

A study on mission and system of transformable spacecraft

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Transformable spacecraft, which consists of multiple panels connected by actuators, can transform to different configurations in order to achieve several purposes. Furthermore, driving the panel in an appropriate order, it is possible to change the attitude without disturbance by non-holonomic turn. This presentation shows an astronomical observation missions which takes advantage of aforementioned special features of transformable spacecraft and feasibility study on the system for the mission is introduced.

可変構造宇宙機によるミッションおよびそのシステム検討について

摘要

内力アクチュエータで結合された複数のパネルなどの形態要素から構成される可変構造宇宙機では、複数の実用性を有する構造物を構築可能である。また、適切な順序で形態変更を繰り返すことで、ノンホロノミックターンによる無擾乱の姿勢変更を行うことが可能である。このような特性を活用した天体観測ミッションの検討を進めており、本発表ではミッションおよびその実現のためのシステムと要素技術に関する報告を行う。

1. Introduction

Transformable spacecraft is composed of elements such as panels and boxes, which are connected by hinges with internal force actuators. The transformable spacecraft is capable of "Attitude control by Non Holonomic Turn (NHT)" and "Function mode switching by changing its form", and the significant feature of this spacecraft is to achieve simultaneous transition of function and attitude. Furthermore, by utilizing the variable structure of the spacecraft, it is also possible to realize orbit keeping control and heat shielding aimed at passive cooling for mission component. Then, it is also possible to simultaneously achieve four functions: "Attitude control by NHT", "Function mode switching", "Orbit keeping control", and "Heat shielding".

The final goal of this research and development is to launch a demonstration spacecraft (small size

satellite), demonstrate representative features for the transformable spacecraft, and conduct a model science observation mission. The transformable spacecraft will be put into the artificial HALO orbit around Sun-Earth L2 point and perform engineering missions and scientific missions on that orbit. The goals of the missions is as follows.

Engineering mission goal:

- Construction of technology for transformable spacecraft system.
- Construction of operation technology for propellant-free and disturbance-free spacecraft using transformable mechanism and advanced astrodynamics technology.

Scientific mission goal:

- Construction of space infrared interferometer on orbit

and astronomical observation by the system.

- Astronomical observation in wide-field observation mode realized by using multiple telescopes composing the interferometer in different directions

This paper is organized as follows. In the chapter 2, science mission and spacecraft configuration for the mission is introduced, and overview of transformable spacecraft for currently considering science mission is shown in chapter 3. Chapter 4 shows the current status of each subsystems and key technologies. Experimental demonstration of panel deployment control is given in chapter 5. Finally, summary is given in chapter 6.

2. Science mission and spacecraft configuration for the mission

2.1 Background on science mission

Artificial HALO orbit around SEL2 has thermal stability, one of the features of the transformable spacecraft is a heat shielding function, which has a high potential for passive cooling. Therefore, it is considered to be superior in astronomical observation at infrared wavelengths. On the other hand, space infrared interferometers have not yet been realized in orbit, and there are high expectations for various scientific results. Since the space infrared interferometer is not affected by atmospheric fluctuations, it does not require an adaptive optics system, and by utilizing the attitude change of the spacecraft itself, the UV-plane can be filled and the image of the observation target is obtained more efficiently than those on the ground, it has a great advantage over the ground interferometer.

As described above, realization of space infrared interferometer is very valuable, but in order to obtain more significant scientific results, a longer baseline length is required for the system. As a results, larger structure is required for space infrared interferometer. As a first mission of the space infrared interferometer, even if it was not possible to arrange a sufficient baseline length, it will attract researchers by conducting technical demonstrations including the construction of assembly technology for future large space interferometers, and the demonstration will lead to next advanced mission by space infrared interferometer.

In order to achieve a space infrared interferometer by transformable spacecraft as first mission, a system

consisting of two telescopes are being studied and the fundamental configuration is as Figure 1. As Figure 1 shows, fundamental system consists of two mirrors, 2 collimator lens, 2 delay lines, two single mode fiber, 1 beam combiner and 1 detector. Two light from two telescopes are connected via single mode fiber to beam combiner, and then combined beam enters the detector. In order to match the phases of two light, delay lines are used and they are driven by precise actuator, e.g. piezoelectric actuator. As a beam combiner, optical fiber coupler and planar lightwave circuit [1] are under consideration. The reason why single mode fiber is used is to avoid or decrease the influence of the transformation of the spacecraft on the light pass of the interferometer because transformable spacecraft change its configuration in orbit for switching the mission modes.

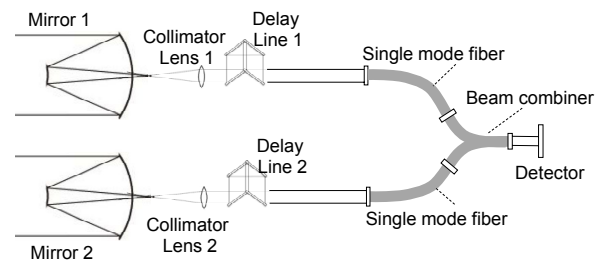


Figure 1. Fundamental configuration of interferometer.

As a simple example to illustrate the typical configuration for interferometer achieved by transformable spacecraft is shown in Figure 2.

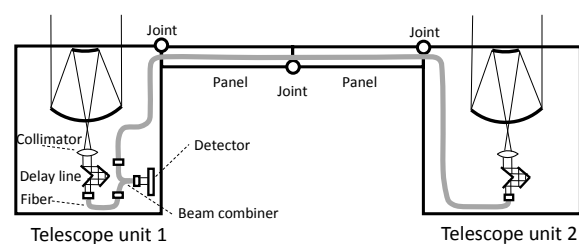


Figure 2. Interferometer by transformable spacecraft.

Figure 2 shows that two telescope units are connected two panels via joints and motor drive systems are installed to each joints. The detector is mounted on the telescope unit 1 and the light from the telescope unit 2 is guided to the telescope unit 1 by single mode fiber in order to make the light interfere on the detector. While the system works as interferometer in that configuration, the system achieve other observation mode by changing the configuration. For example, actuating the joint, it is possible to point two

telescope units to different direction, and then it is possible to observe wide-field area. Note that to achieve wide-field observation, two independent detectors and some systems to split each beam are required. Such a system can be achieved by a dichroic mirror and for simplicity the detail is not depicted in the Figure 2.

Transformable spacecraft which realizes above-mentioned interferometer and other functional modes is proposed in this study and being studied. Figures 3. to 5. show the three modes of the transformer spacecraft, which include the above-mentioned interferometer mode. Each figure corresponds to stowed launch configuration mode, the space inferred interferometer mode and the wide-field observation mode, respectively.

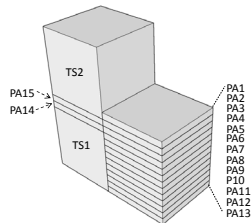


Figure 3. Stowed launch configuration mode.

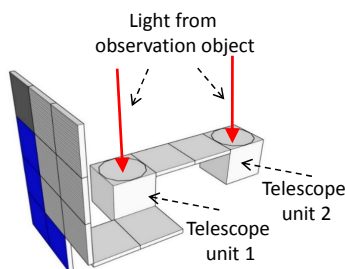


Figure 4. Space inferred interferometer mode.

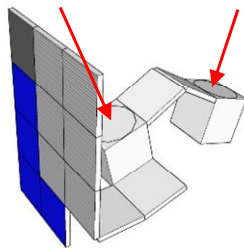


Figure 5. Wide-field observation mode.

The space craft consists of 15 panels and 2 boxes. There are two types of panel structures. One is the panel 1 on which component is mounted, the other is the panel 2 without any component. There are nine Panel 1 and six panel 2, and they has same dimension, $1000 \times 1000 \times 100 \text{ mm}^3$. Each panel has different mass and the average mass of Panel 1 and Panel 2 are 21.3kg and 6kg, respectively.

The box structures include telescope unit and one side is open in order to capture the light from observation target. The box, i.e. telescope unit has mass of 20kg and dimension of $1000 \times 1000 \times 1000 \text{ mm}^3$. In addition to panels and boxes, service module is also installed and the mass of the module is 43 kg, which is not depicted in Figure 3 to 5. The total mass of the space craft is 265 kg. The spacecraft has 4 panels which solar array panel is mounted on the surface. The panel of blue color 1 in Figure 4 and 5 means the panel with solar array pane. Supposing thin film solar cell, 6% generation efficiency at 100 deg. , the maximum power generation is 300W.

Since transformable spacecraft have many panel structures, the allocation of functions to each panel structure is one element that determines the performance of the spacecraft. Although there are various choice of panel function allocation, a configuration as shown in Figure 6 is studied as an example which can extracts features of the spacecraft effectively. Figure 6 is the layout when the panel is fully expanded and it shows property of joints, surface materials and the representative function of each panel. For attitude control by non holonomic turn, appropriate allocation of actuated joint is required and larger number of actuated joint contribute to degree of freedom of attitude control performance and improvement of the system reliability in the view point of redundancy. On the other hand, larger number of actuated joint leads to the increase of the total mass of the system because actuated joint requires the motor drive system. Therefore, unactuated joints are introduced and it is actuated by spring after the satellite is separated from launch vehicle.

3. Overview of subsystems of the transformable spacecraft

3.1. Astrodynamics

Astrodynamics focusing on attitude control and orbit control is very important to make use of the representative features of transformable spacecraft. In this study, in order to simultaneously achieve attitude control using non holonomic turn and keeping artificial HALO orbit using solar radiation pressure, panel structure and configuration are studied. Furthermore, In observation mode, high attitude control is also required, but it is difficult to achieve the required control accuracy with non holonomic turns. So an attitude control method using the

torque generated by solar radiation pressure is also proposed. Detail is given in the reference [2][3].

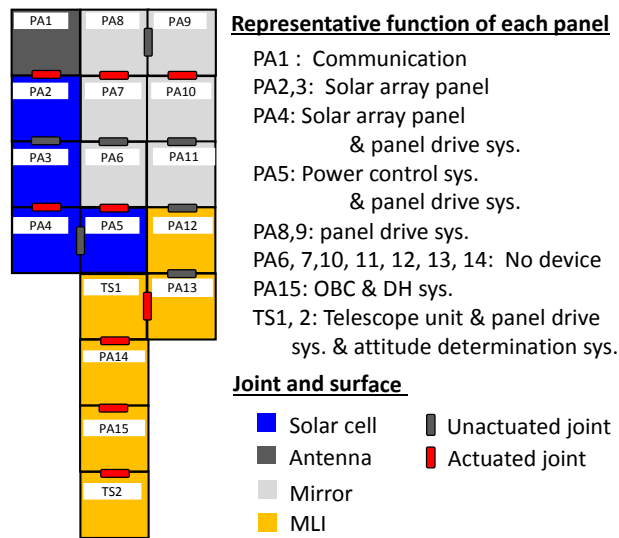


Figure 6. Function allocation of panels

3.2. Communication system

Phased array antenna is used for communication with ground station. Furthermore, the phased array antenna is also used for inter-panel communication in order to reduce harness between panels. Assuming a phased array antenna, antenna pattern analysis is being studied. The analysis results revealed that transformability has influence on the antenna pattern and effective use of advantage of phased array antenna is being studied.

3.3. Thermal design and control

40K is required for mission component, e.g. cooling of infrared detector. In order to take full advantage of transformable spacecraft, passive cooling is employed and no refrigerator is mounted. And then, it is expected to eliminate the disturbance source, e.g. reaction wheel for conventional attitude control method. However, there is a constraint on panel configuration for passive cooling and such a constraint has influence on the power generation and attitude control stability. That means that the requirement for thermal system should be satisfied in consideration with requirements from other systems, and multipurpose optimization is required. However, it is not easy to carry out such an optimization in this phase and thermal analysis on simplified model and feasibility study is being performed for future practical optimization. Detail is given in the reference [4].

3.4. Panel structure

Requirements for the panel structure are as follows:

- Several common panel structures are prepared for different use of panels.
- Panel can deploy 0 deg. to 270 deg. (0 deg. is the angle when folded for launch)
- The structural mass of each panel is 6 kg or less.

Panel structure which satisfies above requirement is designed. 2 types of panels are prepared, one is the panel with component (Panel 1) and the other is without component (Panel 2). Panel consists of Honeycomb panels and CFRP ribs to improve strength (Figure 7). Mass of Panel 1 is 6.3 Kg. (Panel 2 is not designed yet and it is assumed that design condition and constraints are more easy than those of Panel 1). Each panel is connected to two hinges and motor drive system is installed to one of them (Figure 8). FEM analysis shows the first-order mode of Panel 1 is 48 Hz. The pins at the four corners for launch lock are fixed as boundary condition. The mass of 14kg is placed as dummy mass in the center of the panel. The results is obtained for conservative conditions, therefore the result is acceptable (Figure 9).

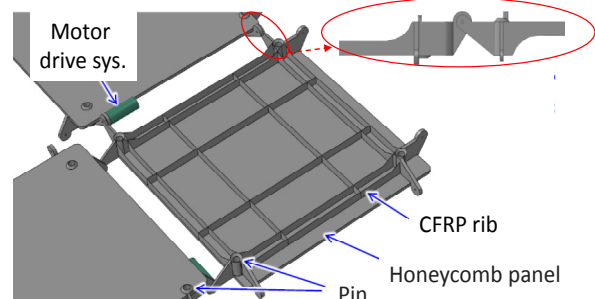


Figure 7. Panel structure.

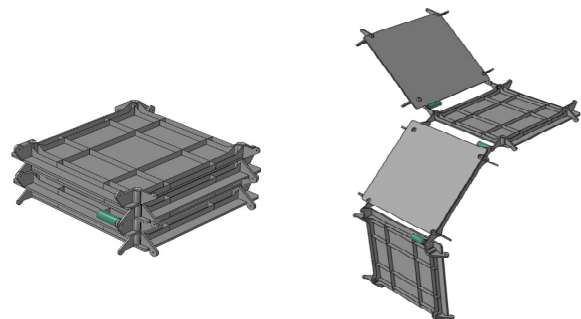


Figure 8. Deployment of panels.

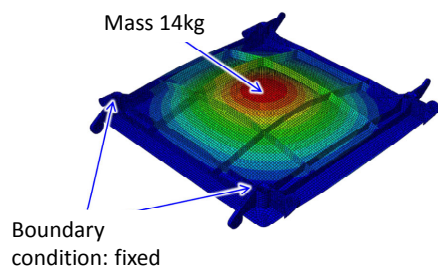


Figure 9. Natural frequency analysis.

3.5. Motor drive system

Requirements for the panel drive system are as follows:

- Bi-directional drive and repeatable motion.
- Redundant drive system for high reliability.
- Positioning accuracy is 1 mm at the panel end.
- Sufficient deployment speed and torque for effective operation.
- 5 years operation at appropriate temperature (under thermal control) in vacuum environment.

Panel drive system which satisfies above requirements is designed and three type of system is proposed (Figure 10) and each proposed type has following features in common. Two-motor-drive systems is employed and is capable of forward or reverse rotation for reliability. Modulated wave resolvers for high resolution angle measurement. 0.2 rad / sec deployment speed and 62 Nm output torque by the two motors ($31 \text{ Nm} \times 2 = 62 \text{ Nm}$). A thermal control system is also installed together with the panel drive system. Determination of the type and modification for embedding the system into the panel hinge is future tasks.

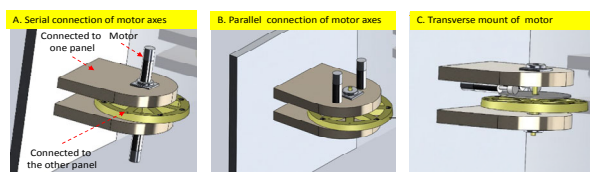


Figure 10. Panel structure.

4. Demonstration for fundamental study of panel deployment

In order to synthesize the lights from different mirror on one detector for interferometer, two optical path lengths have to be controlled and two control systems are used. The control system is divide to “Rough control” and “Precise control”. “Rough control” is the control of panel configuration by actuated joint between panels in order to

capture the light from star by same pixel of detector and required precision is the order of pixel size. “Precise control” is the control of light path by the actuator (piezoelectric element) in order to adjust the light path length for synthesize two lights and required precision is the order of wavelength. Figure 11 is a conceptual diagram of a control system that combines “Rough control” and “Precise control”.

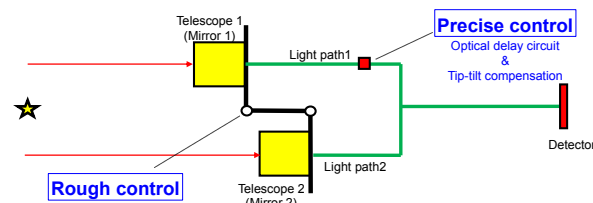


Figure 11 “Rough control” and “Precise control”

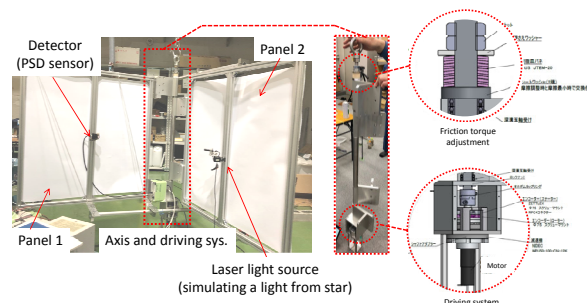


Figure 12 Experimental setup

First, a verification experiment is performed to evaluate the feasibility and performance of “Rough control”. Figure 12 shows the experimental setup. The two panels are connected by a joint that can be driven by an actuator. A rotation angle sensor (Modulated wave resolver) is connected to the rotation axis of the actuator, and the rotation angle is measured. In addition, a laser light source is mounted on one panel, simulating the light from the observation target. The other panel is equipped with a PSD sensor that simulates a detector and can determine the position of the laser spot incident on the detector with high accuracy. Control sequence of “Rough control” is as follows;

- (1) Panels are driven by feedback control with modulated wave resolvers (rotation angle sensor).
- (2) After the laser spot come into the detector, feedback control with the information from detector becomes active.
- (3) Panels are controlled so as to the laser spot converges to a predetermined position on the detector by the controller mentioned in (2). In this case, the predetermined position center of the detector

Results of “Rough control” experimental demonstration are shown in Figure 13 and 14, which are the time histories of panel deployment angle and command voltage to the motor drive system. As both results shows, control mode is changed around 21 s from control sequence (1) to (3). That means the laser spot comes into the PSD sensor at around 21 s, and feedback controller by the information of PSD sensor become active in order to make the laser spot to converge to the center of the PSD sensor. According to the results, it is confirmed that controller sequence can work as expected. However, the controller accuracy does not satisfied the required accuracy, and improvement of “Rough control”

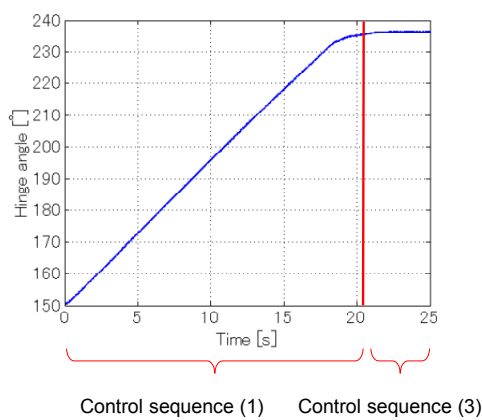


Figure 13. Time history of deployment angle to the motor drive system

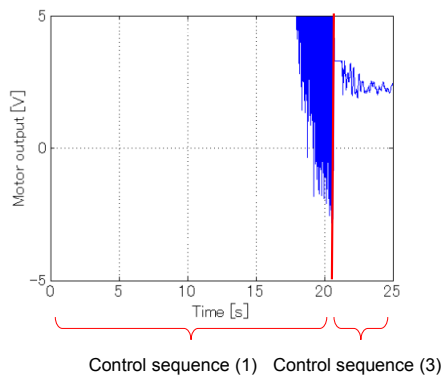


Figure 14. Time history of command voltage to the motor drive system

and experimental validation of “Precise control” should be carried out as future work.

5. Summary

As a science mission which can extract typical features of transformable spacecraft, inferred interferometer mission is proposed and panel configuration and system of the spacecraft is studied. Furthermore, each subsystems and key technologies are studied in order to realize the mission. As one of the important key technologies, experiment of panel deployment control is demonstrated and the feasibility and performance were investigated.

6. Reference

- [1] M Benisty, M., et al., "An integrated optics beam combiner for the second generation VLTI instruments", *Astronomy and Astrophysics*, Volume 498, Issue 2, pp.601-613 (2009).
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