The Synchronization Mechanism for Solar Array with a Three-Stage Deployment

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Abstract

Cable-and-pulley system (also called Closed Cable Loop, CCL) is a common type of synchronization mechanism to coordinate the motion of a multiple panel solar array. Typically, in applications the transmission ratio of a cable-and-pulley system is constant during the deployment. For other applications, the synchronization characteristic can be changed by varying the configuration of the pulley. The solar array of GF-3, a satellite operating on dawn-dust orbit, required a particular kind of two-stage deployment: during the first stage the four-panel stack rotates 90° around the root hinge; during the second half the root hinge rotates from 90° to 180° and each panel hinge rotates from 0° to 180° synchronously. The unique feature of the GF-3 solar array synchronization mechanism is that the root pulley consists of two half pulleys: a fixed pulley and a swing pulley. The design of such a root pulley changes the ratio between the root hinge and panel hinge. Although the deployment of the solar array contains three stages actually, the trajectory approximately meets the requirement. The detailed working principles and considerations of the synchronization mechanism are provided. The synchronization mechanism has been proven both in ground test and flight.

Introduction

GF-3 is a satellite operating on dawn-dust orbit, equipped with two deployable solar array wings[1]. There is a particular layout of the solar array, characterized by the axis of rotation of the solar array drive mechanism parallel (rather than the more common normal) to the mounting surface of the solar array on the satellite. The root hinge must deploy 180 degrees, but more importantly, the trajectories of all panels have to be confined to a limited area that requires a two-stage deployment movement of the panels as shown in Figure 1.

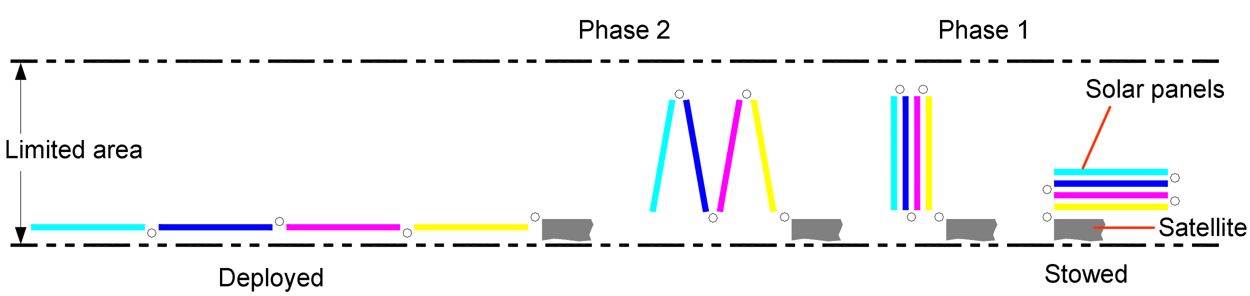

Figure 1. The two-stage deployment

There are several ways to achieve the trajectory, such as adding a special latch at 90°stroke of the root hinge. However, varying the synchronization characteristic is a better choice for this application due to the key advantages, such as simplicity, reliability, light weight, and more importantly, continuous controllable deployment and ability to reverse at any position. On the basis of the traditional cable-pulley system, the trajectory can be changed by varying the roll-on and roll-off rules of the root cables, and the key is how to

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derive the profile of the root pulley. Yannick Baudasse presented a new synchronization concept of solar array deployment used in Cosmo SkyMed [2]. The root pulley is changed into two parts: an unwinder arm and a winding with special contour. At the first 90° of deployment, root cables neither roll on nor roll off and just overpass the axis of rotation. After 90°, the arm begins to swing and the cable which it is attached to rolls off. Then, another root cable begins to wind on the winding, which means roll on. So, there is a nonlinear synchronization ratio between root hinge and panel hinge. Frans Doejaaren presented another solution used in Sentinel 1 [3]. The root pulley consists of two coupled pulleys that are offset when installed and use different radii. This adapted design changes the roll on and roll off characteristics of the cables such that the wing deploys approximately as required. The above two methods are simple enough, but resulted in the actual trajectory with more than acceptable deviation from the ideal one.

In the development of the GF-3 solar array, we found a synchronization method that could reduce the deviation remarkably. The method is an improvement on Yannick`s design. The improved deployment of the solar array contains three stages. During the first stage, the four-panel stack rotates about 70°driven by the root hinge. During the second stage, the root hinge rotates from 70° to 110°, and each panel hinge rotates from 0° to 40° following a changing ratio (from null to 2:1) with respect to the root hinge. During the third stage, the root hinge rotates from 110° to 180°, and each panel hinge rotates from 40° to 180° following a 2:1 ratio. Although the synchronization ratio during the second stage is nonlinear, the process is transient. Therefore, the actual trajectory is much closer to the ideal trajectory.

The unique feature of the GF-3 solar array synchronization mechanism is that the root pulley consists of two half pulleys with same radii: a fixed pulley and a swing pulley, which is shown in Figure 2. In the folded state, the center of the swinging pulley is away from the center of the fixed pulley. During the first deployment stage, the root cables show the same performance as Yannick`s. During the second stage, the swinging pulley gradually approaches the fixed pulley. The cable attached to swinging pulley rolls off. At the same time, the other root cable rolls on the fixed pulley. At the end of the second stage, the center of the swinging pulley coincides completely with the center of the fixed pulley to form a complete root pulley. During the third stage, the synchronization characteristic is identical to the traditional cable-pulley system.

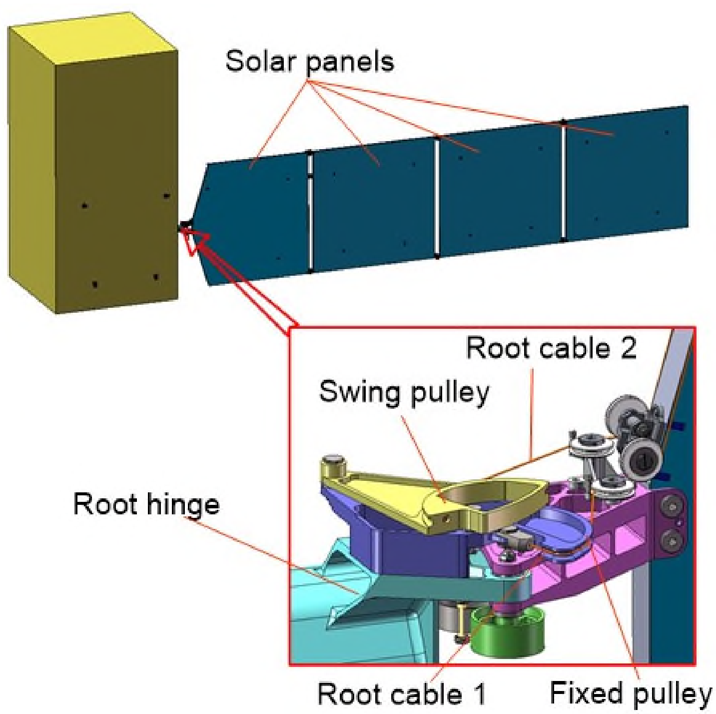

Figure 2. The root pulley of GF-3 solar array

Description of Synchronization Method

Overview

According to the requirement for solar array deployment, the angular velocity ratio between the panel hinge and root hinge is 0:1 during the first stage, and 2:1 during the second stage. In a cable-and-pulley system, only with zero radii of root pulley could the ratio be 0:1, which means that the cables should be placed across the axis of the root hinge. Nevertheless, due to the ratio 2:1, the radii of root pulley should be twice than the panel pulley in phase 2. That is to say, there is a “snap action” of the root pulley between phase 1 and phase 2, which is the main design challenge of synchronization mechanism.

It is hard to achieve that the radii of the root pulley rises suddenly from 0 to twice of the panel pulley. Meanwhile, the angular velocity of the panel hinge will increase immediately from 0 to twice of the root hinge even if the radii of root pulley can be changed successfully. This would cause a shock that is detrimental to deployment. The more important aspect of the requirement is that the trajectories of the mass centers of all panels have to be confined to a limited area. Therefore, it is a significant design challenge to add a transition between phase 1 and phase 2. The ratio needs to change smoothly from 0:1 to 2:1 with no jerk, and the trajectories must meet the requirement.

In a cable-and-pulley system, the rotation of the hinges is coordinated by the cables rolling on and rolling off the pulleys. If the cable rolls on the pulley during rotation, it must roll off on the other side due to the constant length of cable. If there is a reference point located on an intermediate position of the cable, the distance between the point and pulley decreases when rolling on, and increases when rolling off. Therefore, the mechanism that can alter the distance will perform the same function as the pulley. In GF-3, the root pulley is substituted by two half pulleys: a fixed pulley and a swing pulley, with the result that the ratio can change smoothly from 0:1 to 2:1.

Fixed Pulley and Cable

The schematic of the fixed pulley and cable during the deployment is shown in Figure 3. The fixed position of the cable passes through the spin axis of the root hinge. In phase 1, the cable rotates around the spin axis, but the distance between the reference point and fixed pulley is constant during the deployment. Therefore, the cable need not roll off the panel pulley on the other side. In phase 2, the cable rolls on the fixed pulley gradually during the rotation, and the distance between the reference point and pulley decreases at the same time. At the end of phase 2, the cable makes tangential contact with the circular contour of fixed pulley. The ratio between panel hinge and root hinge becomes 2:1 for the radii of the fixed pulley is twice of the panel pulley. In phase 3, the cable rolls on the fixed pulley continually, and the process is consistent with a traditional cable-pulley system.

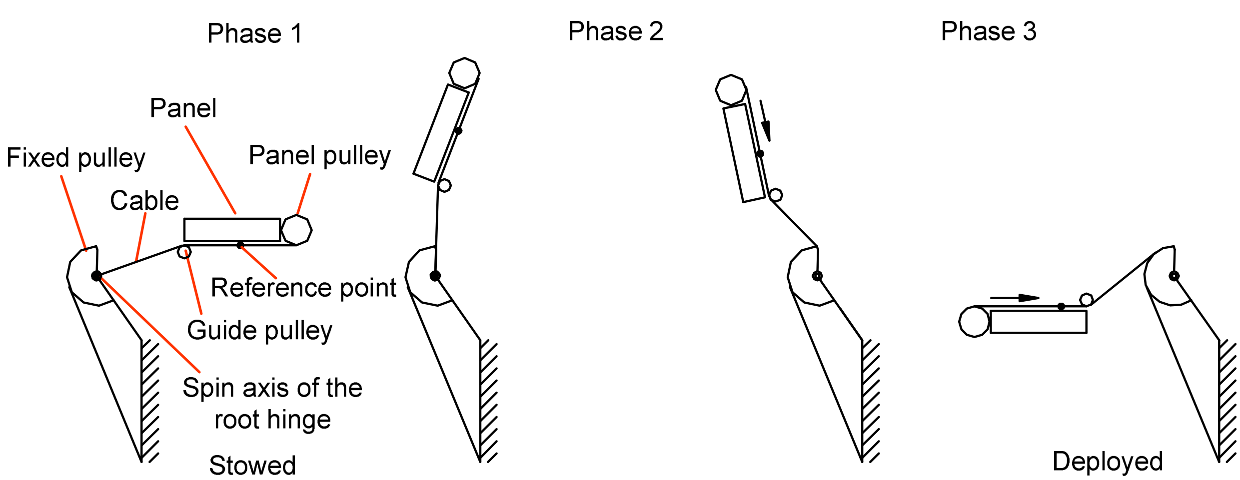

Figure 3. The schematic of fixed pulley and cable

Swing Pulley and Cable

The schematic of the swing pulley and cable during the deployment is shown in Figure 4. The cable winds on the swing pulley at the stowed configuration. In phase 1, the swing pulley tends to rest on the right stop by the tension of cable. The cable rotates around the axis of root hinge, where it contacts with the swing pulley. The distance between the reference point and swing pulley is constant during the deployment. At the end of phase 1, the extended line of cable between guide pulley and swing pulley just crosses the axis of the swing pulley. In phase 2, the swing pulley rotates counterclockwise and is apart from the right stop by the tension of cable. The distance between the reference point and swing pulley increases at the same time. At the end of phase 2, the swing pulley rests on the left stop, and the cable just makes tangential contact with the circular contour of swing pulley. The center of swing pulley's circular contour overlaps the axis of the root hinge at the same time. In phase 3, the cable rolls off the swing pulley continually, and the process is in accordance with a traditional cable-pulley system.

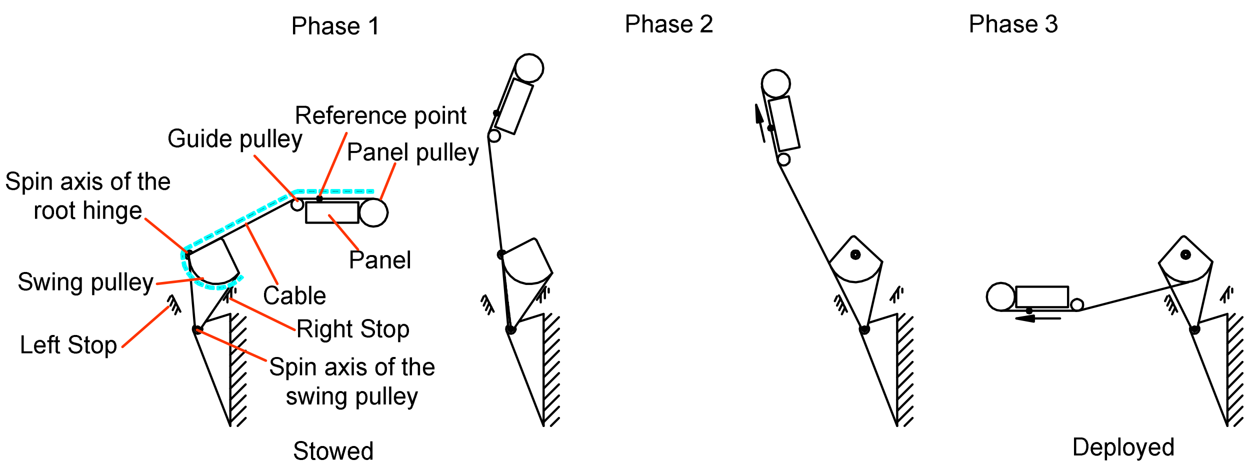

Figure 4. The schematic of swing pulley and cable

Deployment of Solar Array

Both the cable-fixed-pulley system and cable-swing-pulley system have a three-stage synchro process, which is the underlying premise for the deployment function. Furthermore, although they are installed separately, they must be kept consistent during deployment. The deployment of the solar array with two panels coordinated by such a cable-pulley system is shown in Figure 5. It illustrates an approximate synchronization principle. In phase 1, the outer panel keeps stacked with the inner panel because both cable 1 and cable 2 cross the axis of root hinge during deployment. In phase 2, the reference point 1 moves away from the panel pulley along with the cable 1 rolling on the fixed pulley gradually. Meanwhile, the reference point 2 approaches the panel pulley due to the swing pulley rotating off center of the axis of root hinge. The outer panel deploys against the inner panel. At the end of phase 2, the center of the swinging pulley coincides completely to the center of the fixed pulley to form a complete root pulley, and both of the cables make tangential contact with the root pulley. In phase 3, all panels deployed synchronically.

Phase 2 is the key process of the deployment. There are several problems that must be solved including:

- When should it start and finish?
- In such a cable-pulley system, the length of the cables rolling on the fixed pulley and rolling off the swing pulley must match with each other well. However, there is an obvious structural difference between the fixed pulley and swing pulley. How can they adapt to each other?

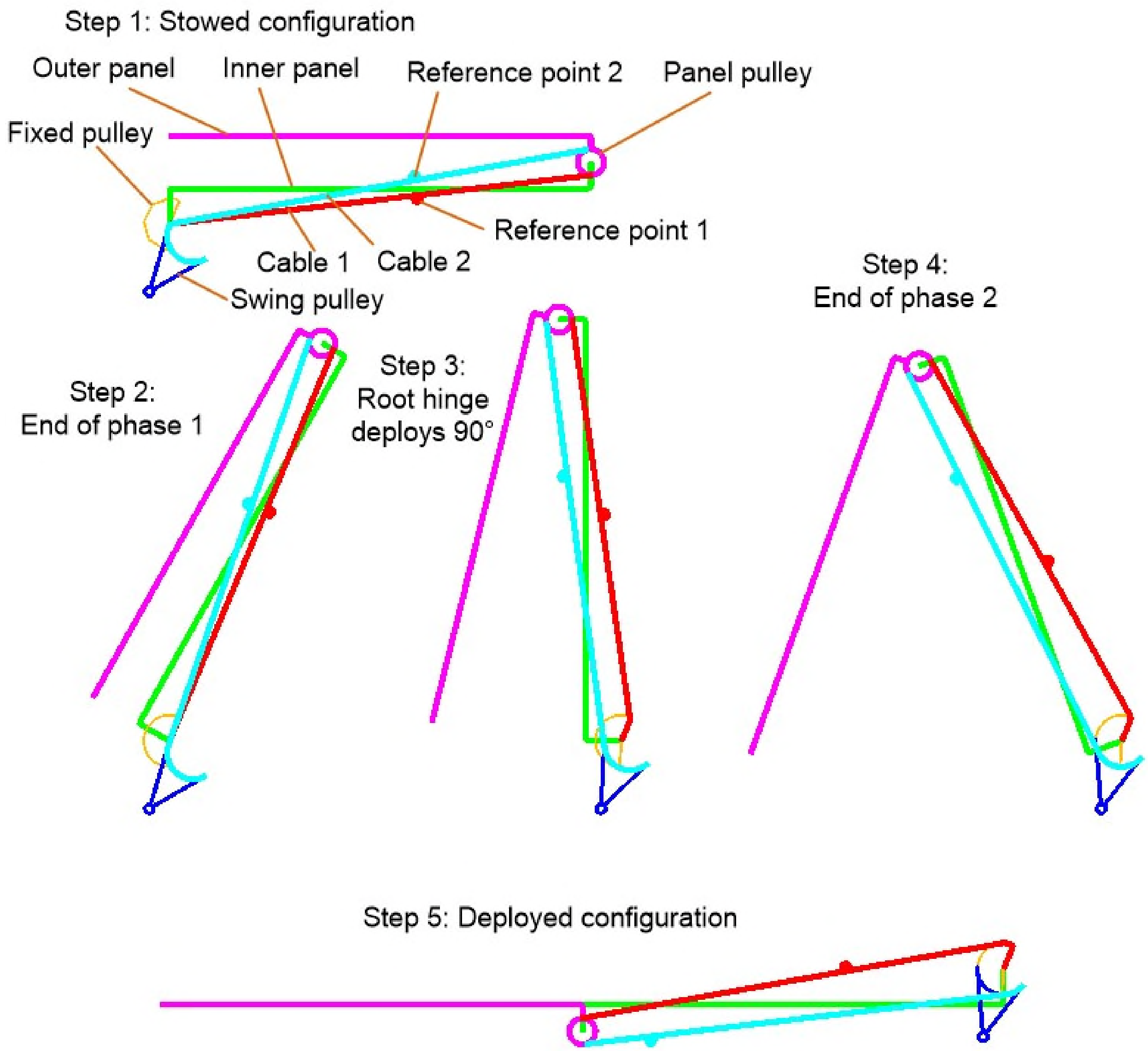

Figure 5. Deployment of solar array

Design and Analysis

Mathematical Model
Although the synchronization mechanism is not significantly bulkier than the standard one, the motion is much more complex. The baseline concept must be optimized by the mathematical model. The length of the cables is the only connection between the fixed pulley and swing pulley. Therefore, the mathematical models of the fixed pulley and swing pulley should be established respectively.

The mathematical model of the fixed pulley in phase 2 is shown in Figure 6. The displacement of the reference point on the cable is equal to the length variation of the cable between the guide pulley and the center of fixed pulley where the cable is fixed. The length variation is an important parameter that is derived from the following set of equations.

$$\Delta L_f = \left(\widehat{A'B'} + B'C + OC\right) - \left(\widehat{AB} + OB\right) \quad (1)$$

Where ΔL_f – the length variation of the cable
A, A' – the tangency point between the cable and guide pulley
B, B' – the other tangency point between the cable and guide pulley
C – the point where the cable contacts with fixed pulley
O – the center of the fixed pulley and also the axis of root hinge
OC – equal to the radii of the fixed pulley

The model can be simplified if the radii of guide pulley is ignored. Equation 1 can be simplified to:

$$\Delta L_f = A'C + OC - OA = A'C + OC - OA' = \sqrt{OC^2 + OA^2 - 2 \cdot OC \cdot OA \cdot \cos\theta} + OC - OA \quad (2)$$

Where θ – the angle of root hinge rotation

Equation 2 defines phase 2. Particularly, at the end of phase 2:

$$\mathrm{OA} = \frac{OC}{\cos\theta} \quad (3)$$

If root hinge rotated an angle α in phase 1, then ΔL_f and θ must meet the constraint:

$$2(\pi - \alpha - \theta) = \pi - \frac{2\Delta L_f}{OC} \quad (4)$$

In Equation 4, $(\pi - \alpha - \theta)$ is the angle of root hinge rotation in phase 3, while $\pi - \frac{2\Delta L_f}{OC}$ is the angle of the panel hinge rotating in phase 3

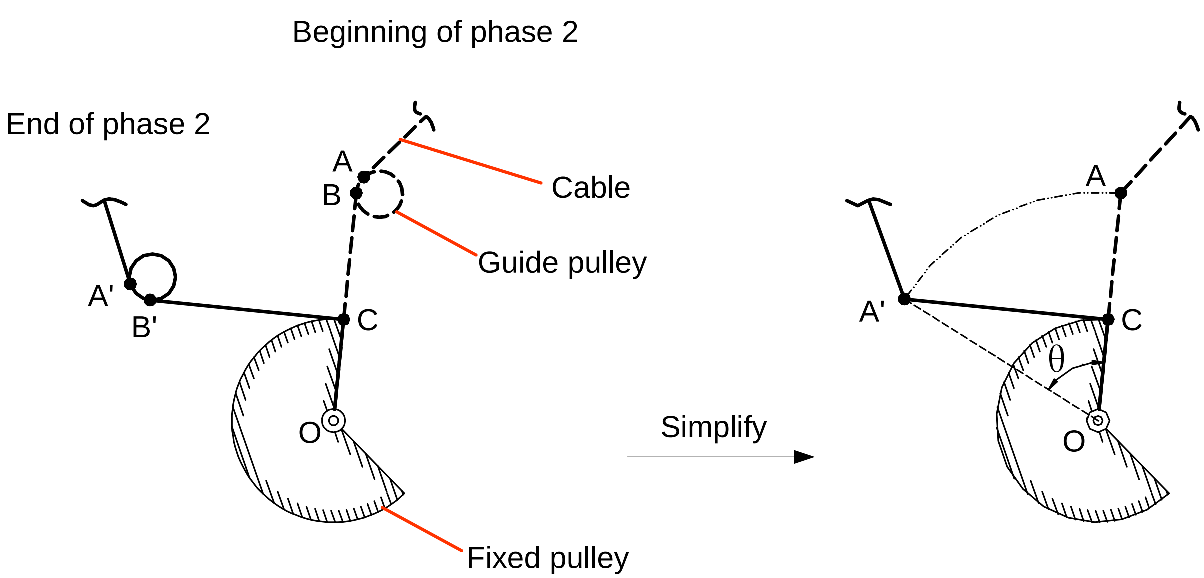

Figure 6. Mathematical model of the fixed pulley

The mathematical model of the swing pulley can be created similarly, which is shown in Figure 7. The relationship of the parameters can be described by Equation 5.

$$\Delta L_s = \left(\widehat{A_1B_1} + B_1C_1\right) - \left(\widehat{A_1'B_1'} + B_1'C_1'\right) \quad (5)$$

Where ΔL_s – the length variation of the cable
A_1, A_1' – the tangency point between the cable and guide pulley
B_1, B_1' – the other tangency point between the cable and guide pulley
C_1, C_1' – the point where the cable contacts with the swing pulley

O_1 – the axis of the root hinge

The model can be simplified with the radii of guide pulley ignored. Equation 5 can be simplified to:

$$\Delta L_s = A_1C_1 - A_1'C_1' = A_1'O_1 + O_1P_1 - A_1'P_1$$
$$= O_1A_1 + O_1P_1 - \sqrt{{O_1A_1}^2 + {O_1P_1}^2 - 2 \cdot O_1A_1 \cdot O_1P_1 \cdot \cos(\pi - \theta)} \quad (6)$$

Where θ – the angle of root hinge rotation
P_1 – the axis of the swing pulley

Equation 6 defines phase 2. Particularly, at the end of phase 2:

$$\theta = \sin^{-1}\frac{OC}{O_1A_1} + \sin^{-1}\frac{OC}{O_1P_1} \quad (7)$$

Where OC – equal to the radii of the fixed pulley or swing pulley

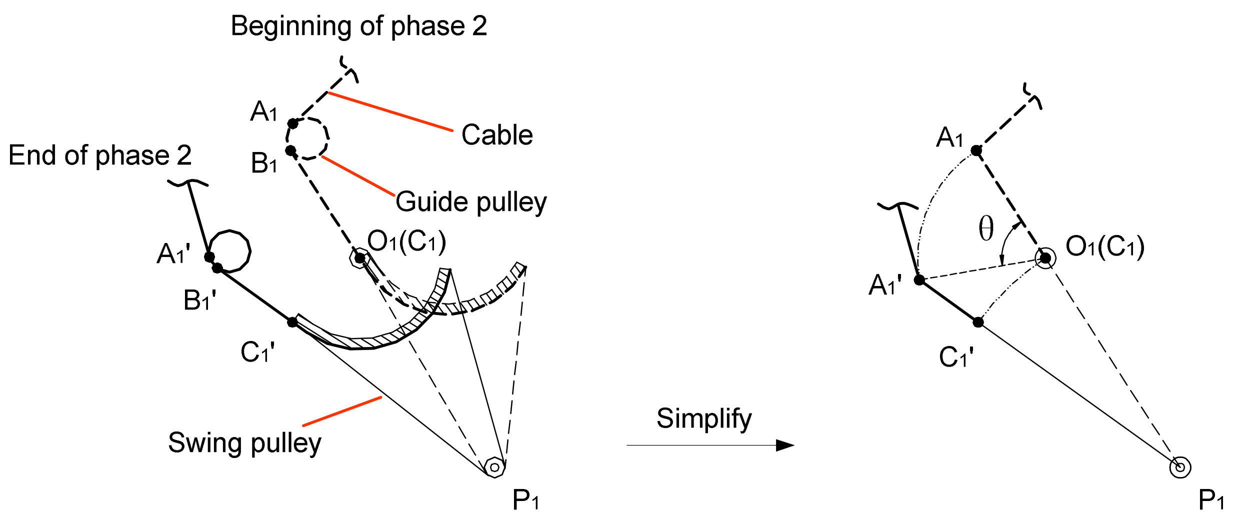

Figure 7. Mathematical model of the swing pulley

Examining Equations 2 and 6, we draw the conclusion that either the cable rolling on the fixed pulley or rolling off the swing pulley uses the characteristic of a triangle in geometry ($\Delta A'CO$ in Figure 6 and $\Delta A_1'O_1P_1$ in Figure 7), though there is an obvious structural difference between them.

In order to make the fixed pulley and swing pulley work consistently during phase 2, ΔL_s must be equal to ΔL_f at any moment. Unfortunately, the radii of guide pulley cannot be ignored due to its effect on ΔL_f and ΔL_s. The equations should be more complicated in engineering application, and it is too difficult to find an analytic solution. It is a simple and effective way to perform a numerical analysis.

Result of Design

In the development of the synchronization mechanism, the dimensioning parameters were determined by the result of numerical analysis. The length variation tolerance between rolling on cable and rolling off cable (ΔL_f - ΔL_s) is shown in Figure 8. The minimum was -0.47 mm during the deployment while the maximum was +0.65 mm. The tolerance was small enough to be accepted because the total length of each cable was more than 2000 mm.

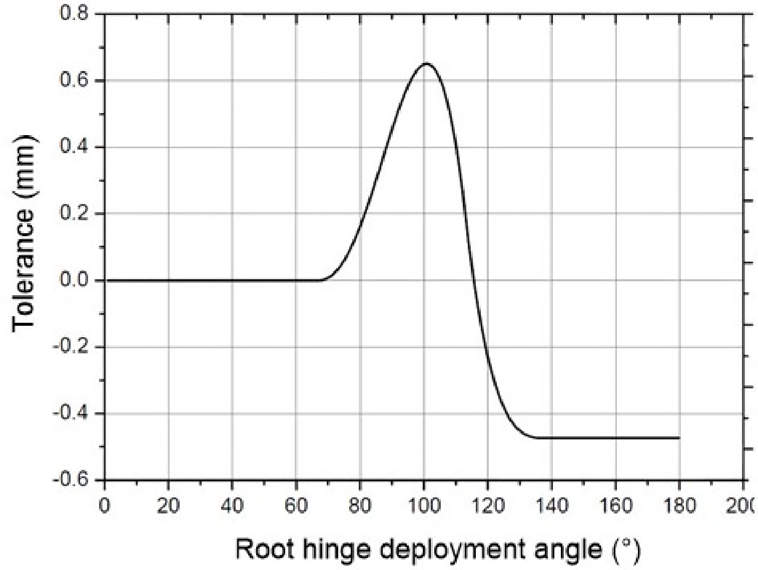

Figure 8. The length variation tolerance

The synchronization characteristic is shown in Figure 9. The nominal characteristic was fully compatible with the ideal one before 70° and after 110° of root hinge rotation. There was a transient and smooth transition in nominal characteristic between 70° and 110°of root hinge rotation.

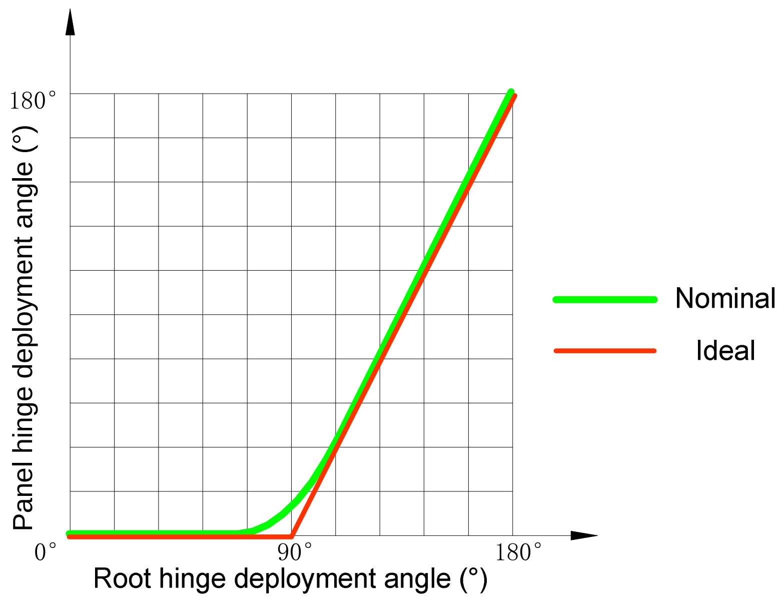

Figure 9. The synchronization characteristic

Figure 10 shows the configuration of the fixed pulley and swing pulley that are installed on the root hinge at the deployed state. The deployment of root hinge can be divided into three stages that shown in Figure 11. It illustrates the state of the pulleys and cables during the deployment.

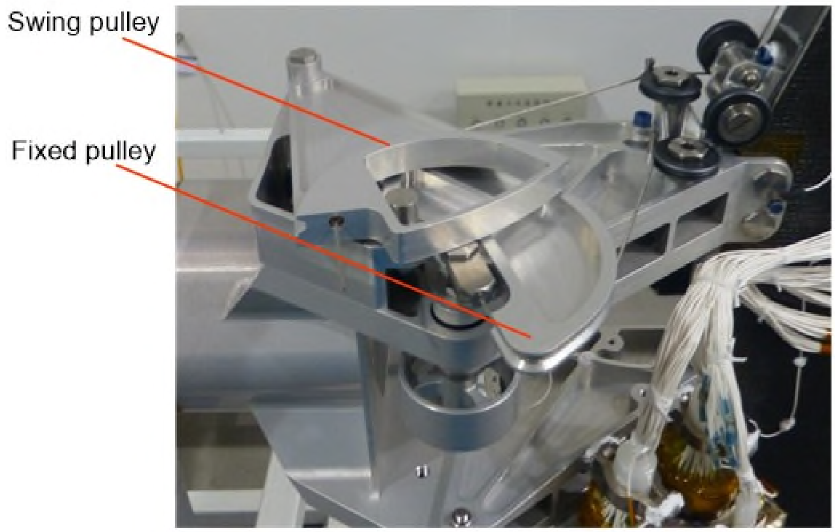

Figure 10. Deployed configuration of root hinge

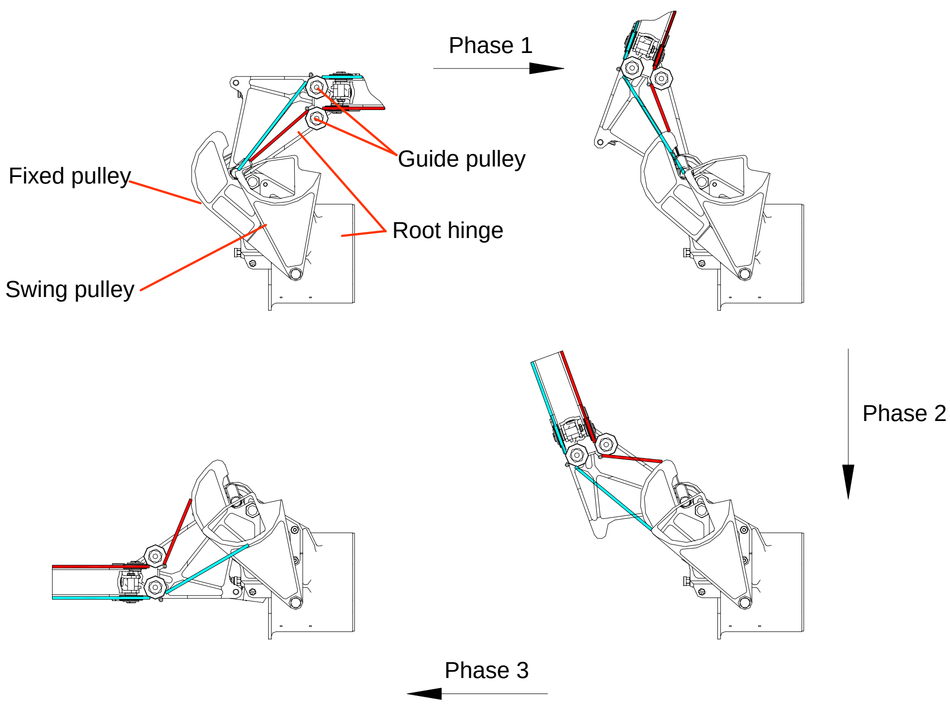

Figure 11. The three-stage deployment of root hinge

Deployment Test

The performance of the synchronization mechanism was verified in ground test using both an engineering model and flight model. The solar array was off-loaded by an air pad for testing (see Figure 12). The trajectories of the air pads were controlled by the synchronization mechanism, and it had to be confined to the area of the table, which corresponded to the requirements.

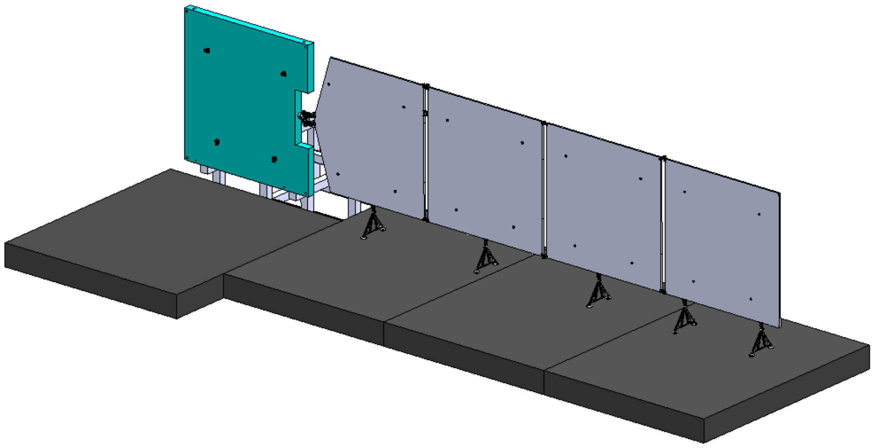

Figure 12. Using air pad for ground testing

The process of deployment using the flight model is shown in Figure 13. The realized synchronization characteristic was similar to the nominal characteristic, and the main difference between the two was that each panel hinge deployed a small angle in phase 1 of testing because of the flexibility of the cables. Nevertheless, the more important consideration was that the trajectories of the panels met the requirements excellently, as the angle was too small to affect trajectories significantly.

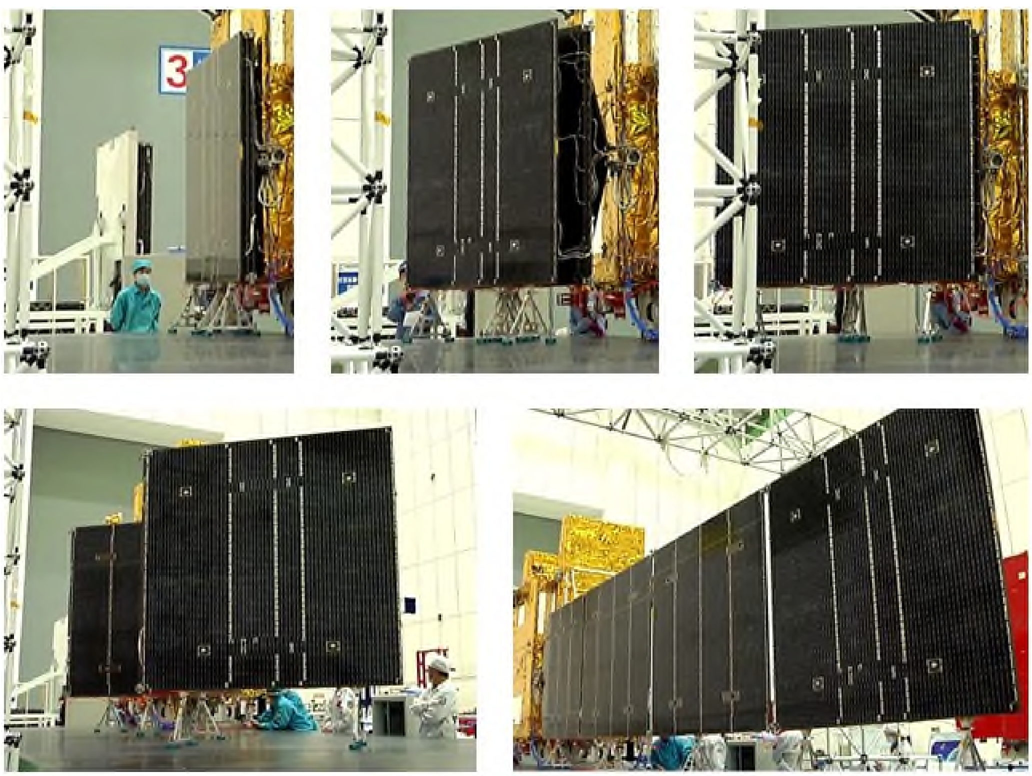

Figure 13. The deployment of the flight model

There were several tests in the development, and the performance of the synchronization mechanism was stable. Furthermore, the GF-3 was launched in August 2016, and the solar array deployed successfully on orbit. The synchronization mechanism demonstrated excellent performance during flight.

Conclusion

The synchronization mechanism of the solar array in this paper performs a three-stage deployment in order to meet the requirement to confine the trajectories of all panels to a limited area. The main design challenge of the synchronization mechanism is to change the ratio smoothly from 0:1 to 2:1 by adding a transient transition. The root pulley is divided to two parts called the fixed pulley and swing pulley in order to achieve the function. Although there is an obvious structural difference between the fixed pulley and swing pulley, they both use the characteristic of a triangle in the mathematical model to change the length of the cable rolling-on or rolling-off that performs a non-linear ratio. The coordination between fixed pulley and swing pulley is complex, and the dimensioning parameters are determined by the result of numerical analysis. The primary advantage of the method is that the trajectories of the panels meet the requirements excellently. The performance of the synchronization mechanism has proven to be effective and stable by ground test and flight usage. The synchronization mechanism is not significantly bulkier than the standard one, and it can be adapted to other multiple elements deployment that have a similar requirement.

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