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Ground Experiment Evaluations of Reconfigurable Brachiating Space Robot RBR

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Abstract

We have developed the system of "Reconfigurable Brachiating Space Robot (RBR)". This space robot is designed based upon the modularized design, the cable reduction and the distributed control technique. This robot is capable of moving over the "KIBO" (Japanese Experimental Module) of the International Space Station in a brachiating manner and also capable of arm reconfiguration according to the various task requirements. This paper presents the capabilities of the RBR, mainly, the capability of grasping the handrails and the reconfiguration mechanism. We conduct experiments for evaluation of brachiation and reconfiguration of the RBR, and explain the result of these experiments.

1. Introduction

It is important to develop space robots supporting space activities, such as external vehicular activities (EVA) and internal vehicular activities (IVA) for future space utilizations. Especially, EVA supporting robot is important to reduce operation time, because it takes much time for the preparation of EVA in comparison with operation time, and EVA are very expensive and impose large load on astronauts. It is necessary to develop multi-functional space robots which can conduct tasks supporting the astronauts inside/outside spacecraft. In order to fulfill this requirement, we have developed a reconfigurable brachiating space robot (RBR)[1-3] to be tested on the -"KIBO" (Japanese Experimental Module) of the International Space Station (ISS). This research work was funded by a part of "Ground Research for Space Utilization" promoted by NASDA and Japan Space Forum, and the duration of the research was set about 3 years (1997.12-2000.3). Group leaders were Yoshiaki Ohkami (1997.12-1999.3) and Saburo Matunaga (1999.4-2000.3). This was a joint project with Tokyo Institute of technology (Titech), Tohoku University, Toyota Technological Institute (TTI), National Aerospace Laboratory (NAL), Communications Research Laboratory (CRL), Toshiba Corporation, Kawasaki Heavy Industry (KHI), Shimizu Corporation, Nissan Mortor Co.,Ltd., and NASDA.

(1-1-1 Standard Configuration)
Fig.1 Conceptual model of RBR

A conceptual model of RBR is shown in Fig.1. This robot consists of multi 6 degree-of-freedom (DOF) arms and one main body named "Center Hub". The center hub has three connection ports for connecting three reconfigurable arms. The major characteristics of the RBR are the center hub system topology, the reconfiguration function and the movable ability by brachiation. The RBR can move inside or outside of the ISS using the handrails which are used by the astronauts for moving on the KIBO or the ISS, and change its configuration for required tasks. This paper presents results of ground experiments for the main characteristics functions of the RBR, which are the reconfiguration, brachiation and integration motions.

2. Ground Experiments of Reconfiguration

We conduct the ground experiments of the reconfigurating motions. The reconfigurating motions are classified into two motions: reconfigurating motion using the outer pivot and self-reconfigurating motion without the outer pivot. In this section, we present the ground experiment system of the reconfiguration using the reconfigurable arms with the distributed controllers. Next, we show the results of these ground experiments.

2.1 Ground Experiment System

Fig.2 shows the ground experiment system for reconfiguration. The components of this system are a center hub, left arm, right arm, and an outer pivot. The center hub has one pivot and end-effector for connecting or disconnecting the arm. Each arm has 6 DOFs in motion. The left arm has one end-effector on tip and is fixed to the center hub. The right arm has one end-effector on tip and one pivot on root. The outer pivot can supply the power and the communication signal to the arm system through the connectors of the end-effector, and communicate with the center hub. All communication ports and the left arm's arm-to-arm communication line are used for the communication to control the right arm. If the pivot or the end-effector of the right arm is connected to any communication port, the right arm can be controlled.

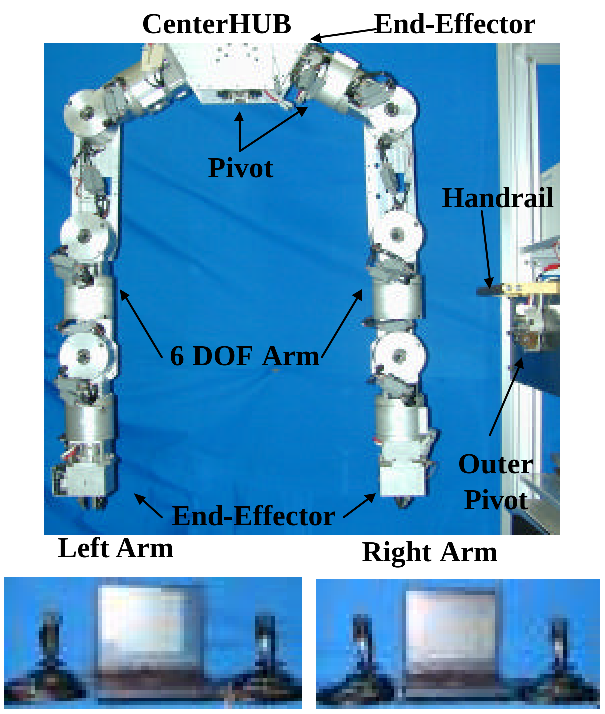

Fig.2 Ground Experiment System

Fig.3 shows the control/network and power supply system of this experiment system. One PC controls one arm via two 3 DOF joysticks. Two operators control two arms via the two joysticks on the joints angle control mode. The right arm can be separated from the center hub, so four connecting ports are set for the right arm, two end-effectors in the left arm and the center hub, two pivots in the center hub and a wall. All connecting ports have two connectors for the power lines and the communication lines. The Ethernet line of the left arm is used for the TIA/EIA-485 line for the right arm.

2.2 Reconfigurating motion

In this section, we verify the reconfigurable function that is one of the most important characteristics of the RBR system. At first, the right arm is connected to the end-effector of the center hub, supplied the power and communication signal from the center hub shown in Fig.2.

The sequence of the reconfigurating experiment using the outer pivot are the followings: 1) connect the end-effector of the right arm to the outer pivot, 2) separate the pivot of the right arm from the end-effector of the center hub, 3) connect the pivot of the right arm to the end-effector of the left arm, 4) disconnect the end-effector of the right arm from the outer pivot. Two operators control two arms on the direct kinematics mode.

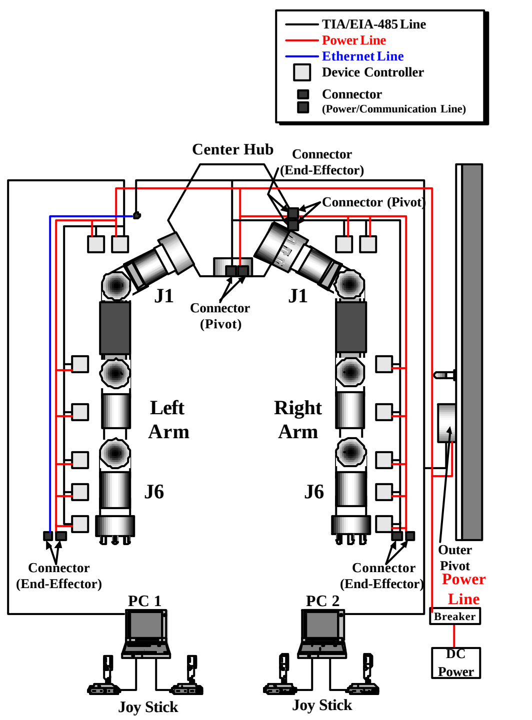

Fig.3 Control/Network and Power Supply System

One of results of this experiment is shown in Fig.4. The end-effector of the right arm is connected to the outer pivot shown in Fig.4 (a). Then, the right arm is supplied the DC power and the communication signal via the outer pivot, so the pivot of the right arm can be disconnected from the center hub shown in Fig.4 (b). Next, two operators control cooperatively two arms approached and connected shown in Fig.4 (c). The

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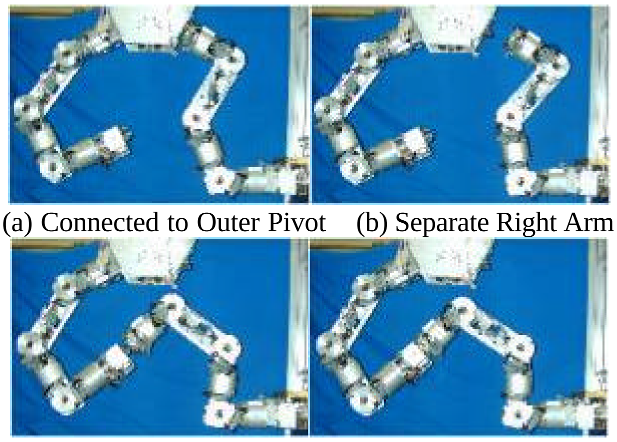
right arm is supplied the DC power and the communication signal via the end-effector of the left arm, so the end-effector of the right arm can be disconnected electrically and mechanically from the outer pivot shown in Fig.4 (d). Last, the end-effector of the right arm is connected to the outer pivot, two arms are disconnected, and the right arm is connected to the center hub and disconnected from the outer pivot. The two arms are changed to the initial configuration. When the right arm is connected to the outer pivot and the end-effector of the center hub or the left arm, the arm forms the closed loop. However the joints of the both arms are controlled within ±0.7deg, so the arms are stable. The results of the experiments showed the reconfigurable arm of the RBR can change the configuration with the outer pivot.



(a) Connected to Outer Pivot (b) Separate Right Arm

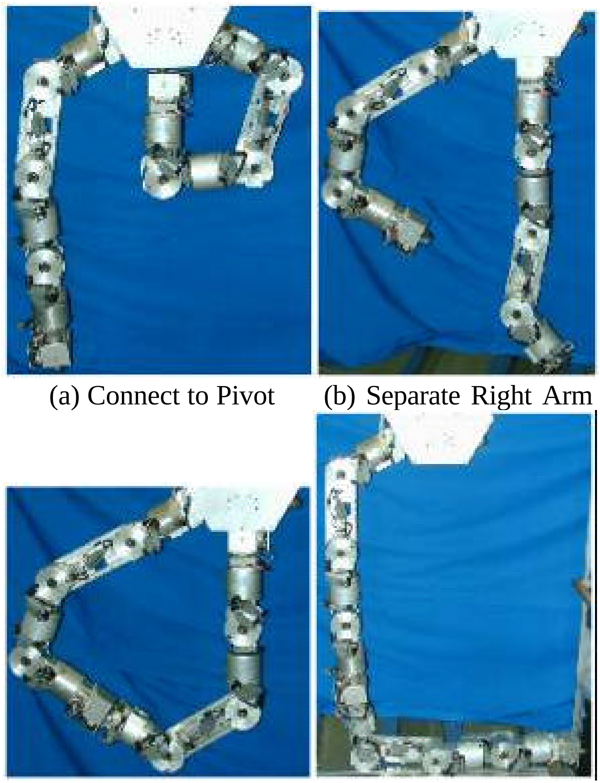
(c) Approach (d) Connect Two Arms

Fig.4 Experiment of Reconfigurating Motion

2.3 Self-reconfigurating motion

Self-reconfiguration is the reconfiguration using only the pivot of the center hub without the outer pivot or any outside port.

The self-reconfigurating experiment sequences are the followings: 1) connect the end-effector of the right arm to the pivot of the center hub, 2) separate the pivot of the right arm from the end-effector of the center hub, 3) connect the pivot of the right arm to the end-effector of the left arm, 4) disconnect the end-effector of the right arm from the pivot of the center hub. At first, the right arm is connected to the end-effector of the center hub. Two operators control two arms on the direct kinematics mode. The results of this experiment are shown in Fig.5. First, the end-effector of the right arm is connected to the pivot of the center hub as shown in Fig.5 (a). Next, the root of the right arm is separated from the center hub as shown in Fig.5 (b), and approached and connected to the left arm as shown in Fig.5 (c). Last, the end-effector of the right arm is disconnected from the center hub, but the arms cannot support own weight on ground, because the system has been designed for motion in micro-gravity environment. So the operator supports the arm and set the arm on the ground as shown in Fig.5 (d). Continuously, the operator can control the right arm via the left arm. Then, the arm becomes a redundant arm with 12 DOFs in motion. The results of the experiments showed that the reconfigurable arm can change own configuration without the outer devices.



(a) Connect to Pivot (b) Separate Right Arm

(c) Connect Two Arms (d) 12DOF Redundant Arm

Fig.5 Experiment of Self-Reconfiguration Motion

2.4 Teaching and Playback Experiment

In the previous sections, we presented the experiments operated by the operators. In this section, we show results of teaching and playback experiments using the results of reconfiguration experiments. We use the motion of the sequence 1 in sec. 2.2 that the right arm is connecting to the outer pivot. The results of this experiment are shown in Fig.6. The left graphs show the joint angle (solid line) and the reference angle (broken line). The right graphs show the motor current of the joints or the end-effector. The right arm is started to approach the outer pivot at t=0s. The end-effector of the arm is contacted with the outer pivot at t=16s, and is started to open own three claws. On the end-effector, the motor current is controlled. The end-effector is given the current command -1.0A. However, the current is -0.4A, because of the current limit ±0.4A. The end-effector is connecting to the outer pivot mechanically at t=21s, and the arm is forming the closed loop. Then, the motor current of the joint is increased. However the joints of the both arms are controlled within ±0.7deg, so the arms are stable. At t=24s, the end-effector and the outer pivot is connected mechanically, and the connectors of the end-effector is moved, and the end-effector and the outer pivot is connected electrically at t=44s. The end-effector is embedded a small CCD camera. Fig.7 shows the CCD Camera Image of the right arm's end-effector. Fig.7 (a) shows the approach sequence and (b) shows the connection state of the end-effector and the outer pivot. On the approach sequence, the end-effector deviates from the outer pivot in 5mm. However, if the tip position of the arm is controlled within 5mm, the end-effector can be inserted to the outer pivot, and the form of the arm can be change the connection state with opening of the claws of the end-effector. At the connection state, monitoring the motor current of the all joints, we can avoid generating the large load to the joints due to forming the closed loop even without any force-torque sensor.

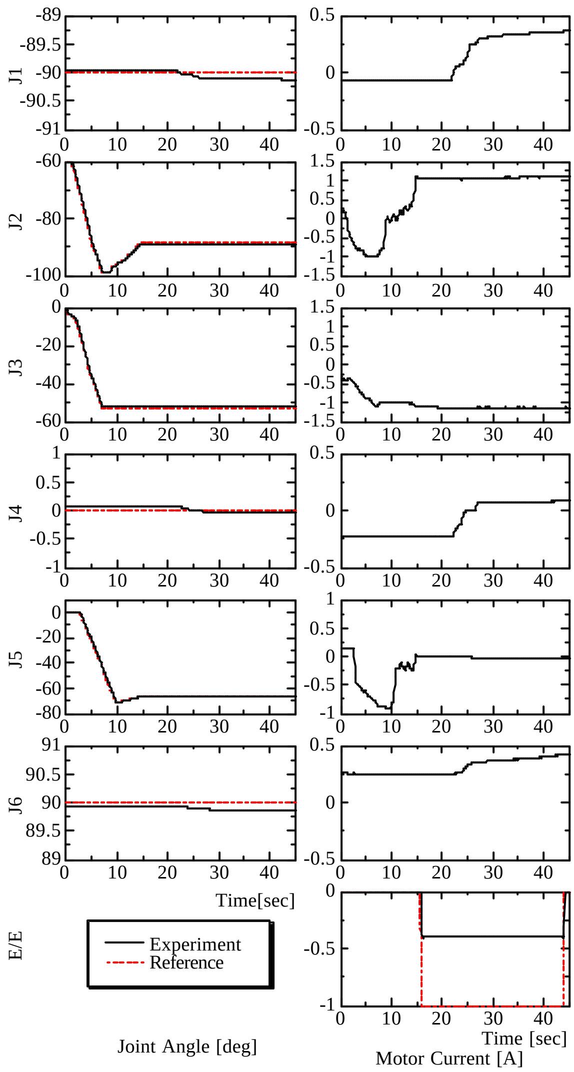


Fig.6 Result of Teaching and Playback Experiment


(a) Approach Sequence (b) Connect to Outer Pivot
Fig.7 CCD Camera Image of End Effector

3. Ground Experiments of Brachiation

We conduct the ground experiments of the brachiating motions using the end-effector with the handrails. In this section, we present the ground experiment system of the brachiation. Next, we show the results of these ground experiments of the brachiation and integration motion, which is combined the reconfiguration and brachiation.

3.1 Ground Experiment System for Brachiation

Figure 8 shows the ground experiment system of brachiation. The components of the robot are the same as the ground experiment system of reconfiguration as shown in Fig.2, are a center hub and two arms, and the network and power supply systems are the same as shown in Fig.3. The robot is supported by a linear guide with four wires. The linear guide can move freely left and right. Thus, the robot can move under the gravity. This experiment testbed is simulated the standard experiment payload in exposed facility on KIBO/ISS. On the bottom of the testbed, four handrails are set every 40cm, and the outer pivot is set for integration motion. The handrails are designed for moving the astronauts in the pressurized module on KIBO/ISS, so the inner shape of the claws of the end-effector is designed for grasping the handrail.

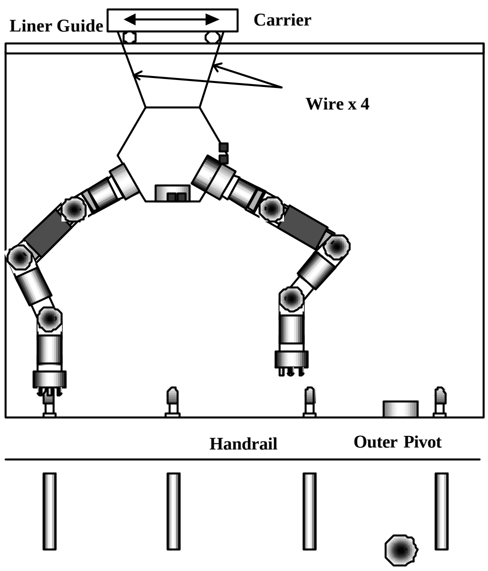


Fig.8 Ground Experiment System for Brachiation

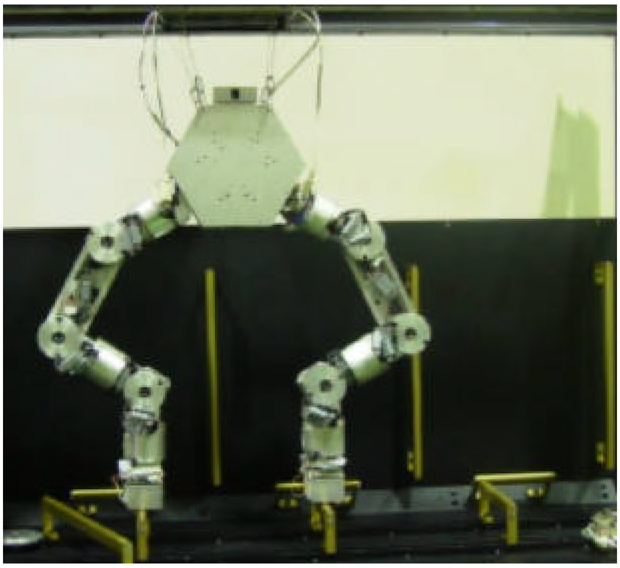
3.2 Brachiating motion

In this section, we verify the brachiation capability that is important characteristic of the RBR system.
The brachiating experiment sequences are the followings: 1) release the handrail grasped by the end-effector of the right arm, 2) leave the end-effector to the upside of the handrail, 3) move the center hub using the left arm, and approach the right arm to the upside of the next handrail, 4) insert the handrail to the three claws of the end-effector of the right arm, 5) grasp the next handrail using the end-effector of the right arm. The RBR can move right and left by repeating the sequence 1–5). On this experiment, the operators do not control both arms, but both arms are controlled under the teaching and playback mode. The teaching data is created from linearizing the joints angle of the each sequence. At first, the end-effectors of the two arms grasp the handrails as shown in Fig.9 (a). Next, the end-effector of the right arm releases the handrail as shown in Fig.9 (b), and grasps the right handrail as shown in Fig.9 (c). Last, the end-effector of the left arm releases the handrail as shown in Fig.9 (d), and grasps the right handrail as shown in Fig.9 (e). On these motions, the RBR moved the right side to 40cm. Fig.10 (a) shows the CCD camera embedded in the end-effector of the right arm, when the end-effector of the right arm is placed at a tilt position from the handrail as shown in Fig.8. At the tilt position, the CCD camera got the handrail. However, when the end-effector of the right arm is placed upside of the handrail, the CCD camera did not get the handrail. Setting the markers on the floor, the arm can grasp the handrail automatically with the image processing using the image of the CCD camera embedded in the end-effector. Repeating these motions, the RBR can move at the pressurized module or the exposed facility of the KIBO by the brachiation manner. These results show that the RBR has the capability of brachiation with grasping the handrail.

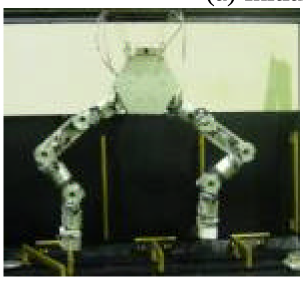
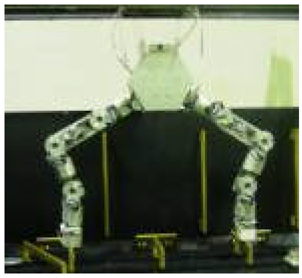
3.3 Integration motion

In this section, we verify the capability of the combination with brachiation and reconfiguration that is important characteristic of the RBR system.

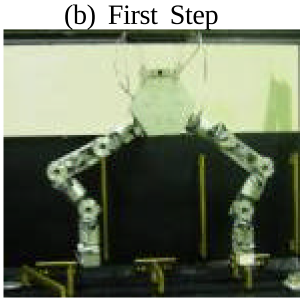
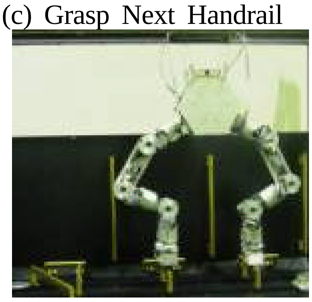
The integration experiment sequences are the followings: 1) the RBR moves the right direction with brachiation manner, 2) connect the end-effector of the right arm to the outer pivot fixed on the floor, 3) separate the pivot of the right arm from the end-effector of the center hub, 4) the center hub moves the left direction using the left arm, and the right arm works on the stand alone. The result of the experiment is shown in Fig.11. At first, the end-effectors of the two arms grasp the handrails as shown in Fig.11 (a). Next, the end-effector of the right arm releases the handrail as shown in Fig.11 (b), and approaches the outer pivot fixed on the floor as shown in Fig.11 (c), and connect to the outer pivot as shown in Fig.11 (d). Last, when the RBR supplied the communication signal and DC power via the end-effector of the right arm from the outer pivot, the pivot of the right arm disconnects from center hub as shown in Fig.11 (e). Then, the left arm carries the center hub to the left side, and the right arm works independently of the center hub as shown in Fig.11 (f). This experiment simulates the camera-setting mission.



(a) Initial Position

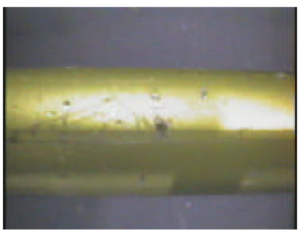



(b) First Step (c) Grasp Next Handrail

(d) Second Step (e) Final Position

Fig.9 Experiment of Brachiating Motion



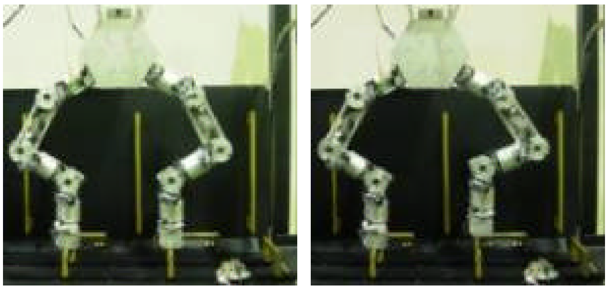

(a) Tilt Position (b) Grasping Position

Fig.10 CCD Camera Image of End Effector (Brachiating Motion)

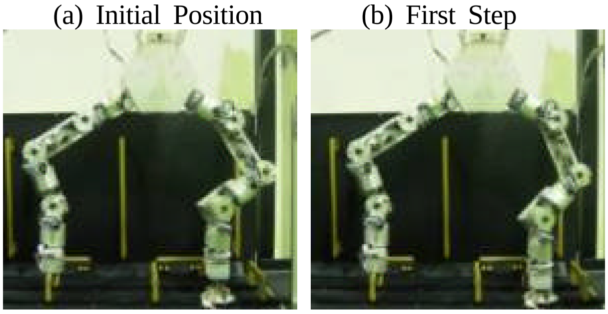
On the camera-setting mission, the RBR moves the inspection point with the brachiation manner, and makes reconfiguration to the main body and the single arm which has the CCD camera for the inspection. If the RBR has three arms, the main body of the RBR has two arms so that the RBR can move continuously. The single arm is provided the communication signal and the DC power via the outer pivot installed the inspection point, so the single arm can inspect around the outer pivot using its degree-of-freedom. The result of this experiment shows that the RBR can move and work on the exposed facility of the KIBO at the ISS, and make reconfiguration its shape for the required tasks.

5. Conclusions and Future Plan

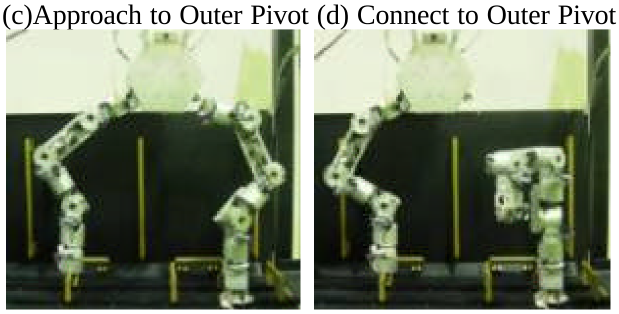
In this paper, the main characteristics of the Reconfigurable Brachiating space Robot (RBR) was presented. We showed the ground experiment system and the results of the ground experiments in order to evaluate the system performances. We obtained the following results.



(a) Initial Position (b) First Step



(c)Approach to Outer Pivot (d) Connect to Outer Pivot



(e) Disconnect Right Arm (f) Stand Alone Mode

Fig.11 Experiment of Integration Motion

i) Verification of the reconfiguration capability with the DC power supply and the information transmission via the connectors of the outer pivot.
ii) Verification of the self-reconfiguration capability with the pivot of the center hub without the outer pivot.
iii) Verification of the brachiation capability with grasping the handrail using the end-effector.
iv) Verification of the integration motion combined the reconfiguration and the brachiation.

In this experiments, we monitored the motor current of all joints, so that we can avoid generating the large load to the joints without the force-torque sensors. It is planned to carry out the evaluation experiments as followings.

i) Brachiating capability in a standard configuration using handrails in the 3-dimensional testbed already installed at TITech.
ii) Performances and characteristics of the end-effector, the pivot and the joints in quasi-micro-gravity condition using parabolic flight in an airplane.

Based upon the results from the experiments described above, onboard experiments will be proposed on the ISS/JEM exposed facility.

Acknowledgement

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