II, whereas synchronizing mechanism II drives panel 4; thus, panels 3 and 4 simultaneously rotate at 180° . Synchronizing mechanism II introduces 1 component and increases 2 kinematic pairs, thereby resulting in 1 DOF, which is calculated through the formula of the planar mechanism DOF. Therefore, the increased framework and kinematic pairs produce 1 DOF.

Fig. 7 synchronizing mechanism II

Each set of synchronizing mechanism can reduce 1 DOF. Introducing two sets of synchronizing mechanism produces 2 DOFs of the antenna. Two driving sources are needed to ensure a smooth movement.

Parameter optimization of the synchronizing mechanism. The original parameters of the two synchronizing mechanisms are obtained through the graphing method. Unlike the angular displacements of panels 1 and 2, which are measured during moving, the original parameters of synchronizing mechanism I are inaccurate (Figure 8). Two curves fit well at the beginning and at the end, and the error is significant at the middle time. To coordinate the movement of panels 1 and 2, synchronizing mechanism I should be optimized.

The model of synchronizing mechanism I is established in ADAMS. The vertex coordinates are selected as the design parameters. Panel 1 rotating at 90° and panel 2 rotating at 180° are set as the constraints. The absolute value of 0.5 time of panel 2 angular displacement a minus panel 1 angular displacement b is set as the object. The object is optimized and minimized using the optimization module in ADAMS. The single deploying time is set at 45 s, and the maximum optimized object is changed from 4.57° to 1.84° (Figure 9). The optimal link length of synchronizing mechanism I is summarized in Table 2.

Table 2 Design parameters of synchronizing mechanism I

	Driving link (mm)	Linkage link (mm)			Slave link (mm)
		L1	L2	L3	
Synchronizing mechanism I	410	47.17	40	64.03	40

Fig. 8 Comparison of angular displacements of planar 1 and 2

Fig. 9 Optimized results

Deployable kinematic analysis

Deployment verification. With the help of the interface between PRO/E and ADAMS, the density, rigid body, and hinges as defined by the PRO/E models are imported to ADAMS. The imported models include the rigid components and revolute hinges. The bus and earth are set as fixedly connected. Two rot joint motions are inserted into the locations where motors are installed on the antenna. The rotational speeds of the two joint motions are 2°/s and 4°/s. The rotational speed of the motor near the bus is 2°/s. The simulation time is set at 45 s, and the simulation steps are set at 50.

A part of the simulative deploying process is shown in Figure 10. The deployed angles of the four panels are almost consistent with the smooth, stable, and no-dead positions during the deploying process. All four panels and DSS are deployed to a final location after the deploying movement. DSS has a better expandable performance.

Kinematic parameter measure. The antenna panels serve as the working planes and constitute the most important and heaviest payload of the missions when the satellite is in orbit. Thus, extracting the angular velocity and acceleration of the antenna panels is necessary. The relative angular velocity–time curves of the four panels are shown in Figure 11. The angular velocity of panel 1 has a fall of 2°/s. Panel 2 is actuated by synchronizing mechanism I, and its angular velocity has a fall of −4°/s. The angular velocity of panel 3 is imported by motor and is constant at −4°/s. Panel 3 is actuated by synchronizing mechanism II, and its angular velocity has a fall of almost 4°/s. Therefore, the angular velocities of panels 1 and 2 fluctuate, and the angular velocities of panels 3 and 4 are smooth.

Fig. 10 Deploying process

Fig. 11 Relative angular velocity of the planar array

The angular acceleration–time curves of the four panels are shown in Figure 12. The angular accelerations of panels 1 and 2 are large, and their maximum value is 0.5°/s. In addition, a shock occurs on panels 1 and 2 at 41.4 s. The angular velocities of panels 1 and 2 are small, and their movements are steady. This result is consistent with the angular velocities of panels 3 and 4.

Summary

This study proposes a novel deployable truss structure for SAR antenna with the advantages of simple deployment and large scale. The deployment behavior of this deployable truss structure is studied through dynamic simulation.

To realize large-scale, two kinds of deployable supporting structures for the satellite SAR antenna are proposed. Their single-wing designs can support four antenna panels. And the rectangular pyramid deployable supporting structure is modeled and designed in detail. A parameterized geometric model is presented to reveal the interrelations of the design parameters. Two kinds of synchronizing mechanisms are designed and optimized to realize one times of deploying movement in orbit. The deployable supporting structure with the rectangular pyramid mechanism has a simple movement and stable deploying process, as exhibited by the multi-body dynamics analysis. In addition, this kind of DSS is applicable to large satellite SAR antennas.

Fig. 12 Relative angular acceleration–time curves of the four panels

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