Normal Paper ☒
Student Paper ☐
Young Engineer Paper ☐

Past Results and Future Missions of STARS Series Satellite

Nohmi. Masahiro[1]

[1] *Faculty of Engineering, Shizuoka University, 3-5-1 Johoku, naka-ku, Hamamatsu, 432-8561, Japan*

Abstract

STARS project interests in a space orbital elevator and space debris removal. The first satellite was "STARS" launched in 2009. It was a mother-daughter satellite, a tethered satellite, and also a robotic satellite (named tethered space robot). The second satellite was “STARS-II” launched in 2014. It was also a mother-daughter satellite, a tethered satellite, and a robotic satellite as well as STARS. However, tether was 300m long (5m long on STARS) and Electro Dynamic Tether (EDT). The third satellite was “STARS-C” deployed into orbit from the International Space Station (ISS) in 2016. It was a 2U CubeSat connected by 100m long Kevlar tether. The newest satellite “STARS-Me” was released from ISS in 2018. STARS-Me performs the first demonstration of orbital space elevator in the world. The project is now developing “STARS-E”, which is larger scale orbital space elevator than STARS-Me.

Keywords: Pico-satellite, Tether deployment, Robotics, Space elevator, Debris removal, Orbital experiment

Introduction

STARS (Space Tethered Autonomous Robotic Satellite) project purposes to evaluate and to verify a space mechanical control system by a university satellite, whose characteristics are: it consists of a mother and a daughter (and also grandchildren) satellites; it becomes a large scale space system using tether; and also robotic mechanical system performs dynamic motion on orbit. Tethered satellite systems (TSS) offer various attractive potential applications in space because of its lightness and compact storage [1]. Therefore, they have been an object of study for over two decades. Gemini-Agena program [2], Tethered Satellite System Project by U.S.A. and Italy [3] were performed for space verification experiments. On the other hand, ROTEX by DLR (Deutsches Zentrum für Luft- und Raumfahrt) [4], and Engineering Test Satellite #7 by JAXA (Japan Aerospace Exploration Agency) [5], etc. have been performed as a space verification experiment for a space robot. In order to accelerate development for these space systems such as tethered and robotic satellites, SATRS project was started in 2005. In recent years, the pico-satellites have been paid a bigger attention in the world [6]. They can be developed in short-term and by low cost. STARS series satellites in the SATRS project are kinds of them. The first satellite "STARS" was launched in 2009 [7]. It was a mother-daughter satellite, a tethered satellite, and also a robotic satellite. The second satellite “STARS-II” was launched in 2014 [9]. It was also a mother-daughter satellite, a tethered satellite, and a robotic satellite as well as STARS. However, tether was 300m long (5m long on STARS) and it was Electro Dynamic Tether (EDT). The third satellite “STARS-C” was released from the ISS (International Space Station) in 2016. It is a 2U Cubesat, those are connected by 100m long Kevlar tether. The newest satellite “STARS-Me” was released from the ISS in 2016 and under operation now. This is an extremely small space elevator. Also, the project has started to develop the next satellite “STARS-E” which is an orbital space elevator. Another future plan of the project is space debris removal as following scenario: a tethered space robot captures a space debris, and the captured debris is transferred to re-entry orbit by Lorentz force using EDT. This paper describes past mission results and future mission plans.

STARS (the 1st satellite launched in 2009)

STARS Outline

Fig. 1 shows the flight model of STARS, which was the first satellite in the STARS project, and whose nickname is "KUKAI." The left and the right figures show the daughter satellite which is a tethered space robot and the mother satellite which has a tether deployment mechanism, respectively, and they are connected by 5m Kevlar tether. Each satellite has two paddles for mounting solar cells, and also antennas named "Solar Paddle Antenna (SPA)," which is attached on the paddle edge. The scale and the mass, without deployable parts, are:

Fig. 1: STARS flight model

- Mother satellite: Mass 4.2 kg, Scale 160 x 160 x 253 mm,
- Daughter satellite: Mass 3.8 kg, Scale 160 x 160 x 158 mm.

Mission Result

STARS was successfully launched at 12:54 (JST) on January 23, 2009. The planned orbit is sun synchronous (Altitude: 666 km, Inclination: 98deg). It was planned to be separated from the rocket at 13:39:11 (JST), and deploy the SPA and transmit CW beacon, automatically. Though these sequences could not be monitored from the ground station, CW beacon transmitted from STARS was received by the ground station at 14:34 (mother) and 14:36 (daughter) on time. Hence, it can be said that the launch, the separation, and the paddle (with antenna) deployment were succeeded. FM packet uplink and downlink, taking camera photographs and their downlink, and inter satellite communication through Bluetooth, were confirmed successfully for the first 10 days.

After the initial check, the first trial for tether deployment was performed, however it was failed. The reason of this failure is considered that the reel launch lock was not released. As a result of the several launch lock release commands, the launch lock was released. However, tether was deployed for several centimetres only. The reason is considered that the compression mechanism (the pulley mechanism) for the deployment springs was troubled during the reel launch lock release.
Fig. 2 shows pictures of the mother satellite taken by the camera mounted on the daughter satellite. Pictures (a) and (b) were taken under the docking condition when tether was not deployed. It is noted from pictures (c) and (d) that the daughter satellite separated from the mother satellite, that is, tether was extended. Also, picture (e) shows the solar paddle of the mother satellite. As a result, it can be said that the tether deployment of several centimetres was succeeded.

Fig. 2: Actual pictures of the mother satellite taken from the daughter satellite

STARS-II (the 2nd satellite launched in 2014)

STARS-II Outline

STARS-II, whose nickname is "GENNAI," was launched on 28 February 2014, as one of piggy bag satellites by the H-IIA rocket. STARS-II as shown in fig. 3 consists of a mother satellite and a daughter satellite connected by Electro Dynamic Tether (EDT). The mother satellite deploys EDT having the daughter satellite at its end. The daughter satellite is a tethered space robot, and it has one arm whose end is attached to the EDT.

Fig. 3: STARS-II CG image

Operation Result

STARS-II was successfully launched at 3:37am (JST) on February 28, 2014. The planned orbital altitude is 390 km, and inclination is 65 deg. Also, it was planned to be separated from the rocket at 04:05am (JST) on the same day. During the 1st pass of 5:13am - 5:23am (JST) on the launch day, CW beacon from the daughter satellite was received at the Kagawa University ground station (JR5YDP). During the pass of 18:36 - 18:47am (JST) on the launch day, CW beacon from the mother satellite was received at another amateur radio station (JD1GDE) in Japan. From the CW beacon data, STARS-II was successfully separated from the rocket, and satellite system started.

Mission Result

Fig.4 shows orbital altitude of 7 piggy-bag satellites on H-IIA #25, derived from Two Line Element (TLE) delivered on Space Track Home Page. 7 piggy-bag satellites are two 50kg satellites, four CubeSats, and 10kg STARS-II. Theoretically, orbital lifetime of a 50kg satellite is longer, and that of a CubeSat (10cm cubic and 1kg mass) is shorter than that of STARS-II. Their results in fig. 4 shows proper lifetimes except STARS-II. If tether was not deployed, STARS-II lifetime would be longer than Cubesat even when the solar paddles were deployed as plotted by the red dotted line. However, as a result, the orbital lifetime of STARS-II was the shortest. It was 52days. Therefore, it is inferred from the orbital altitude change that tether was deployed. However, the main computer could not work well, then the detailed data of the tether deployment and EDT mission could not be obtained.

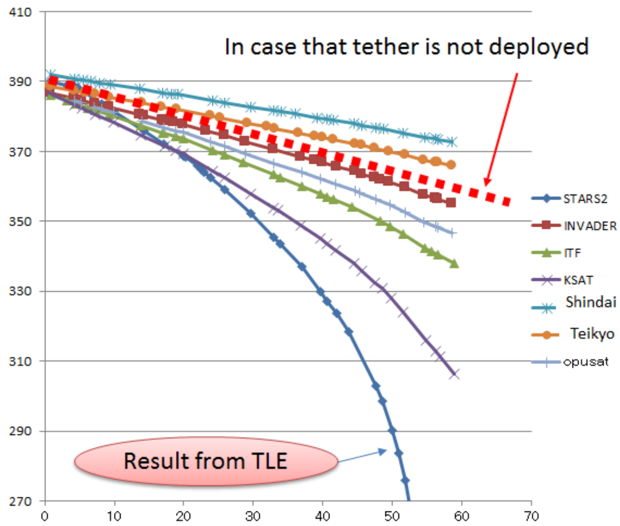

Fig. 4: Altitude change of STARS-II

STARS-C (launched in 2016)

The third satellite "STARS-C" has been developed. It is planned to be deployed into orbit from the ISS (International Space Station) in 2016. As shown in fig. 5, it is a 2U CubeSat, and one is a mother satellite and the other is a daughter satellite, respectively. They are connected by 100m long Kevlar tether. The primary purpose is to obtain basic tether deployment dynamics data, because it could not be obtained in the past missions though tether could be deployed.

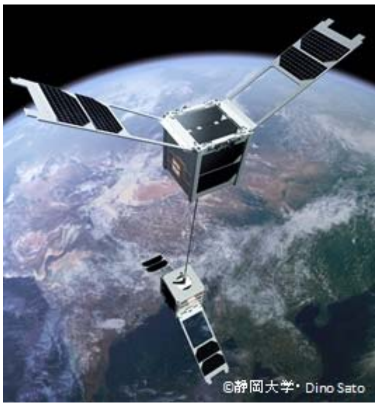

Fig. 5: STARS-C image

Fig. 6 shows the engineering model of STARS-C. Tether is stowed on the spool mounted on the mother satellite (see the left figure). Under docking condition, the tether is covered by the tether box attached on the daughter satellite (see the middle figure). Initial velocities of the mother and the daughter satellites for tether extension can be obtained from spring force. Then, the spool of the mother satellite pulled away from the tether covered with the tether box (see the left figure). And then, tether is extended as if a wool ball comes loose. Finally, tether extension is terminated by breaking force of the tether reel. Unfortunately, the communication system did not work well, and then telemetry data could not be received well. However, tether deployment was evaluated by the same method of STARS-II, though tether seemed to be extended shorter than expected.

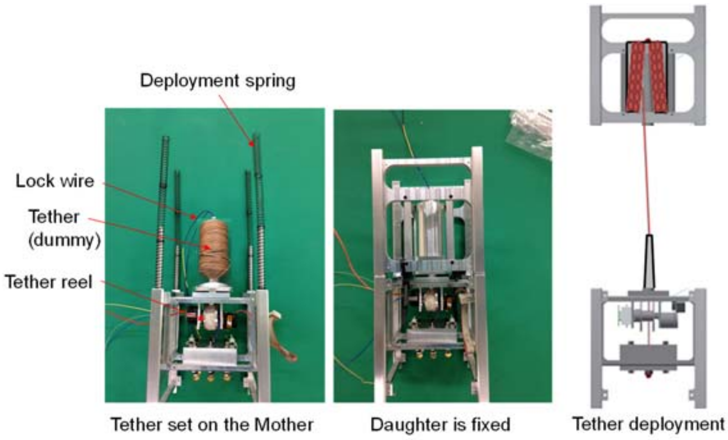

Fig. 6: Engineering model of STARS-C

STARS-Me (launched in 2018)

STARS-Me is an extremely small space elevator. It consists of two CubeSats having basic functions independently, and each satellite communicates with the ground station independently. The two CubeSats are connected by a rigid tape tether. One has a climber and approximately 3m tether, and the other has the tether deployment mechanism consisting of approximately 11m tether. The mission sequences are divided into three. (i) Two satellites are first secured together and put into orbit. Thereafter, they will be unlocked. Each satellite will simultaneously deploy their antenna. (ii) By the command from the ground station, two satellites will deploy the tether using motors. After acquiring each detailed data, the separation distance and the stability are analysed. (iii) The climber will traverse on the tether after being unlocked. The climber has a Bluetooth and communicates with the main satellite. From the data of the climber and each satellite, we analyse the behaviour of the mini elevator.

Fig. 7: STARS-Me image

STARS-Me was launched by the H-IIB rocket on September 23, 2018, and then the HTV vehicle carried it to the International Space Station (ISS). On October 6, 2018, STARS-Me was released from the ISS with other two CubeSats, SPATIUM-I and RSP-00. CW beacon from STARS-Me, which is automatically transmitted after releasing, was received by many amateur grand stations over the world. However, CW beacon from the CV satellite (Call Sign: JJ2YPM) could not be received up to now, though it from the HT satellite (Call Sign: JJ2YPL) is clear Morse signals. Then, we are trying operation of the HT satellite (JJ2YPL), and also investigation the causes of no signal reception from the CV satellite (JJ2YPM) using data of the HT satellite.

STARS-E (under development)

On July 2015, the STARS project started to develop an orbital elevator nano-satellite named "STARS-E." Fig. 8 shows an image of STARS-E. Its primary objective is to perform space elevator demonstration on orbit. Tether is planned to be extended for 2km, and a climber translates on the extended tether. STARS-E consists of mother and daughter satellites, and also one climber. After separating from a rocket, mother and daughter satellites will be separated, that is, tether will be extended. And then, a climber translates on the extended tether. It is very interesting from the viewpoint of mechanical dynamics to study experimental analysis for flexible long tether and climber translation on it in space environment (on orbit), that is a complicated environment for dynamics by gravity and centrifugal forces due to orbital motion.

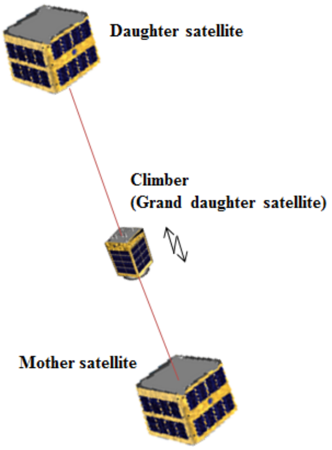

Fig. 8: STARS-E

In 2015, breadboard models of mother and daughter satellites, reel mechanism, and climber have been developed as shown in fig. 9. The reel mechanism for tether deployment has been developed in order to control tether extension actively using the gravity gradient force rather than passive control by spool mechanism as in STARS-II. Also, Kevlar is employed for tether, and its radius is less than 1mm in order to stow 2km long tether. Wheel mechanism has been employed for a climber based on the technologies accumulated in the space elevator challenges in Japan. Separation test for the mother and the daughter, and also vibration test is being experimented.


Fig. 9: STARS-E Breadboard model

STARS for Debris Removal (Future Plan)

Here proposes active debris removal by a future STARS satellite. Fig. 10 shows a novel mission sequence. Debris removal STARS consists of a mother and a daughter satellites, and the daughter is a tethered space robot. First, Electro Dynamic tether is extended along the gravity gradient direction. Second, a tethered space robot at the end of EDT approaches space debris and catches it. This approach is performed roughly by orbital transfer utilizing Laurent force of EDT, and precisely by tether extension and retrieval. Third, translating the tethered space robot having the debris toward the earth, here note that the whole system can be transferred to lower earth orbit by EDT Laurent force. Finally, the debris enters the atmosphere after releasing by the tethered space robot. Additionally, the whole system can be translated to next debris by the opposite Laurent force of EDT.

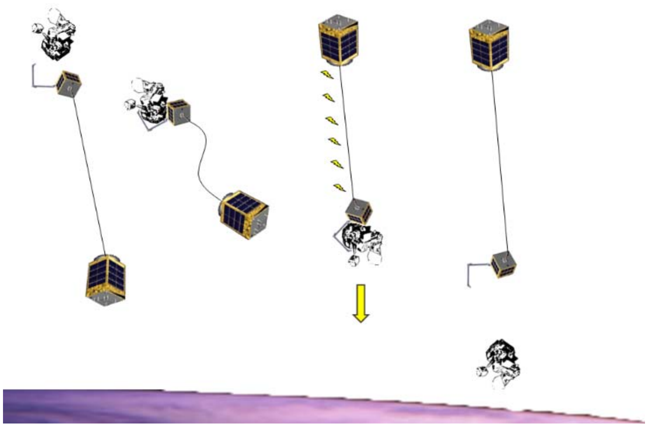
Fig. 10: STARS for space debris removal

Conclusion

This paper has described the past mission results, planned missions, and also future practical mission in the STARS (Space Tethered Autonomous Robotic Satellite) project. As for the past mission results, the first satellite "STARS", the second satellite “STARS-II,” and the third satellite “STARS-C” have been explained. As for planned missions, “STARS-Me” under operation and “STARS-E” under development have been introduced. These satellites characteristics are: it consists of a mother and a daughter (and also grandchildren) satellites; it becomes a large scale space system using tether; and also robotic mechanical system performs dynamic motion on orbit. Finally, future practical mission by STARS is described.

Acknowledgments
Here, note that this work was partially supported by JSPS KAKENHI, Grant Number 20246043 for STARS and STARS-II, 15K06599 for STARS-C, and 15H02224 for STARS-Me and STARS-E.

References

1. Rupp C. C. and Laue J. H., “Shuttle/tethered satellite system,” The Journal of the Astronautical Sciences, Vol. 26, No. 1 (1978), pp. 1-17.

2. Lang D. D. and Nolting R. R., “Operation with Tethered Space Vehicles,” Gemini Summary Conference, Houston, Texas, NASA SP-138 (1967-2), pp. 55-66.

3. Nolan M. B., et al., “Shuttle tethered satellite program,” 35th International Astronautical Congress, Lausanne, Switzerland, Paper No. 84-437 (1984-10).

4. Hirzinger G., Brunner B., Dietrich J. and Heindl J., “Sensor-based space robotics-ROTEX and its telerobotic features,” IEEE Transaction on Robotics and Automation, Vol. 9, No. 5, 1993, pp. 649-663.

5. Oda M., “Space Robot Experiments on NASDA's ETS-VII Satellite - Preliminary Overview of the Experiment Results-,” Proceedings of the 1999 IEEE International conference on Robotics and Automation, Detroit, MI, May 1999, pp.1390-1395.

6. Nakasuka, S., “Students' Challenges towards New Frontier -Enlarging Activities of UNISEC and Japanese Universities,” 26th International Symposium on Space Technology and Science 2008, Paper No. 2008-Keynote-01v, Hamamatsu, Japan, June 1-8, 2008.

7. M. Nohmi, J. Tanikawa, T. Hosoda, A. Uchida, “Evaluation Analysis of the S-520-25 Rocket Experiment for a Tethered Space Robot,” International Symposium on Artificial Intelligence, Robotics and Automation in Space, Torino, Italy, Setember 4th, 2012.

8. M. Nohmi, Y. Yamagiwa, and S. Kawamoto, “STARS-II Mission Plan for Future Debris Removal by A Tethered Space Robot,” 7th International Workshop on Satellite Constellations and Formation Flying, Lisbon, Portugal, March 13-15 (15), 2013.

9. M. Nohmi, “Initial Orbital Performance Result of Nano-Satellite STARS-II,” International Symposium on Artificial Intelligence, Robotics and Automation in Space, MacGill Univ., Montreal, Canada, June 17-19, 2014.