Simulation of Deployable Polyhedral Truss

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Abstract

Deployable space structures are made of bays, which concatenate in a repeatable fashion to form a desired structure. Each of these bays undergoes determined relative motion between the links to transform from an initially folded to the deployed configuration. The typical deployable structure is a Deployable Polyhedral Truss (DPT) used for the large antenna. The DPT has 18 bays forming a regular 18-sided polygon. Each bay is a closed loop mechanism with six links with revolute joints and a telescopic member along the diagonal. Each bay is connected to the adjacent bays through gears. The DPT is stowed during launch and is deployed in the orbit. In this paper the deployment simulation of the DPT is studied in ADAMS software. A macro has been developed to model DPT in ADAMS. The same macro can be used to quickly model any DPT with a given number of bays. The redundancy of the various kinematic pairs in the DPT is presented. In addition the differential locking of DPT is simulated and the possible reasons are explored.

Key words: - Deployable Polyhedral Truss (DPT), Degrees of freedom, Differential latching, and Deployment simulation

1 Introduction

Large deployable mesh reflectors that are automatically unfurlable have been pursued for their potential use for large aperture, lightweight antenna for satellite communication. These deployable structures are made of bays, which concatenate in a repeatable fashion to form the desired structure. Each of these bays undergoes determined relative motion between the links to transform from an initially folded to the deployed configuration. The modular mesh concept was considered in [1]. This has a hexagonal shaped hoop in the deployed configuration. The two concepts of deployable truss structure were considered. First concept is a slide type truss structure, in which the deployment is through slider. The second concept is articulated truss structure, which has two articulated truss members with scissor link that synchronises the deployment. The AstroMesh [2] uses the concept of a pair of ring stiffened geodesic truss domes. The ring has cable actuated synchronized parallelogram mechanisms that deploys the cable net structure. The nets are stiff and statically determinate in the deployed configuration.

The flexible multi-body dynamics software [3] was developed to study the dynamics of 4.8 m modular mesh antenna. The deployable truss structure considered here uses a center axis and six radial ribs with cable net. Each rib has a four bar mechanism with a diagonal member. The driving force necessary for the deployment was evaluated and validated by experiment. The SPADE software [4] was used for radial rib structure cable net antenna, which has the aperture diameter of larger than 20 m, to arrive at the equilibrium shape and deployment motion of reflector. In this paper we present the kinematic analysis carried out for the Deployable Polyhedral Truss (DPT) using macros of the ADAMS software. A simulation of differential latching is presented.

2 System description

The typical deployable structure is a DPT used for the large antenna. The DPT has 18 bays forming a regular polygon. Each bay is closed loop mechanism with six links with telescopic member as a diagonal member as shown in Figure-1.

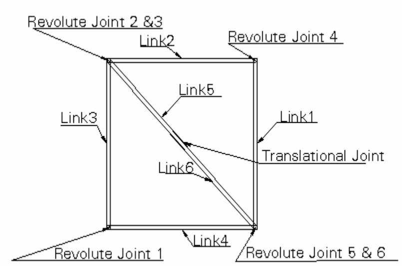

Figure 1 One Bay of DPT

Each bay is a mirror image of the previous bay and is connected to the adjacent bays through gears. ADAMS model of the folded DPT is shown in Figure-2.

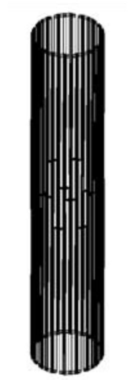

Figure 2 ADAMS model of DPT in stowed configuration

Figure-3 and Figure-4 show the DPT in partially deployed and fully deployed configuration.

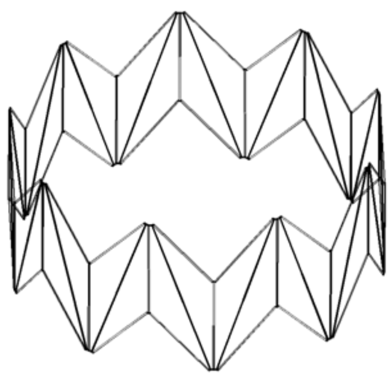

Figure 3 DPT in Partially Deployed Configuration

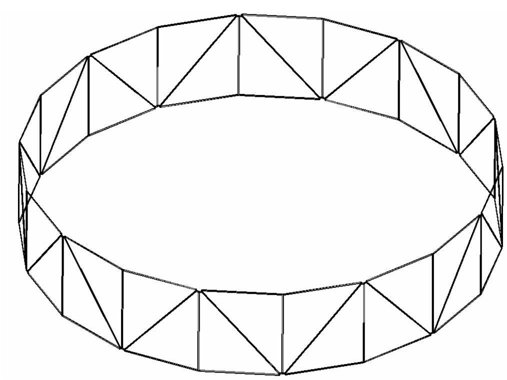

Figure 4 DPT in Fully Deployed Configuration

A cable is routed through all the diagonal members of the truss. One end of the cable is fixed and the other end is pulled by a motor. By shortening the length of the telescopic member, the motor deploys the truss. The DPT is modeled using ADAMS. As all the bays of the DPT are similar, a macro has been developed in ADAMS to model DPT. A macro is a user-defined command in ADAMS, which executes a series of built in ADAMS commands. The same macro can be used to create a DPT with given number of bays to study the kinematic and dynamic characteristics of DPT quickly.

3 Degrees Of Freedom

Degrees Of Freedom (DOF) of a multi body system can be defined as the number of independent coordinates required to represent the motion of the system. Various types of joints connect different bodies of the multi body system. Each joint imposes certain constraints on the multi body system and reduces the mobility of the system. The Degrees of freedom of a multi body system is can be expressed mathematically as

DOF = 6(Number of moving parts) – Total number of constraints. (1)

Normally Degrees of freedom, DOF, of mechanism can be calculated using Grubler's equation[5]. The DOF according to Grubler's can be written as

$$DOF = \lambda(N - J - 1) + \sum_{i=1}^{j} Fi \qquad (2)$$

where, N is the total number of links including the fixed link, J is the total number of joints, Fi is the degree of freedom at the i^{th} joint and λ is six for the spatial mechanism.

Grubler's equation gives lower number of number of Degrees of freedom than actually the system has, if the system has redundant constraints. Grubler's equation is based on number of joints without considering redundant constraints. The concept of redundant constraints can be explained using a simple four bar mechanism shown Figure 5

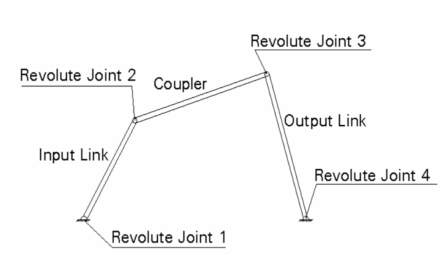

Figure 5 Four Bar Mechanism

The four bar mechanism has 3 moving links and 4 revolute joints. Degrees of freedom of a four bar mechanism according to Grubler's equation (2) we get the DOF as –2.

But the four bar mechanism has mobility. Revolute joint 2 that connect Coupler and input link need not impose 5 constraints. It can permit two rotations without changing the kinematic behaviour of the four bar mechanism. Revolute Joint 3 already imposes these two constraints on Coupler. The Revolute Joint 2 has two rotational redundant constraints, hence it can be treated as spherical joint. Similarly the Revolute Joint 3 that connects coupler and output link need not impose 5 constraints. It can allow the translation of coupler along the rotational axis. Revolute Joint 2 modified as spherical joint already imposes this translation constraint on Coupler. The Revolute Joint 3 has one translation redundant constraint along the axis of rotation, hence Revolute Joint 3 can be treated as cylindrical joint. The Four bar mechanism now has 2 revolute joints, 1 spherical joint and 1 cylindrical joint and all the redundant constraints are removed. Hence, we have N = 4 , J = 4, and Fi for the Cylindrical Joint is 2 and for the spherical joint is 3. The degrees of freedom of the four bar mechanism by Grubler's equation (2) gives 1. s for the is as follows

The above procedure is one possible way of removing redundant constraints, but not the unique way. The same kinematic behaviour of the four bar without redundant constraints can also be obtained by two revolute joints (Input, Ground & Output, Ground), one spherical joint (Coupler, Input) and Universal Joint (Coupler and Output). The other possible way of getting the same kinematic behaviour of a four bar is to have one Revolute Joint (Input, Ground) and three universal Joints at other three places.

The bay shown in Figure 1 has six revolute joints and one translation joint. Hence, N = 6 and J = 7. The Degrees of freedom as calculated by using the Grubler's equation(2) as

$$DOF = 6(6-7-1) + (6*1 + 1*1) = -5$$

But this bay has mobility. All the six revolute joints need not impose 5 constraints. They can allow the rotation about an axis parallel to the plane of the paper without changing the kinematics of the mechanism, which means that there are 6 redundant constraints. Hence, the all six revolute joints can be treated as Universal joints. Accordingly degrees of freedom for one can be calculated by Grubler's equation is as follows

$$DOF = 6(6-7-1) + (6*2 + 1*1) = 1$$

It is possible to identify the redundant constraints for simple mechanisms like four bar and slider crank mechanisms. But it is difficult to identify the redundant constraints for a complicated mechanism like, Deployable Polyhedral Truss consisting of 90 parts (89 moving parts), 108 revolute joints and 18 transnational joints. By using Grubler's equation, we have N = 90 and J = 108 + 18,

$$DOF = 6(90-126-1) + (108*1 + 18*1) = -96.$$

This mechanism as per the above equation is immobile. The commercial software packages like ADAMS, identifies the redundant constraints and we can eliminate them. The Deployable Polyhedral Truss studied in this paper has 111 redundant constraints. Degrees of freedom for the DPT can be calculated by considering the above redundant constraints as

$$DOF = DOF_G + R_c = -96 + 111 = 15 \quad (3)$$

Where, DOF_G is the DOF computed from equation (2) and R_c is the total number of redundant constraints.
To make the DPT single degree of freedom system, the motion of the first bay should be coupled to second bay and to the subsequent bays, possibly by gears. Hence, the number of gear pairs required to make DPT single degree of freedom is 14. From the first bay the first 15 bays either in clockwise or counter clockwise are independent. Accordingly 14 gear pairs can be placed between the first 15 bays.

4 Results and Discussion

In this section the results of kinematic simulation carried out for the DPT in ADAMS is presented and a case of differential latching simulation is presented.

4.1 Kinematic simulation

The following assumptions are made

- The links of DPT are rigid
- The clearances in joints and gears are neglected
- The drive cable axial extension due to tension is negligible.

As all the bays of the DPT are similar a macro has been developed in ADAMS. Macro is user-defined feature of ADAMS to execute a series of ADAMS commands. The macro creates the DPT with links of required length at required positions, revolute and translation joints at the appropriate locations. Macros are very useful for modeling repetitive models. The same macro can be used to model any DPT with a given number of bays. ADAMS model of DPT in stowed configuration is shown in Figure 2. As the system is a single degree of freedom system, one translation motion input is given to the telescopic member (diagonal member) of the first bay. The motion of the first bay is transmitted to the next and subsequent bays through gears. Each bay gets locked when the displacement of the telescopic member reaches 0.772 m. As the velocity input given to the translation joint is 0.01 m/sec, it takes 77.2 sec for the total deployment of the truss.

4.2 Ground deployment simulation

The DPT is deployed in ground several times to validate the functions of each of the subassemblies and to check the whole system. As the dimensions of the DPT in the deployed configuration is very large, this can induce large forces and moments on the support system, due to self weight, if the DPT is supported only at root. The deflections caused by the individual bays due to self weight is may hinder the deployment. In order to over come this difficulty, the whole system needs to be supported to off load its self-weight, during deployment. Hence, each bay of the DPT needs to be supported by means of spring loaded turnbuckle assembly. This assembly has to move along with DPT during ground testing. Hence, a simulation is carried out to evaluate the trajectory of the centre point of the horizontal link. The trajectory is presented in Figure 6. It cab be observed from the figure that the trajectories of these bays are radial spatial curves from the support point. Hence, it is difficult to have a zero-g set up for this configuration. However, the trajectories of center point of bottom links are radial straight lines from the support point.

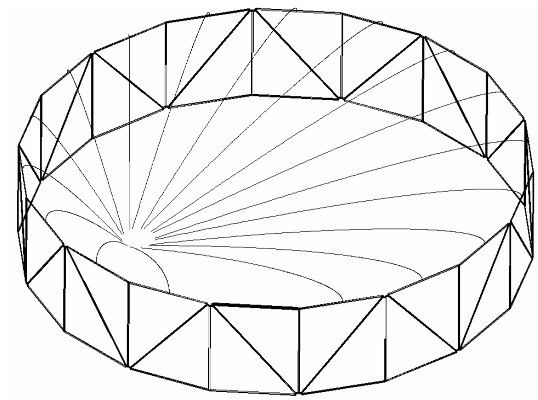

Figure 6. Path traced by mid point of the top link

To over come this difficulty another option was considered. In this option, all the top links were constrained to move in one plane. This was done by providing a slider mechanism at the root. In this configuration, bottom links were allowed to move in all the three directions. The paths traced by the center point of the top links are shown in Figure 7. It can be observed from this figure that the path traced by the top links lie in a plane. This option simplifies the trajectory scheme of the zero-g fixture.

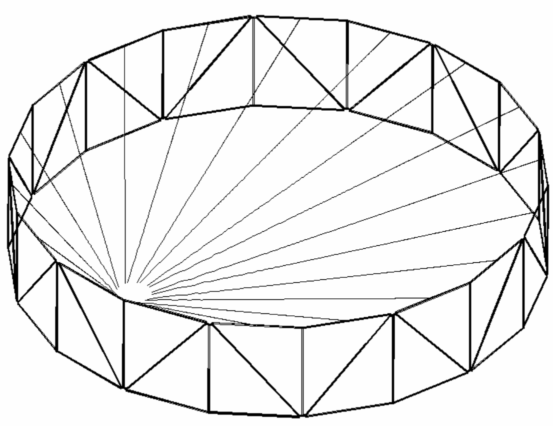

Figure 7. Path traced by the mid point of top links when they are constrained to move in a single plane

4.3 Differential latching simulation

In the previous section, the DPT is a single degrees freedom system, as the motion of all the bays were connected through gears. When the transmission ratio is "one" for a given motion in first bay there will be a definite predictable motion in second and subsequent bays. This can have simultaneous latching (locking) of all the bays. Due to manufacturing limitations, clearances in each joint assembly, the transmission ratio may not be equal to one. The simulations were carried out by varying the following parameters to study the influences of such inaccuracies in manufacturing.

- The tension in the drive cable
- Increasing the dimensions of the alternate bays by 10 mm
- Changing the transmission ratio

The influence of change in drive cable tension between different bays was studied in ADAMS by applying the different tensions along the telescopic members. The simulation showed that the loss of tension in drive cable between bays resulted only in delayed deployment but all the bays have latched simultaneously as the transmission ratio was assumed to be one.

The influence of change in dimension of the links between the bays is studied by increasing the dimensions of the alternate by 10 mm. 17 th bay has latched first followed by 1,3,5,7,9,11,15,2,4,6,8,12,14. A time difference of nearly 3.0 sec was observed between the first and last latching. 16 th and 18 th bays did not get latched as the truss becomes an irregular polygon. Further studies are needed to be carried out to understand this phenomenon.

Due to limitations in manufacturing process, it is difficult to achieve the transmission ratio one in all the bays. The simulations studies were carried for the transmission ratio of 0.99. A velocity input, v_o, 0.01 m/sec is given to the first bay and 0.0099 m/sec to the second bay, which simulates the transmission ratio of 0.99. Similarly for the *n th* bay the velocity input V_n is given as

$$V_n = V_o 0.99^{n-1} \tag{4}$$

where, $n \le 15$.

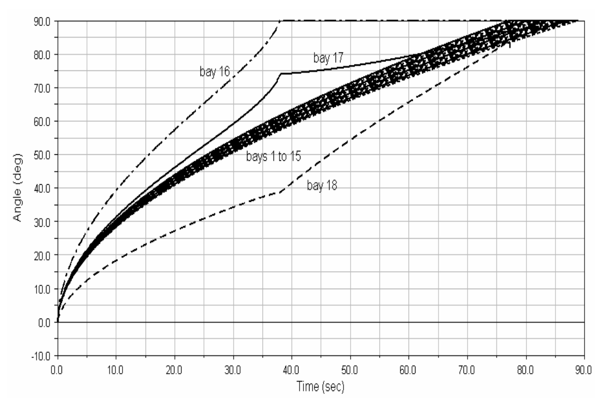

Figure 8. Angle of opening of different bays with time

The simulation was carried out for the above input. Each bay gets latched once the telescopic member moves by 0.772 m or the link 2 (Refer Figure 1) rotates by 90 degrees from the initial position. Each locking of the bay reduces the degrees of freedom of the DPT by one. Simulation is continued till all the bays have latched. Figure 8 shows the angle of opening of Link 2 of each bay with time.

It can be observed from the figure that bay 16 has latched first, next 17 th bay followed by bays 1 to 15. The Bay 18 has latched last. It is obvious that the bays 1 to 15 latches in order since the velocity of each bay gets reduced from bay 1 to bay 15. Hence, the curves from bay 1 to bay 15 closely follow one another. Latching of bay 16 produces a abrupt change in the slope of the deployment angle in bay 17 and bay 18. Each latching of the bay produces change in the slope of the deployment angle in bay 18 since the bay 18 has latched last. The slope changes of bays 16,17 and 18 are shown again in Figure 9.

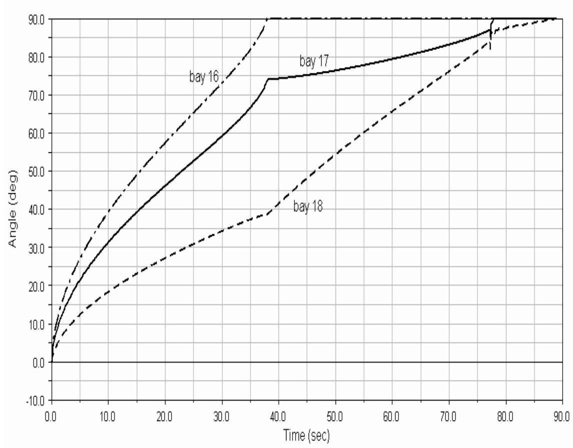

Figure 9. Angle of opening of bays 16,17 & 18 with time

The time difference between the first latch up (bay 16) and the last latch up (bay 18) is 46.7 sec. This time difference can increase, if the transmission ratio decreases further.

5.0 Conclusions

The DPT with 18 bays is simulated using ADAMS software. A macro has been developed to model a DPT with a given number of bays. It was observed that the Grubler's equation gives lower number of degrees of freedom than actual number, if the system has redundant constraints. These redundant constraints have been identified in DPT and included in Grubler's equation to calculate the correct degrees of freedom. The kinemtic simulation was useful in arriving at a suitable trajectory for the zero-g testing in ground. The differential latching was carried out to by simulating the transmission ratio. It was observed that the time difference was very large even for the transmission ratio of 0.99. The methodology used in this paper can be extended to the large repetitive space modules very easily using the macros of ADAMS.

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