A STUDY OF AN ASTRONAUT SUPPORT ROBOT WITH A MORPHABLE-BEAM-BASED EXTENDABLE ARM

*Hiroki Nakanishi[1], Yusuke Ota[1], Mitsushige Oda[1], Saburo Matsunaga[1]

[1]*Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo, Japan,*

E-mail: nakanishi.h.af@m.titech.ac.jp

ABSTRACT

Astronaut support or substitute robots are often employed to reduce the workload of astronauts to provide increased safety and economical advantage. Fundamental functions of space activity are manipulation and locomotion. The authors focus a morphable beam which is used as flexible water pipe or a spine of desk light. The structure has a characteristic of pseudo-plastic deformation. This beam can be changed its shape by an applied force larger than a threshold. When the applied force is smaller than the threshold, the beam can maintain its shape. In this study, a novel robot system that the beam is used as a retractable arm or leg is investigated. The main body of this robot can move to any place by deploying and bending the beam appropriately. In this paper, the basic concept and feasibility study of the space robot system based on the morphable beam are discussed.

1 INTRODUCTION

In order to reduce the workload of astronauts, increase safety, and provide economic advantages, robots are used to support or take the place astronauts. Fundamental functions of space activity are manipulation and locomotion. Currently, the Space Station Robot Manipulator System (SSRMS) [1], the Special Purpose Dexterous Manipulator (SPDM), and the Japanese Experiment Module Remote Manipulator System (JEMRMS) [2] are working on the International Space Station (ISS). They provide manipulation and inspection of extravehicular objects. Furthermore, the SSRMS manipulates an astronaut as a transportation device around the ISS. These robot systems are based on a serial link manipulator. They have long links to obtain large working space. Therefore, when these robots are not working, large storage space is required. In order to satisfy both large working space and small storage space, the Robot Experiment on JEM (REX-J) mission demonstrated extendable robot arm and locomotion with retractable tethers [3]. Figure 1 shows the concept of the tether-based locomotion. The tether has a capability of long extension and roll-up. However, for fixing the robot, at least three tethers have to be controlled without slack.

The authors focus a morphable beam (Fig. 2) which is used as flexible water pipe or a spine of desk light. The structure has a characteristic of pseudo-plastic deformation. This beam can be changed its shape by an applied force larger than a threshold. When the applied force is smaller than the threshold, the beam can maintain its shape. Matsunaga et al. proposed a morphable beam deployment system for a monitoring camera of a satellite (Fig. 3) [4]. Yoshikawa et al. proposed a morphable beam shaper which can move on a morphable beam and bend the beam at any position (Fig. 4) [5]. These studies achieved making morphable beams any length and shape. However, it is difficult to control the extension path of morphable beam with these systems. When the shapers in these systems bend the beam, the end tip of the beam is swung.

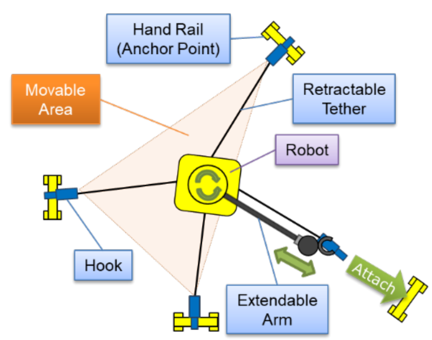

Figure 1: Tether-based locomotion

Figure 2: Morphable beam.

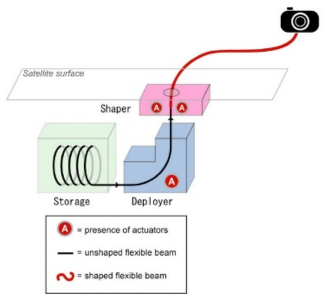

Figure 3: Morphable Beam Device (MBD) [4]

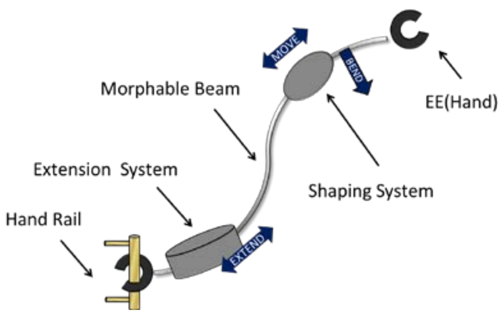

Figure 4: Moving Beam Shaper System [5]

In this study, a novel robot system based on a morphable beam that the beam is used as a retractable arm or leg is investigated. The proposed system has a beam shaper and a reel mechanism on the end tip of the beam. The system deploys the beam and moves by the reactive force from the beam. This method can control the extension path of the beam. When the main body of a mobile robot is placed on the end tip of the beam, the robot can move to any place within the reach of the beam like the tether-based robot of REX-J. However, in case of the morphable beam, only one beam is enough to support the main body. This system cannot be used only the mobile robot, but also many purpose. In this paper, the basic concept and feasibility study of the space robot system based on the morphable beam are discussed.

2 EXTENDABLE ARM SYSTEM BASED ON MORPHABLE BEAM

2.1 Basic Concept

The basic concept of proposed system is shown in Fig. 5. This system consists of a main body, morphable beam and end effectors for fixing the system to a space structure. The main body of the system includes a beam shaper, deployment / storage mechanism (DSM) which has a reel and sprocket to windup and drive the beam, and the other robot module for a mission. The example of the motion of the robot is shown in Fig. 6. The beam shaper and DSM is placed on the end tip of the beam. The end tip of the morphable beam can move to any position by deploying and bending the beam appropriately.

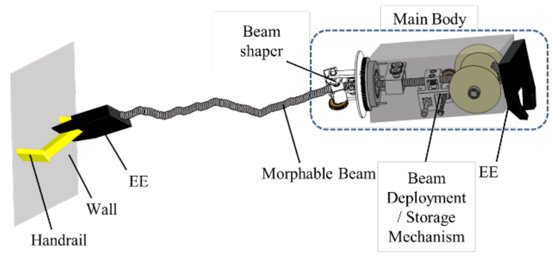

Figure 5: Basic concept of proposed morphable-beam based Robot.

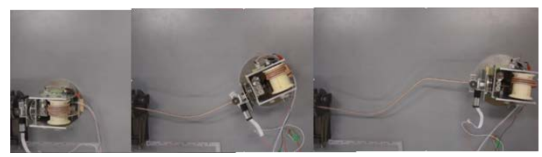

Figure 6: Example of the extension motion.

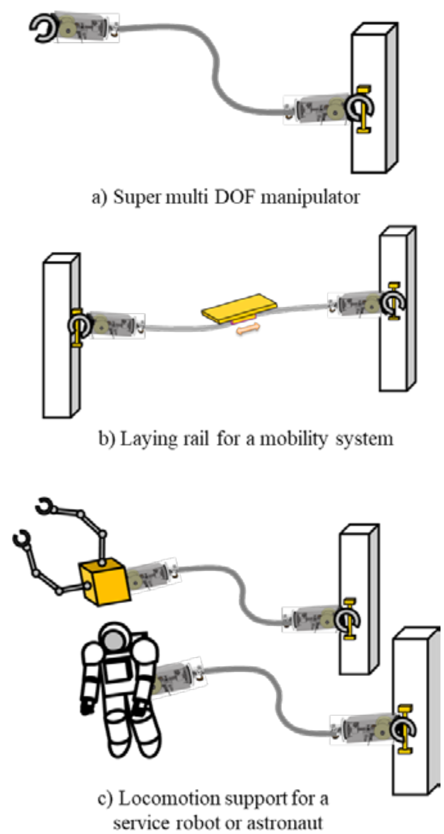

Figure 7: Application example of morphable-beam based Robot.

2.2 Applications of the system

Various applications of this system are expected. Figure 7 shows candidates of the applications. When the main body is defined as a robot hand, the robot system is an extendable super multi-DOF robot manipulator (Fig.7a). In case that the main bodies placed on the both side of the end tip of the beam, the manipulator realize an inchworm locomotion with handrails on the space structure like the SSRMS on ISS. After the manipulator extends and grasps another handrail or grapple fixture, the beam can be used as a rail for a mobility system (Fig. 7b). When an astronaut or a service robot attach to the main body, this system become a long leg and safety tether. They can move in three dimensional space safely without any thruster systems.

3 DEFORMATION CHARACTERISTICS OF MORPHABLE BEAM

3.1 Structure of Morphable Beam

In order to control the shape of the morphable beam, the deformation characteristics of the beam is necessary. Morphable beams are deformed by outer force over a threshold. When the outer force is under the threshold, the beam preserves its shape. The mechanism of the beam to realize above characteristics can be divided into some types. In this study, stand tube and casing carcass tube are used. Stand tube is made with a combination of round spring steel and triangle rods in metal materials. Casing carcass tube is made from a continues metal strip which is locked into position by one overlapping joint. Figures 8 and 9 show image of each morphable beam respectively.

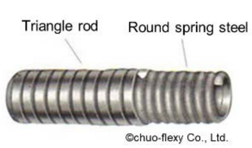

Figure 8: Stand tube.

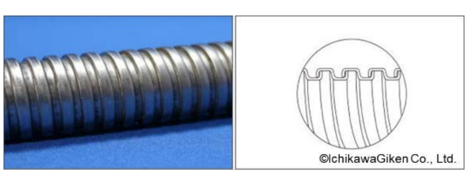

Figure 9: Casing carcass tube.

3.2 Deformation Characteristics of Morphable Beam

The deformation characteristics are very complicated because of its structure and inner frictions. However, the characteristics can be approximated by a hardening plastic material [6]. The authors verified the deformation characteristics of morphable beams used in the proposed system with three-point bend test. The specifications of the beams are shown in Table 1. The test results are shown in Figs. 10-12. Regardless of the structures, each result shows that these beam have a hardening plastic material.

Table 1: Spec of morphable beams.

	Stand tube (Small)	Stand tube (Large)	Casing tube
Inside diameter [mm]	3.0 ± 0.2	5.3	8.0 ± 0.2
Outside diameter [mm]	5.3 ± 0.2	11	10.0 ± 0.2
Material	Stenress and Copper	Hard steel	Stenless

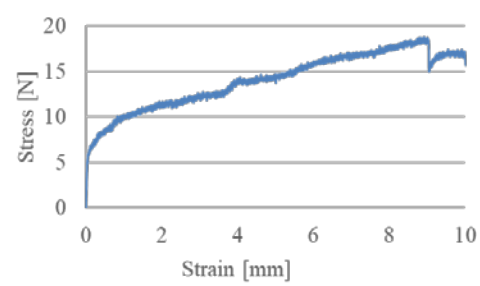

Figure 10: Stress-strain diagram (Stand tube (small)).

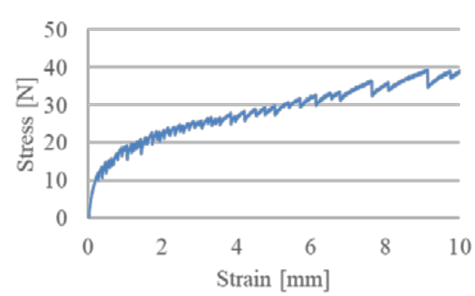

Figure 11: Stress-strain diagram (Stand tube (large)).

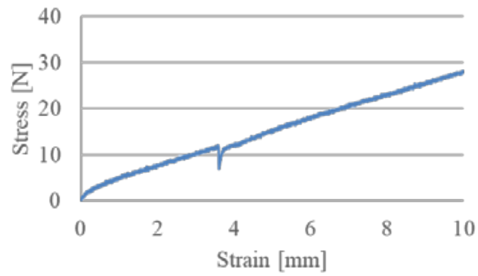

Figure 12: Stress-strain diagram (Casing carcass tube).

Table 2: Result of Stress-strain test.

	Stand tube (Small)	Stand tube (Large)	Casing tube
Bend elastic constant [GPa]	1.55	2.39	0.667
yield moment [Nm]	0.0561	0.831	0.123

4 DEVELOPMENT OF BEAM SHAPER AND DEPLOYMENT / STORAGE MECHANISM

Beam shaper is one of the most important mechanism in the proposed system. Pushing-through bending and push bending is major method of the beam shaping. In the development of the previous works (Fig. 3 and 4), the shaper was designed. The basic concepts of beam shaper in MBD [4] and moving beam shaper [5] are shown in Figs. 13 and 14. The MBD's beam shaper realized a pushing-through bending with simple mechanism. However, the beam under shaping makes S-curve before the output of the shaper. It makes large resistance for the extension. The moving beam shaper employed a push bending method. This mechanism can take off from the beam and make the locomotion on the beam easy. However, the pushing-through bending is impossible. In the proposed system requires the pushing-through bending and low resistance for beam extension. Our new design of the beam shaper is shown in Fig. 15. In this system, the drive axis of the shaper is offset and realize the one-point contact bending not to make the beam S-curve.

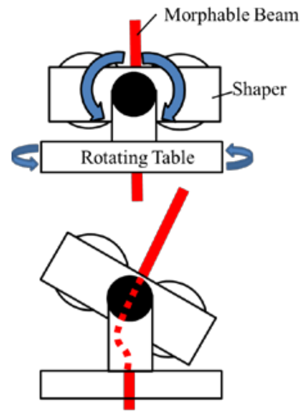

Figure 13: Beam shaper of MBD

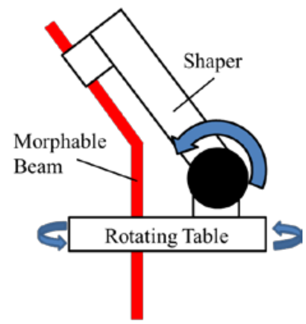

Figure 14: Beam shaper of Moving Beam Shaper

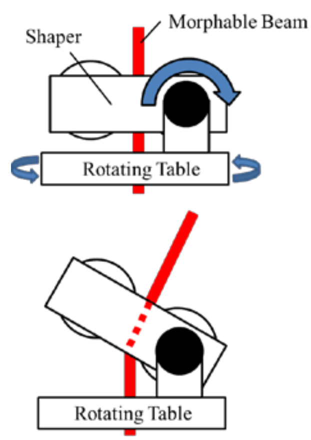

Figure 15: Proposed Beam shaper

5 DYNAMICS OF MORPHABLE-BEAM-BASED ROBOT

5.1 Dynamics Model

In order to move the main body (end tip of the beam) appropriately, the dynamics of the system, especially reaction force of the motion of main body to the morphable beam should be clarified. Here, the main body is assumed as a mass point. The path of the beam is defined as lines and arcs. The motion of the mass point on the beam is shown in Fig. 15. $\boldsymbol{t}$ and $\boldsymbol{n}$ are tangential and normal unit direction vectors respectively. s is the position on the beam. The velocity and acceleration of the mass point $\boldsymbol{v}$ and $\boldsymbol{a}$ are given as follows:

$$\boldsymbol{v} = \boldsymbol{t}\frac{ds}{dt} \tag{1}$$

$$\boldsymbol{a} = \frac{dv}{dt}\boldsymbol{t} + \frac{v^2}{\rho}\boldsymbol{n} \tag{2}$$

where ρ is the radius of curvature. The reaction force of the main body to the beam is modeled as Fig. 16. The applied reaction force $\boldsymbol{F_r}$ and moment $\boldsymbol{M_r}$ to point P_n are given as follows:

$$\boldsymbol{F_r} = -m\boldsymbol{a} \tag{3}$$

$$\boldsymbol{M_r} = (\boldsymbol{P_{EE}} - \boldsymbol{P_n}) \times (-m\boldsymbol{a}) \tag{4}$$

When the beam shaper bends the morphable beam, the reaction of the bending moment $\boldsymbol{M}$ is added as Eq. (5).

$$\boldsymbol{M_r} = (\boldsymbol{P_{EE}} - \boldsymbol{P_n}) \times (-m\boldsymbol{a}) + \boldsymbol{M} \tag{5}$$

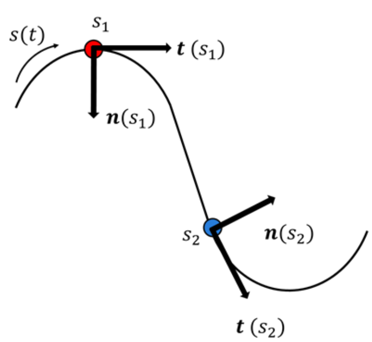

Figure 15: Motion of the mass point on the path of morphable beam

5.1 Beam Shaper Mechanism and Bending Moment

The reaction moment is generated in the beam shaper. The static force model of the proposed beam shaper is shown in Fig. 17. In this case, the bending moment by the shaper is formulated as:

$$M = F\cos\theta + F_p \cdot u. \tag{6}$$

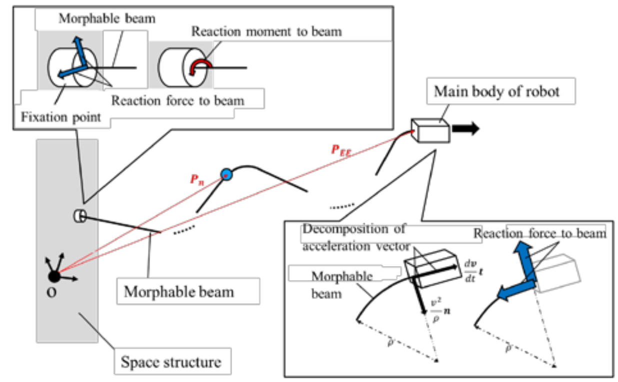

Figure 16: Reaction forces of the main body motion.

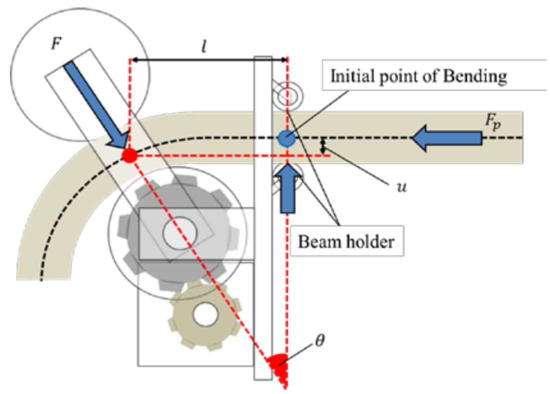

Figure 17: Beam shaper model.

6 EXPERIMENT

In order to verify the design of the proposed system, the author developed a BBM of the morphable-beam-based robot arm. The BBM and experimental setup is shown in Fig. 18. The main body of the system is floating on a precision surface with air. The body also equipped an acceleration meter. The root of the morphable beam is fixed to a force / torque sensor on the wall. Using this setup, some basic motions are verified.

6.1 Linear Motion

At first, a linear motion was applied to the system. Figure 19 shows an image of the motion.

6.2 Push Bending Motion

The push bending motion was verified. In this experiment, the shaper could bend the beam to 45deg. When the bending angle was increased, a spring back after unloading of bending force was increased. This result matches the deformation characteristics of the morphable beam. The result of the bending angle of the beam with the shaper is shown in Table 3.

6.3 Pushing-through Bending Motion

The pushing-through bending motion was verified. Figure 19 shows the result of the motion. A bending and moving are realized simultaneously.

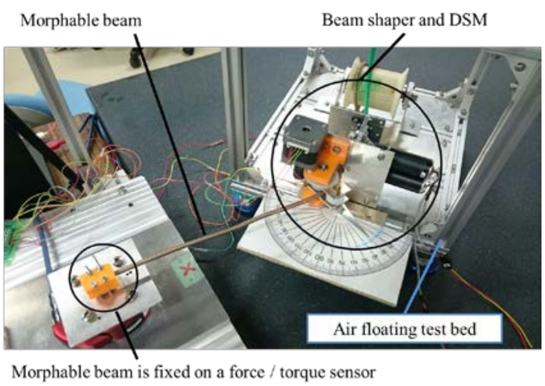

Figure 18: Experimental setup.

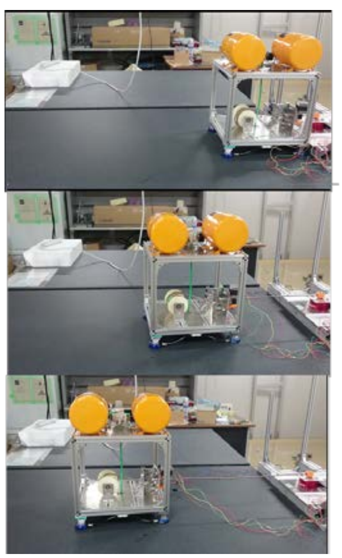

Figure 19: Linear motion.

Table 3: Result of beam bending.

Shaper angle	11°	22°	33°	44°	55°	66°
Beam angle	0°	6°	18.5°	29°	39°	48.5°
Beam angle after unloading	0°	5.5°	18.5°	29°	34°	45°

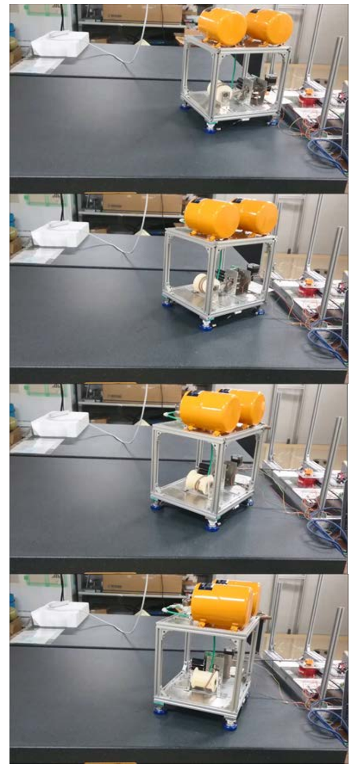

Figure 19: Pushing-through bending motion.

7 CONCLUSION

In this paper, a novel robot system based on a morphable beam that the beam is used as a retractable arm or leg was discussed. The basic concept, dynamics, fundamental experiments with BBM model are described. The proposed system has a beam shaper and a reel mechanism on the end tip of the beam. This method realized a small storage and long reach locomotion like the tether-based robot of REX-J with only one beam.

Acknowledgement

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References

[1] P.K. Nguyen, P.C. Hughes (1994), Teleoperation: From the Space Shuttle to the Space Station, *AIAA Progress in Aeronautics & Astronautics* Vol.161, pp.353-410

[2] Sato N, Wakabayashi Y (2001), JEMRMS Design Features and Topics from Testing, *Proc, of i-SAIRAS 2001*

[3] Oda M, et al. (2009) Proposal of a Tethered Space Walking Robot – REX-J: Robot Experiment on JEM –, *Trans. of the Japan Society for Aeronautical and Space Sciences, Space Technology Japan,* Vol.7, No.ists26, pp. Td7-Td12.

[4] Matsunaga S, Iljic T, Tanaka Y, Miura Y (2009) Morphable Beam Device and Beam Shape Generation Algorithm, *Trans. JSASS Space Tech. Japan*, 7 (ists26), pp.Pd_125-Pd_130.
[5] Yoshikawa K, Yuichiro T, Naoki U, Nakanishi H, Oda M (2016) Test Results of Key Mechanical Functions for a Super Multi-DoF and Extendable Space Robotic Arm, *Trans. JSASS Space Tech. Japan*, 14 (ists30), pp.Pk_55-Pk_63.
[6] Covis A. Marins, Celso P. Pesce, Jose A. P. Aranha (2003) Structural Behavior of Flexible Pipe Carcass During Launching, *Proc. of 22nd International Conference on Offshore Mechanics and Artic Engineering*, Vol. 2, pp. 537-546.