A 100-meter-class plate space structure construction method using a deployable truss

Daisuke JODOI* and Toyotoshi KUROSE**

* Japan Aerospace Exploration Agency
  2-1-1 Sengen, Tsukuba-shi, Ibaraki-ken 305-8505, Japan
  E-mail: joudoi.daisuke@jaxa.jp
** Kawasaki Heavy Industries, Ltd.
  1 kawasakimachi, Kagamihara-shi, Gifu-ken 504-8710, Japan

Received: 9 February 2017; Revised: 22 May 2017; Accepted: 27 June 2017

Abstract
In almost all Space Solar Power Systems (SSPS) concepts proposed in the world, constructing large space structures of several hundred meters or more is necessary. On the other hand, a largest space structure realized by traditional hand made construction methods is the International Space Station (ISS). However, the problem is that this construction method is dangerous, expensive and time-consuming. Therefore, an automatic construction method for large space structures is required to solve the problems. In this paper, we propose a construction method for the 100-m-class plate structure composed of many panels toward the realization of the SSPS. The advantages of this method are that very difficult technologies are not required and it is a concrete method. From the result of the ground experiments, we showed that the basic functions of a truss deployment machine in the proposed construction method is feasible.

Key words: Construction, Large space structure, Deployable truss, Space Solar Power Systems, Phased array antenna

1. Introduction

The Space Solar Power Systems (SSPS) has the potential to solve global issues for energy, climate change, environment and so on because the SSPS has the advantage of being able to supply large-scale clean energy steadily to multiple points. In almost all SSPS concepts proposed in the world, constructing large space structures of several hundred meters or more is necessary. On the other hand, a largest space structure realized by traditional hand made construction methods is the International Space Station (ISS) whose size is about 100m x 70m. The ISS was constructed by extravehicular activities and robot arm operations of astronauts. However, the problem is that this construction method is dangerous, expensive and time-consuming. Therefore, an automatic construction method for large space structures is required to solve the problems.

Some automatic construction methods have been proposed so far, but those methods require very difficult technologies and are not fully embodied. The issues of four typical construction methods are as follows. Regarding the construction method studied in SPS2000, a high-function robot to assemble pipe elements is required and how to attach solar/antenna panels to a truss structure is not embodied. Regarding the construction method studied in the former USEF, the synchronization deployment of many panels and rendezvous-docking of large flexible structures are required and a robot used for the rendezvous-docking are not embodied. Regarding the construction method studied in SPS-ALPHA, the control of numerous robotic arms is required and the assembly sequence of antenna/mirror modules is not embodied. Regarding the construction method studied in SpiderFab, 3D printing in space exposure environment and a high-function robot to assemble elements manufactured by the 3D printing are required and how to attach mission equipment to a structure is not embodied.
Therefore, in this research, we aim to propose a more easy and concrete construction method for a large space structure and to show its feasibility by carrying out ground experiments toward the realization of the SSPS.

This paper describes the detail of the construction method, the result of the ground experiments and so on.

2. Target and conditions to study construction method

It is necessary to set a target and conditions in order to study a construction method for a large space structure. The target and conditions in this study are shown below.

(1) Target

The target of this research is a 100-m-class plate space structure composed of many panels. Its reasons are as follows:

- A power transmission system is a mandatory subsystem for the microwave-based SSPS and a plate structure composed of panels that have a certain thickness.
- The construction of kilometer class space structures for the SSPS should be studied step by step because it is too difficult at the present time. Regarding 100-m-class large structures, it is possible to study the construction method because the ISS has already been realized by traditional hand made construction methods.
- The result of this research can be applied to antennas for radar, communication and so on because the power transmission system of the microwave-based SSPS is a phased array antenna.

(2) Conditions

Regarding the construction method of a structure, it is desirable to be able to construct a required structure at low cost, in a short time, with high reliability. It is also necessary to be able to enlarge the size of the structure beyond the 100m class since the SSPS requires kilometer class large structures. Based on the above, we set preconditions and requirements, shown in Table 1, in order to study the construction method for the 100-m-class plate space structure.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Item</th>
<th>Content</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precondition</td>
<td>Launch Vehicle</td>
<td>H-IIB Rocket</td>
<td>We assume that the size of rocket fairings does not change drastically in the near future.</td>
</tr>
<tr>
<td></td>
<td>Orbital Altitude</td>
<td>500km</td>
<td>Technology demonstrations in a LEO have been studied in R&amp;D of the SSPS.</td>
</tr>
<tr>
<td></td>
<td>Panel</td>
<td>Areal density: 4kg/m² (not include interfaces), Thickness: 20mm</td>
<td>We assume technologies of the near future.</td>
</tr>
<tr>
<td>Requirement</td>
<td>Structure</td>
<td>To make size more than 100m x 100m</td>
<td>The 100-m-class plate structure is the target of this study.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>To increase stiffness after reducing the number of launch</td>
<td>The stiffness requirement of the SSPS is uncertain in the present time.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>To make the gap between the panels less than 10mm</td>
<td>It is necessary to suppress grating lobes from a power transmission system.</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
<td>To reduce the number of launches</td>
<td>It is desirable to reduce the transfer cost that have an impact on a construction cost.</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>To increase construction speed</td>
<td>It is desirable to shorten construction duration.</td>
</tr>
<tr>
<td></td>
<td>Reliability</td>
<td>To simplify mechanisms and machines for construction</td>
<td>It is desirable to reduce the occurrence of failures.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>To facilitate ground tests</td>
<td>It is desirable to reduce failure risks under construction on an orbit.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>To facilitate the recovery from deadlocks under construction</td>
<td>It is desirable to be able to continue construction even when deadlocks occur.</td>
</tr>
<tr>
<td></td>
<td>Scalability</td>
<td>To be able to enlarge size more than 100m class</td>
<td>The SSPS requires kilometer class large structures.</td>
</tr>
</tbody>
</table>
3. Proposed construction method

3.1 Overview of construction method

Based on the target and conditions in Section 2, we devised a construction method using a deployable truss as shown in Figure 1. Its overview is as follows:

1. The truss deployment machine equipped with the folded truss arrives at an objective orbit.
2. The folded truss is deployed in the deployment direction by the truss deployment machine. (Fig. 1a) The deployable truss is equipped with panels.
3. The truss deployment machine moves in the connection direction. (Fig. 1b)
4. The truss deployment machine moves to the tip of the deployed truss in the deployment direction. (Fig. 1b)
5. The deployment of the second line is started. (Fig. 1c)
6. The truss deployment machine connects the second line to the first line while deploying the second line. (Fig. 1d)
7. The deployment of the second line is completed.

The truss after the third line is constructed by repeating 3 to 7 of the above sequence. When the container of the truss deployment machine is empty, a new truss is launched and added.

![Fig. 1 Sequence for construction.](image)

3.2 Systems for construction

The following are the details of the deployable truss and the truss deployment machine for the construction method of Section 3.1.

(1) Deployable truss

Figure 2 shows the overview of the deployable truss. The deployable truss looks like a thin plate in the storage state. The diagonal members of the deployable truss are extended and shrunk by the force of the truss deployment machine under the deployment. When the diagonal members are fixed as shown in Figure 3, the shape of the deployable truss is fixed. Panels are mounted on the plane surface of the deployable truss.

Figure 4 shows the overview of connection mechanisms between the lines of the deployable truss. The connection mechanisms are set to the four corners of the unit of the deployable truss. The position of the connection mechanisms of a new line is slightly higher than the previous line before connecting the lines as shown in Fig. 4. When the new line moves along the guide rail of the truss deployment machine, it is pushed down to connect the lines.

(2) Truss deployment machine

Figure 5 shows the overview of the truss deployment machine. We assume that the machine is folded and put into the rocket fairing at launch, and the 100-m-class structure is constructed by launching 6 or more machines equipped with the folded trusses. The following are the details of mechanisms composing the truss deployment machine:
The truss sending mechanism sends out the folded truss from the container of the truss deployment machine. Specifically, the motor drives the timing belt with the claws to send out the truss as shown in Fig. 5.

The first truss deployment mechanism deploys the first line of the deployable truss and first two units of next line. Specifically, the motor drives the timing belt with the claw to deploy the truss as shown in Fig. 5.

The deployment direction movement mechanism moves the truss deployment machine along a line in the deployment direction. Specifically, the motor drives the timing belt with the claw to move the machine as shown in Fig. 5.

The connection direction movement mechanism moves the truss deployment machine along a line in the connection direction. Specifically, the motor drives the rack and pinion to move the machine as shown in Fig. 5. The service unit doesn’t only construct the structure together the connection direction movement mechanism but also maintains panels.

Fig. 2 Overview of deployable truss.

Fig. 3 Overview of diagonal members.

Fig. 4 Overview of connection mechanisms.
3.3 Correspondence to requirements

Regarding the proposed construction method, Table 2 shows correspondences to the requirements described in Section 2 (2).

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Correspondence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>To make size more than 100m x 100m</td>
<td>We devised the sequence as shown in Fig.1.</td>
</tr>
<tr>
<td></td>
<td>To increase stiffness after reducing the number of launch</td>
<td>We increased stiffness by using the truss structure.</td>
</tr>
<tr>
<td></td>
<td>To make the gap between the panels less than 10mm</td>
<td>The gap between the panels is 10mm or less excluding some areas as shown in Fig. 6. Regarding the areas where the gap between the panels exceeds 10mm, it is necessary to study the influence on the generation of grating lobes in the future work, but we consider that the existence of the areas is acceptable because the ratio of the areas to the whole is small.</td>
</tr>
<tr>
<td>Cost</td>
<td>To reduce the number of launches</td>
<td>The number of the launches is 6 or more not considering a satellite bus. We assume that it is possible to transport about 80 panels, whose size is 7m x 3m each, by one launch, and the panels transported by second or later launch are docked to the structure by the robot arm of the service unit.</td>
</tr>
<tr>
<td>Time</td>
<td>To increase construction speed</td>
<td>We increased construction speed by using the deployable structure equipped with panels.</td>
</tr>
<tr>
<td>Reliability</td>
<td>To simplify mechanisms and machines for construction</td>
<td>We suppressed complexity of the truss deployment machine by equipping the deployable truss with the deployment and connection mechanisms.</td>
</tr>
<tr>
<td></td>
<td>To facilitate ground tests</td>
<td>We made it possible to carry out ground tests by hanging test equipment with wires.</td>
</tr>
</tbody>
</table>
To facilitate the recovery from deadlocks under construction, we made it possible to recover deadlocks under construction by equipping the connection mechanisms with a removal function as shown in Fig. 7.

We devised the sequence as shown in Fig. 1.

### Scalability

| To be able to enlarge size more than 100m class | We devised the sequence as shown in Fig. 1. |

### 3.4 Advantages of construction method

The following are the advantages of the construction method:

- It is unnecessary to use very difficult technologies such as high-function robots, the rendezvous-docking of large flexible structures, the control of numerous robotic arms, 3D printing in space exposure environment and so on.
- It is possible to carry out a relatively short-term and low-cost development of the systems for the construction because the materials, structures and mechanisms of the systems have been used in space.
- It is easy to change the structural properties because the structural style is a truss.

### 4. Ground experiments

#### 4.1 Purpose

We carried out ground experiments for the following basic functions of the truss deployment machine in order to...
show the feasibility of the proposed construction method:
- The function to deploy and connect the deployable truss, and
- The function to move the truss deployment machine in the connection direction.

4.2 Method

We carried out a deployment experiment in order to demonstrate the function to deploy and connect the deployable truss and a movement experiment in order to demonstrate the function to move the truss deployment machine in the connection direction.

4.2.1 Overview of experimental equipment

(1) Deployment experiment

Figure 8 shows the configuration of the deployment experiment. Regarding the deployable truss, the size of the unit is 1685mm x 920mm x 20mm (170mm in the deployment state), the mass of the unit is about 8kg and the number of units is 12 (6 units x 2 lines). Regarding the truss deployment machine, the size is 4600mm x 1200mm x 2300mm, the mass is 93.5kg and the machine is driven by an operator using a control console. Regarding the gravity compensation equipment, the size is 3000mm x 3000mm x 12000mm, the equipment hangs the deployable truss and the truss deployment machine using wires and can follow the movement of the truss deployment machine.

(2) Movement experiment

Figure 9 shows the configuration of the movement experiment. The deployable truss, the truss deployment machine and the gravity compensation equipment are the same as those used in the above experiment. Regarding the connection direction movement mechanism, the size is 1400mm x 150mm x 200mm and the mass is 21.6kg. Regarding the service unit, the size is 2030mm x 1040mm x 200mm and the mass is 10kg. We didn’t only use the gravity compensation equipment but also use the jig for the movement of the truss deployment machine in the connection direction.

4.2.2 Experimental procedure

(1) Deployment experiment

Figure 10 shows the experimental sequence to demonstrate the function to deploy and connect the deployable truss. In the initial state, the first line is deployed. (Fig. 10a) The truss deployment machine deploys the second line and connects the tips of the two lines. (Fig. 10b) And then the machine connects the second line to the first line while deploying the second line. (Fig. 10c)

(2) Movement experiment

Figure 11 shows the experimental sequence to demonstrate the function to move the truss deployment machine in the connection direction. In this experiment, the connection direction movement mechanism and the service unit are driven by manual operation. First, the service unit is connected to the truss deployment machine. (Fig. 11a) Next, the machine is moved in the connection direction. (Fig. 11b) Finally, the machine is moved in the deployment direction. (Fig. 11c)
4.3 Results

(1) Deployment experiment

Figure 12 shows an experimental process recorded by a video camera. We were able to carry out the sequence of Fig. 10 successfully. At that time, the motions of the truss and the machine are smooth and have no interference. We carried out the experiment 3 times and the operating time of the experiment was 531.85 seconds at the shortest, 532.05 seconds on average and 532.4 seconds at the longest, that was almost the same as the expected time.

We measured the output voltage of the motor torque monitors in order to check the driving force of the
mechanisms of the truss deployment machine. Figure 13 shows the measurement values. Regarding this figure, the colored time zone shows that the mechanisms under operation. In the graph, there are many pulses whether the mechanisms are driving or not. We considered that the pulses are not the responses of the mechanisms but the motor’s current fluctuation by driving the motors to control the positions of the truss deployment machine or mere noise from the occurrences of the pulses. The gear friction loss of the motors was large because we used the motors whose torque is much larger than required considering the effect of gravity in the ground experiment. Therefore, we were not able to detect well the torque fluctuation of the motors during the deployment and connection of the truss. However, we confirmed that deadlocks don’t occur because the measured voltage is the same as the voltage, shown in Table 3, when the mechanisms are driven with no load. We considered that it is required to detect the driving force in order to carry out monitoring the motions of the mechanisms and checking the soundness of the mechanisms in the future. Therefore, it is necessary to optimize the motors and improve the detection accuracy of the motor torque based on the result of the experiment.

As a result of the experiment, we confirmed that it is feasible to deploy and connect the deployable truss as the function of the truss deployment machine.

(2) Movement experiment

Figure 14 shows an experimental process recorded by a video camera. We were able to carry out the sequence of Fig. 11 by manual operation successfully. At that time, the motions of the connection direction movement mechanism and the service unit are smooth and have no interference.

As a result of the experiment, we confirmed that it is feasible to move the truss deployment machine in the connection direction as the function of the machine by the manual operation.

![Fig. 12 Process of deployment experiment.](image)

![Fig. 13 Measured output voltage of motor torque monitors.](image)
5. Conclusion

We proposed the construction method for the 100-m-class plate structure composed of many panels toward the realization of the SSPS. In this method, the truss deployment machine connects two lines of the deployable truss while deploying the one line, and the advantages are that very difficult technologies are not required and it is a concrete method.

We carried out the two ground experiments: the deployment experiment and the movement experiment. As the result of the experiments, we showed that the basic functions of the truss deployment machine in the proposed construction method is feasible.

As future work, it is necessary to study the following toward the on-orbit demonstration of the proposed construction method:

- how to realize functions other than the basic functions demonstrated by the experiments,
- how to stabilize the shape and attitude of the structure under construction, and
- how to recover failures under construction.

References


Mankins, J. C., SPS-ALPHA: The first practical solar power satellite via arbitrarily large phased array, NIAC Phase 1 Final Report (2012).
