Tether-based Robot Locomotion Experiments in REX-J mission

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Abstract

Locomotion is an important factor of astronaut support robots for construction, repair, or inspection. The requirements for it are long reach, smallness, and lightness. Tethers are good candidate because they can make long reach and are very light. They are also compact when they are reeled up. The authors have proposed a re-configurable tether-based locomotion method. In the concept, the robot attaches / detaches its tethers to / from handrails on spacecrafts and locomotes by controlling the length and tension of the tethers. From Aug. 2012 to May 2013, JAXA conducted the REX-J (Robot Experiment on JEM) mission which is the demonstration experiment of the proposed method on the International Space Station. This paper describes the results of the locomotion experiments.

1 Introduction

The importance of space infrastructures is increasing year by year. Currently the construction and maintenance of such infrastructures are done by EVA (External Vehicular Activity) of astronauts. However, these operations are dangerous and expensive. Therefore, there are great hopes that unmanned space robots which support or substitute the astronauts.

In order to realize such astronaut support robot, one of the most important issues is the locomotion technology. The locomotion mechanism is required long-reach, lightweight, and robustness. The apprication of tethers is one of the good candidates for such locomotion system. Tethers are good candidate because they can make long reach and are very light. They are also compact when they are reeled up. The robot suspended by three or more tethers anchored around the work area. Its position can be controlled by controlling the length of the tethers. The concept is shown in Fig. 1. Nowadays, the tether-based locomotion is used in movable cameras for football games

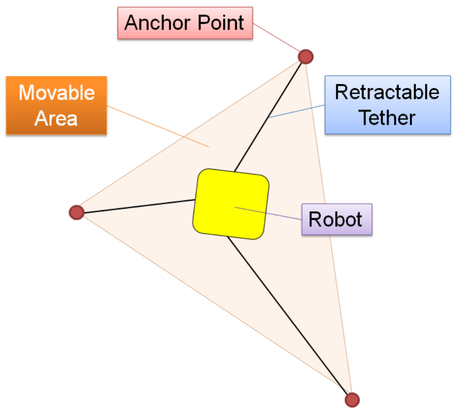

Figure 1. Tether-based locomotion concept

[1]. NASA and McDonnell Douglas demonstrated the Charlotte^{TM} IVA (Intra Vehicular Activity) support robot in the STS-63 Space Shuttle mission [3]. It moved on the experiment panel in the SpaceHub by using eight tethers In these systems, end tips of the tethers are fixed and the movable area is limited. Reconfiguration of the anchor point of the tethers is required to work on the larger scale structure like a space solar power satellite (SSPS) .

The authors have developed a novel locomotion system for an astronaut support robot using an extendable robot arm and several tethers [2]. The robot is supported by three or four tethers attached to the handrails for EVA on a space structure such as the ISS. By controlling the length of the tethers, the robot can move within a triangular plane or a tetrahedron space as defined by the anchor points of the tethers. The anchor point can be replaced by an extendable robot arm based on a STEM (Storable Tubular Extendible Member) [4] used in an extend mechanism of a satellite antenna. That means the robot can redefine its movable area/space itself and reach any place where the handrails installed. The concept image of the self-reconfigurable tether-based locomotion is shown in Fig. 2.

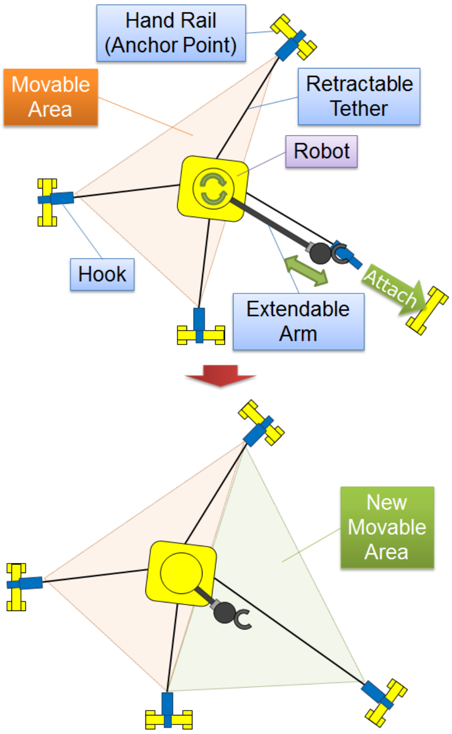

Figure 2. Self-reconfigurable tether-based locomotion concept

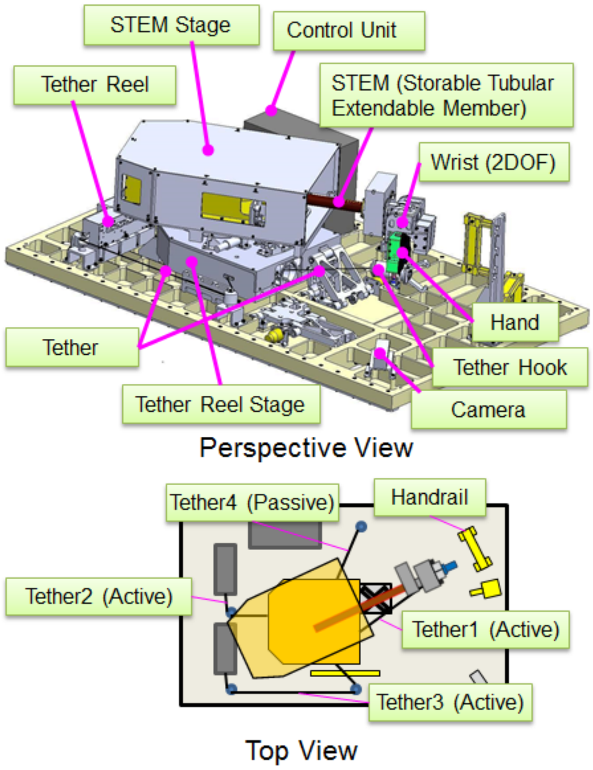

Figure 3. Experimental setup of REX-J

To evaluate the utility and dynamics of the tether-based locomotion robot, an engineering test robot mission "REX-J (Robot Experiment on JEM)" was conducted on the International Space Station from Aug. 2012 to May 2013. In this experiment, the attachment of the tether's end-tip to a handrail and robot locomotion using three tethers in micro-gravity environment are carried out.

When control tethers for robot locomotion, maintaining of tether tension and position (tether length) control are important. In case of the system on the ground, the tension maintaining is guaranteed by the gravity. However, the space robot requires controls of position and tension simultaneously. In the REX-J mission, some tether control methods were applied for the robot locomotion. This paper presents the control methods for tether-based locomotion and the results of the experiments in REX-J mission. The motion and position accuracy of the locomotion under each control methods are evaluated.

2 REX-J Mission

2.1 Overview

The dynamics of the tether-based locomotion in the space is different from the ones on the ground in that the gravity prevents the tethers from the slackness. Thus, the experiment in a micro-gravity environment is required to evaluate the utility of the tether-based locomotion for space robot. Though there are some micro-gravity emulation methods, the elimination of the gravity influence for all part of tethers during enough time is very difficult.

REX-J is a demonstration experiment for the tether based locomotion in the International Space Station (ISS). The experimental system was launched by H-IIB / HTV-3 on July 21, 2012. The main purposes of the mission are as follows:

- Evaluation of utility and characteristics of extendable arm.
- Attachment of tether end to handrail with extendable arm.
- Robot locomotion using tethers.

2.2 Experimental Setup

The REX-J experimental setup consists of a base plate, tether locomotive robot, tether reels, camera, hand rails, etc. The robot includes a tether reel unit and extendable arm. The overview of the REX-J system is shown in Fig. 3. The size of whole system is 1150 [mm] $\times$ 700 [mm] $\times$ 365 [mm], 83 [kg]. The robot size is 460 [mm] *times* 300 [mm] $\times$ 250 [mm], 27 [kg].

In the REX-J mission, STEM Robot Arm (SRA) is used as an extendable arm. The SRA consists of a CFRP

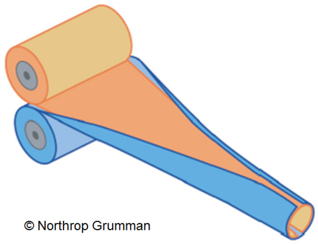

Figure 4. Bi-STEM mechanism

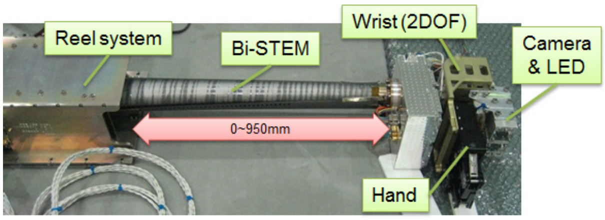

Figure 5. Overview of SRA

Bi-STEM boom, hand and wrist joints (2 DOF). The Bi-STEM (Storable Tubular Extensible Member) consists of dual reeled strips. The strips become curled into a tube and increase its stiffness while it is reeled out [4]. (Fig. 4 [4]) The Size of the reel system is 300 [mm] $\times$ 160 [mm] $\times$ 100 [mm]. The maximum length of the STEM part is 950 [mm]. An overview of the SRA flight model for the REX-J mission is shown in Fig. 5.

The robot equips three active tethers and one passive tether. The active ones are for locomotion and the passive one is for safety. The end tip of an active tether has a hook mechanism to attach to a handrail. The hook opens while it is grasped by hand. In the REX-J mission, the SRA has demonstrated grasping the hook, carry and attach it to a handrail successfully. Fig. 6 is mission pictures at the tether installation.

After success of the tether attachment to the handrail, the experiments of tether-based locotomotion was carried out. The specifications of the tether reel system are shown in Table 1. The robot moved on the base plate by controlling the tethers 1~3 in Fig. 3 total 54 times. Fig. 7 is mission pictures at the locomotion.

3 Tether-based Locomotion Experiment

3.1 Control Sequence

The important issues of the tether-based locomotion in the space are as follows:

- The length of tethers should be control adequately to move the body to the destination.
- The slack of the tethers should be prevented.
- The out-of-plane vibration should be prevented or convergenced immediately.

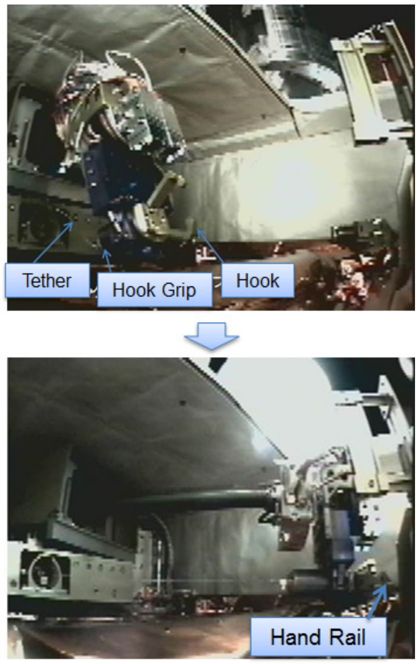

Figure 6. Tether installation to handrail

Table 1. Specifications of the tether reel system

Size	L199, W107, H60 [mm]
Weight	0.9 [kg]
Motor	Maxon EC-max16 brushless DC motor
Winding Speed	Max 7.0 [mm/s]
Control Method	Position or Current (Torque)
Resolution	0.05 [deg] (0.014 [mm]), 20 [mA]
Tether	ϕ1.2 [mm], Technora®Para-aramid

In the REX-J mission, the adequate tether length at the destination was calculated by a statics analysis [5]. This is an inverse linear problem and is solved by the iterative calculation shown in Fig. 8. These calcurations were executed by the operator on the ground because of the computational capability of the robot. The obtained each lengths of the tethers were uploaded to the robot.

The slackness of tethers is compensated by the gravity on the ground. However, in the micro-gravity environment, the one have to be prevented by the control. If the tether lengths are perfectly controlled anywhere, the slack does not occur. However, the adequate length is non-linearly changed even in case of a linear locomotion. The length control of the tether reel of the REX-J robot is based on a PTP at a constant velocity. Thus, even if the slack is not occur at the destination, it is expected in

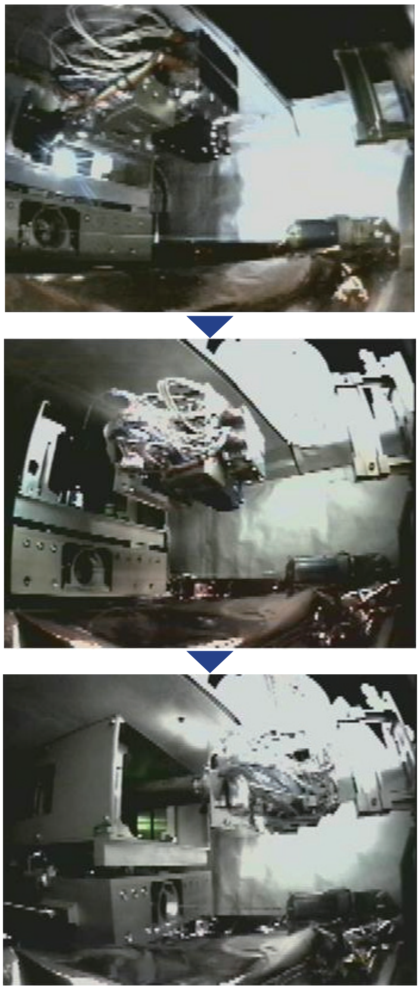

Figure 7. Tether-based locomotion

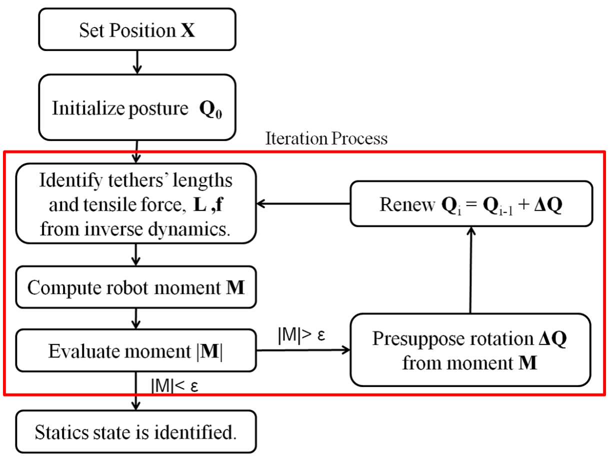

Figure 8. Algorithm for statics analysis

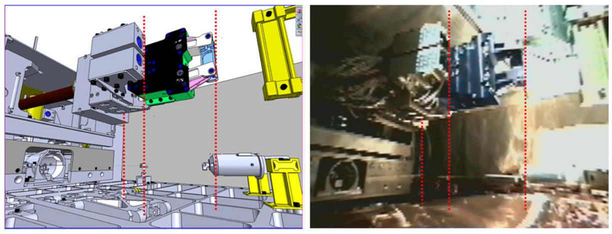

Figure 9. Comparison between CAD (left) and camera data (right)

the path. In the REX-J mission, basically the tether in the motion direction is wound up with a constant force. The other tethers are controlled their lengths to get to the destination.

3.2 Experiment

In the mission, the following experiments were conducted:

- Position estimation
- Single locomotion
- Repeat locomotion
- High-speed locomotion (Advanced)
- Length control of all tethers (Advanced)
- Length control of single tether (Advanced)

4 Experimental Result

4.1 Position Estimation

In this mission, the robot position was estimated from the rotation data of the reel motor in the telemetry. Before the locomotion experiments, the accuracy of the position estimation was evaluated. The photo taken by the camera (see Fig. 3) was compared with the CAD data (Fig. 9). The result showed that the etimation has enough accuracy.

4.2 Single Locomotion

The accuracy of the locomotion path when the robot was given a destination was evaluated. The image of the locomoiton and the coordinate axis are shown in Fig. 10. The result of the motion is shown in Fig. 11. The red line in the figure is the predicted locomotion path by the static analysis in section 3.1. The blue line is the locomotion path calculated from the telemetry. The motion accuracy was about 1 [mm]. The cause of the error is considered as the position error of the tether hook on the handrail.

4.3 Repeat Locomotion

The position accuracy of the repeat motion was evaluated. In that case, the position errors accumulate because the input for control of the reel motor is difference values. In the experiment, the three destinations were given. The

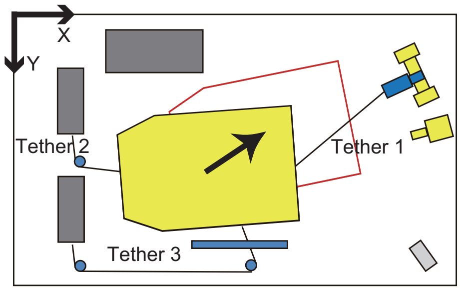

Figure 10. Single locomotion experiment

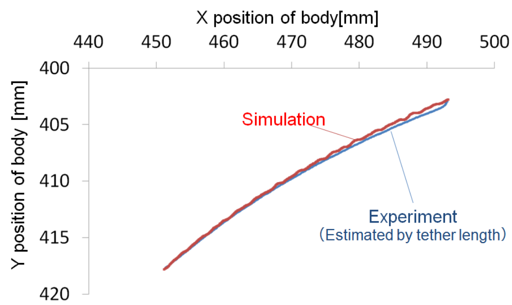

Figure 11. Result of single locomotion

robot repeated the triangle locomotion. The locomotion image is shown in Fig. 12. The result of the locomotion is shown in Fig. 13. The red squares mean the destinations and the blue circles mean the result of the locomotion. The numbers shows the order of the locomotion. The errors accumulated as repeat the motion. After six motions, the maximum error was about 5%. The causes of the errors are considered as not only the hook position error but also the winding error of the tether controlled with constant force. If the tether is wound up faster than the others with length control, the amount of the winding up of the tether with constant force control is larger than the preliminary analysis. Then, the tether with length controls cannot reach the adequate length.

In order to reduce the errors, the compensation analysis was conducted after each locomotion and change the each inputs. The result of this case is shown in Fig. 14. The error was reduced to about 1%.

4.4 High Speed Locomotion

In the locomotion experiments above, the reel speed were suppressed for safety (under 2 [mm/s]). This experiment was a challenge for the high velocity locomotion. The reel speed was set 5 [mm/s] and the position accuracy and vibration are evaluated. The result is shown in Fig. 15. The position accuracy did not get worse and the major vibration was not measured.

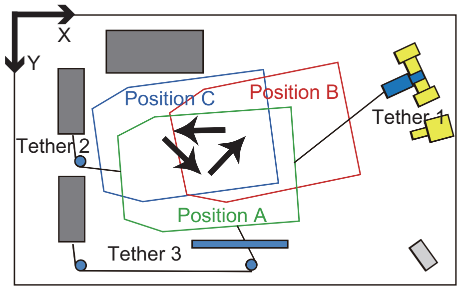

Figure 12. Repeat locomotion experiment

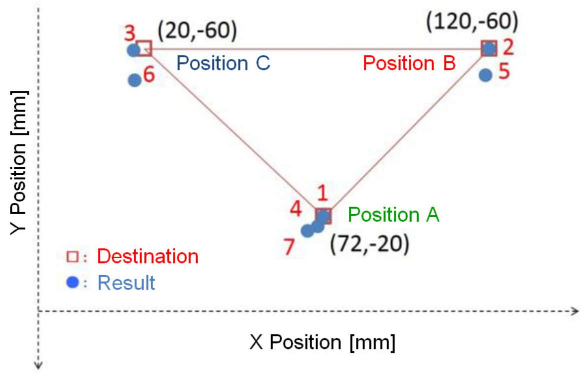

Figure 13. Result of repeat locomotion

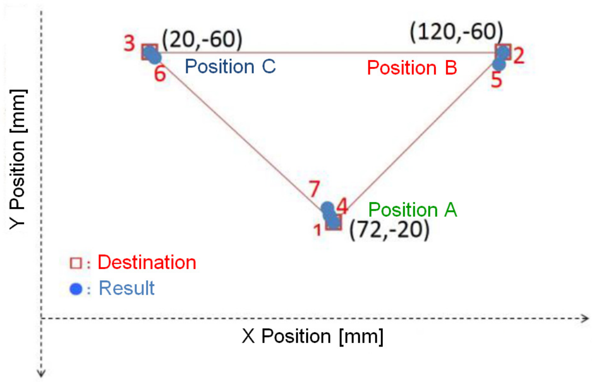

Figure 14. Result of repeat locomotion (with compensation)

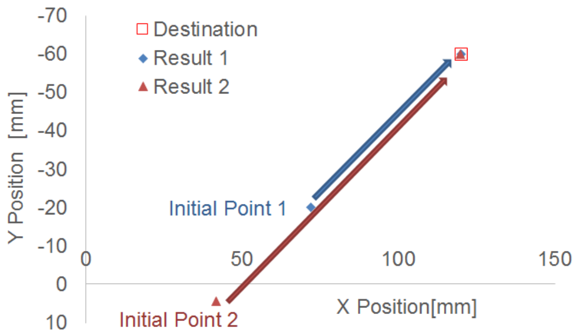

Figure 15. Result of high-speed locomotion

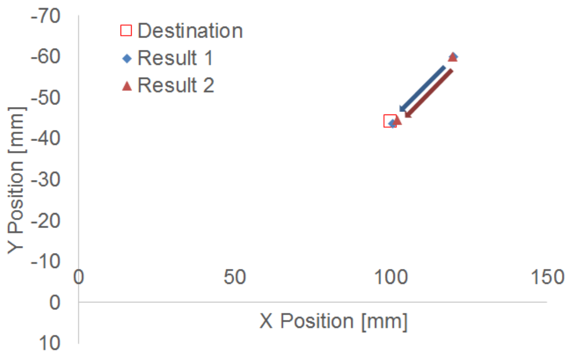

Figure 16. Result of all tethers with length control

4.5 All Tethers with Length Control

One of the reasons why the position error occurs is winding error of the tether with the constant force. On the other hand, if all tethers controlled with the length, the slackness can occur on the motion path. In this experiment, all tethers were controlled with the length to improve the position accuracy on the destination. The slackness was prevent by reducing the distance of the locomotion. The result is shown in Fig. 16. Unfortunately, the improvement of the position accuracy was not observed. The reason was that the statement at the initial point was different each other. Though the positions of them are same, the length and tension of the tether controlled with the constant force in before locomotion. The amount of the reel rotation was perfectly same.

4.6 Single Tethers with Length Control

If the locomotion does not need the position accuracy very much, the simple control method is better. In this experiment, the length control was given to only a tether in the opposite direction of the locomotion. The other tethers in the locomotion direction are controlled with constant force. The result is shown in Fig. 17. The motion accuracy and variability got worse. The maximum error

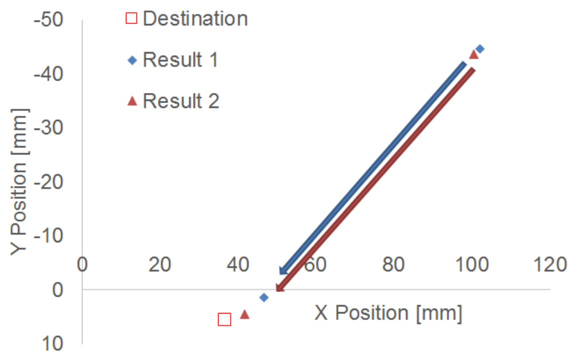

Figure 17. Result of single tether with length control

was about 10 [mm]. The motion stability was not different from the other experiment.

5 Conclusions

This paper presented the control methods for tether-based locomotion and the results of the experiments in REX-J mission. The motion and position accuracy of the locomotion under each control methods were evaluated. All the locomotion challenge was successful. The position accuracy and stability was good. These results indicate the usefulness of the tether-based locomotion for space robot.

Acknowledgment

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