On-orbit Demonstration of Innovative Multifunctional Membrane Structure for Ultra-lightweight Solar Arrays and Array Antennas by 3U CubeSat OrigamiSat-1

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ABSTRACT

The 3U CubeSat OrigamiSat-1's deployable membrane structure is 1m-by-1m in size after deployment and is stowed in less than 1U CubeSat (10cm-by-10cm-by-8cm), including a hold-and-release mechanism. The major significance of the structural concept is that it allows the attachment of thin-film devices, such as thin-film solar cells or flexible substrates for antennas throughout the membrane. This was achieved by two features: (i) use of textile and (ii) invention of hybrid boom made of tubular carbon composite and metal convex tape. In addition, a visual membrane measurement system consisting of stereo cameras was developed. This paper describes the new technologies developed for this CubeSat.

INTRODUCTION

Membrane deployable structures have been widely studied for enabling future space applications. Possible applications of membrane structures include deorbiting system, solar array, reflectors, sun shield, phased array antenna, solar sail, aerobrake/aerocapture system, and occulter. Some applications require to attach thin-film devices on membranes, such as thin-film solar cells and antenna substrates. However, the compact stowage and the reliable deployment of such “multifunctional” membrane structures, on which thin-film devices are attached, are very challenging. Especially, it is difficult to predict deployment motion and deployed shapes of space membrane structures through ground tests. This is because the effects of gravity and atmosphere have a significant impact on the behavior of membrane structures on the ground. For this reason, numerical structural analyses were intensively used during the development of the world-first solar sail demonstrator IKAROS. But still, flight demonstrations are important to evaluate the accuracy of numerical analyses. Small satellites will provide such opportunities.

Multifunctional deployable membrane space structures have been studied and demonstrated on the ground for solar arrays, reflectarray antennas, and active patch array antennas. Flight demonstrations have been conducted for one-dimensionally deployed solar array using composite booms, and two-dimensionally deployed solar power sail using spin stabilization.
dimensionally deployed multifunctional membrane using booms has not been demonstrated in space yet. Such technology will enable to realize large and ultra-lightweight solar arrays or array antennas that do not require satellites to spin.

To this end, the present authors developed 3U CubeSat, OrigamiSat-1, for demonstrating and observing the deployment of the proposed multifunctional membrane in space. The multifunctional membrane is stowed, including the hold-and-release mechanism, inside a smaller unit than 1U (10cm by-10cm-by-8cm) in the launch configuration. Then a 1m-by-1m square multifunctional membrane is to be deployed using elastic energy stored in the diagonal booms. Figure 1 shows the flight model in the launch configuration. Figure 2 shows the drawings. Figure 3 explains the folding pattern of the multifunctional membrane. Dummy thin-film devices, whose thickness is equivalent to thin-film solar cells, are attached throughout the membrane, as shown in Fig. 7. The satellite has multiple cameras in the extendable camera unit so that movies and stereo pictures of the membrane can be taken in orbit. Table 1 shows the specifications of OrigamiSat-1.

OrigamiSat-1 was successfully launched into a 500km-altitude low Earth Sun-synchronous orbit in January 2019 by the Epsilon-4 rocket, coordinated by Japan Aerospace Exploration Agency (JAXA). However, the membrane deployment mission has not conducted yet because of the communication anomaly. As of the end of May 2021, there is still a possibility to conduct the satellite’s main missions soon. The present authors are also starting the development of a successive mission, HELIOS.13

This paper describes the new technologies during the development of the CubeSat. First, the system design of OrigamiSat-1 is described (Section 2). Then, the deployable multifunctional membrane technology is summarized in Section 3. It also discusses the verification strategy on the ground. Finally, the on-orbit measurement system for membrane motions and shapes is described in Section 4.

Table 1: Specifications of OrigamiSat-1

<table>
<thead>
<tr>
<th>Size</th>
<th>Approx. 100×100×340 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>4.1 kg</td>
</tr>
<tr>
<td>Launch</td>
<td>Epsilon-4 rocket in January 2019</td>
</tr>
</tbody>
</table>
CUBESAT MISSION AND DESIGN

Mission Objectives

The objective of OrigamiSat-1 is to accomplish the following three missions.

(M1) Membrane deployment mission: To contribute to the realization of future applications, a multifunctional membrane structure is deployed, and its deployment motions and deployed shapes are measured in orbit.

(M2) Deployable structure experiment platform mission: To obtain successive space-demonstration schemes for researchers of space deployable structures, commercially available components are mainly used in the entire satellite system. In addition, an on-orbit measurement system for deployable structures, using a stereo camera system, is developed.

(M3) Amateur radio mission: To enhance radio communication skills, 5.84GHz high-speed transmission from space is used.

CubeSat Design

In order to accomplish the three missions, the mission sequence, illustrated in Fig. 5, was planned. (1) the CubeSat is released from a rocket, (2) the deployable antennas are deployed, (3) the extendable mast is extended, (4) the multifunctional membrane is deployed, and finally (5) the 1U-size deployed membrane unit is detached from the 2U satellite to extend the mission lifetime. Figure 6 shows

Figure 4: Multifunctional deployable membrane on OrigamiSat-1 (1st Engineering Model)

Figure 5: Mission sequence of OrigamiSat-1
The system consists of four major subsystems: (i) bus, (ii) membrane deployment system, (iii) extendable camera system, and (iv) ground station. For the bus, most components are composed of commercial off-the-shelf (COTS) components. This design aims at facilitating the future successive space demonstration of advanced space deployable structures by university/company researchers. Armature radio frequencies are used for satellite-ground communication as illustrated in Fig. 7. The satellite uses a passive attitude control using a permanent mag-
In the following two sections, the features of (ii) membrane deployment system and (iii) extendable camera system are described respectively.

MULTIFUNCTIONAL DEPLOYABLE MEMBRANE UNIT

Overview

The membrane deployment system deploys a membrane-boom integrated structure, proposed by the present authors.\textsuperscript{16, 17} Its membrane folding pattern, based on the so-called Flasher pattern, enables the attachment of thin-film devices on the membrane, such as thin-film solar cells and thin antennas. The hold-and-release mechanism of OrigamiSat-1 is shown in Fig. 3. The four walls are held by two liquid-crystal polymer wires and are cut by Nichrome wires.

Devices on Multifunctional Membrane

Figure 8 shows the deployable multifunctional membrane for OrigamiSat-1’s flight model. The dummy thin-film device, 50µm-thick, is still attached throughout the membrane, but the transparent membrane is used. This is to reduce the shadowing effect on the power generation of the satellite bus. On a realistic multifunctional membrane, actual thin-film solar cells will be attached, thus this shadowing effect will not be a problem.

Retro-reflective markers are attached to the membrane for stereo visioning. This is discussed in the next section. Three kinds of actual devices are attached on the membrane. (i) CIGS thin-film solar cells, (ii) Flexible sphere power cells, and (iii) Dipole antenna made of shape memory alloy.\textsuperscript{18} The attachment of these devices demonstrates the ability to stow a relatively thick membrane.

OrigamiSat-1’s membrane accommodates the thickness of the on-membrane devices, because the plain-woven polyester textile is used as a base membrane. The flexibility of the textile ameliorates the effect of thickness in stowage.\textsuperscript{19}

Hybrid Boom: Combination of Composite Tube and Metal Convex Tapes

As illustrated in Fig. 4, the four diagonal booms, wrapped around the hub, consists of tubular carbon composite booms and metal convex tapes (carpenter tapes). This hybrid boom was invented for OrigamiSat-1. In the initial design phase, the authors conducted deployment tests under a micro-gravity environment through parabolic flights of an aircraft.\textsuperscript{20–24} The initial design used only composite tubes, then the deployment force was not strong enough to complete the deployment.

Therefore, two metallic convex tapes are installed in the composite tubes. This combination is very effective to reduce the effect of stress-relaxation of the composites. Since the metallic convex tape has much smaller stress relaxation in the stowed configuration, the hybrid booms can keep the deployment force even after the long stowage period.\textsuperscript{25}

Deployment Test on Ground

A series of deployment tests were conducted for Engineering models, shown in Fig. 9(a), and for the Flight model, shown in Fig. 9(b). The four tips of the diagonal booms were suspended from the ceiling using fishing wires to compensate gravity.

EXTENDABLE CAMERA UNIT

The extendable camera system, illustrated in Fig. 10, takes pictures of the deployed membrane on orbit. It has an approximately 1m-length deployable mast, stereo cameras, and a movie camera.\textsuperscript{15, 26} This subsystem is designed as a major component of the experiment platform for successive space demonstrations of advanced deployable structures. Figure 11 shows the 1m-extendable mast in this unit. The open-section carbon composite mast is unreeled by a motor with a sprocket.

Figure 10 shows the Light Emitting Diode (LED), which is a light source for camera shooting; and membrane pictures obtained in ground tests. The stereo vision enables the shape estimation with a 4.0mm standard deviation, according to the evaluation with a rigid checkerboard. The movie camera, controlled by a Raspberry Pi, records movies during membrane deployment, as illustrated in Fig. 12.

Finally, the root of the extendable mast can be detached, as described in the mission sequence, Fig. 5. The details of this sequence is explained in Fig. 13. Without the detachment, the deployed membrane causes the reduction of orbit lifetime in the low-Earth orbit due to atmospheric drag. After the 1m-by-1m membrane is deployed, the lifetime will be 1 year at the maximum from the initial 500km altitude. The detachment of the deployed membrane enables the extension of the lifetime in orbit so that the amateur radio mission can be continued.
CONCLUSION

OrigamiSat-1 intends the space demonstration of innovative multifunctional deployable membrane structure, proposed by the present authors. It has a 1m-by-1m square membrane, stowed in 10cm-by-10cm-by-8cm size including a hold-and-release mechanism. The membrane is deployed only using elastic energy stored in the diagonal booms. The dummy thin-film devices are attached throughout the membrane, foreseeing the future application as solar arrays and array antennas. The compact stowage and simple deployment mechanism are enabled by two unique features. One is the use of textile as a base membrane, and the other is the invention of the "hybrid" boom. An on-orbit measurement system with stereo cameras and a movie camera for deployable membrane. The 1m-extendable mast works as a selfie stick. The satellite was launched in January 2019, and the operation is still continuing as of the end of May 2021.

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References


Figure 9: Deployment tests on ground

Figure 10: Extendable camera unit, which has approx. 1m extendable mast and stereo camera system\textsuperscript{35}
Figure 11: Extendable mast as a selfie stick

Figure 12: Movie taken during deployment test on ground
Figure 13: Details of membrane detachment sequence