The Design of key mechanical functions for a super multi-DoF and extendable Space Robotic Arm

Kent Yoshikawa*, Yuichiro Tanaka**, Mitsushige Oda***, Hiroki Nakanishi****

*Tokyo Institute of Technology, Tokyo, JAPAN
e-mail: yoshikawa.k.ad@m.titech.ac.jp

**Tokyo Institute of Technology, Tokyo, JAPAN
e-mail: tanaka.y.bq@m.titech.ac.jp

***Tokyo Institute of Technology, Tokyo, JAPAN
e-mail: oda.m.ab@m.titech.ac.jp

****Tokyo Institute of Technology, Tokyo, JAPAN
e-mail: nakanishi.hiroki@mes.titech.ac.jp

Abstract

Robot utilizations are highly required for mission accomplishments as well as economic and safety advantages in space exploration. In a few decades, support and alternation for astronauts are expected to increase. Authors propose MBR (Morphable Beam Robot) as a new type of robotic arm. It has super multi degrees of freedom, extendable, and redundant working capability by using a beam structure which can be shaped freely. MBR has the following advantages: wide-range working capability, complex-shape realization, and compact storage configuration. In order to realize beam shape, "Bending" and "Moving" functions are important.

In this paper, designs of these functions are described. Following contents are included: its classified requirements and technical approach that is reached from systematic analysis, mechanical and engineering studies, some designs and Bread Board Models (BBM), and their results of experiments for functional validations.

1 Introduction

Robotic utilizations are highly required in space exploration because of mission accomplishment, safety and economic advantages. Today, large manipulator systems such as Space Station Remote Manipulator System (SSRMS) or Japanese Experimental Module Remote Manipulator System (JEMRMS) are working in International Space Station (ISS) [1]. In the near future, it is applied to work for orbital structure and spacecraft such as Space Solar Power System (SSPS) [2] and the commercial space station. Thus, robotic mission support requirements will increase.

In these missions, robot is required a same requirement. It is "astronaut support or alternation for their efficient and safety working." ISS is a very large structure which size is about a football stadium, has more than 30 modules, and is operated by only 6 crew. All the crew are very busy and the number is small for their tasks. Thus, robotic supporting is necessary for efficient operation. To build a large structure about a few squire km without robotic supporting is impossible. Not only construction, inspection and repair are also required. Especially, working ability is very important in space robot, and it is expected that it has wide-range working capability and compact storage configuration because of limited launch mass. Thus, authors propose the MBR (Morphable Beam Robot, Fig.1) [3] as a new type space robot which can realize working capability that no existing robot has. The main body of this arm consists of Morphable Beam (Fig.2). It can change its shape by applying force and maintaining the shape. To change its length and shape, it is applied as super multi degrees of freedom (DoF) and extendable robotic arm.

In this paper, the concept and system are described at first, as well as the design and development of two main functions of shaping system are described in detail. In a chapter of a bending function, the study of functions, design, specification, and experimental data, are included. In a chapter of a moving function, the study of functions, design and development are included.

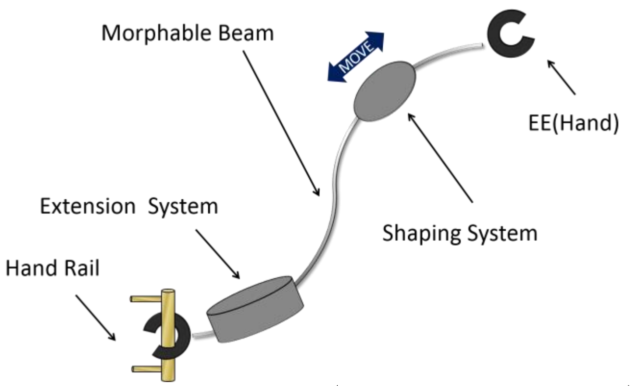

Fig.1 Concept of MBR (Morphable Beam Robot)

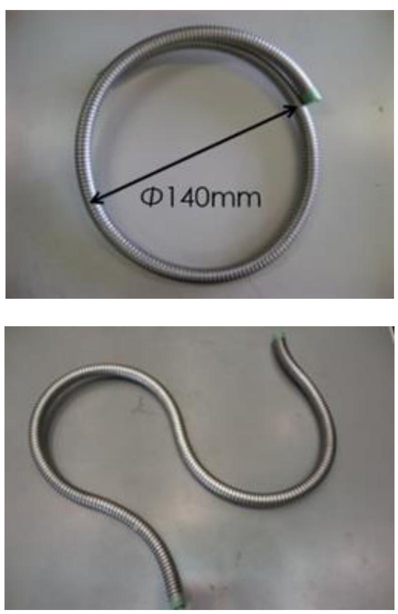

Fig.2 Morphable Beam

2 Concept of Morphable Beam Robot

The main objective of this robot is that it can work 'with' astronauts or dexterous working robots as a helper in orbit. For this objective, the following usages are considered.

During astronaut preparation of an extra vehicular activity (EVA) inside the space station, the robot prepares for their tasks such as moving tools or things to a working area. It also becomes a fixed base for a camera, light, tools, or astronaut. Astronauts can shape the robot manually by their hand. Thus, the robot should be used by automatic control, and it is also required to be used such as a tool of astronauts.

2.1 Task study of MBR

According to the study of astronauts and engineers of human exploration, they hope that the robot support or alternate the following tasks.

(1) Astronaut support
- Pass and grip tools or things
- Transfer astronauts or things to a working area
- Display working procedures
- Lighting a working area
- Check and replace a connecter or switch

(2) Recording
- Shoot and record activities or tasks

(3) Alternation of astronauts
- Inspection of solar array panel or structure
- Pick and place

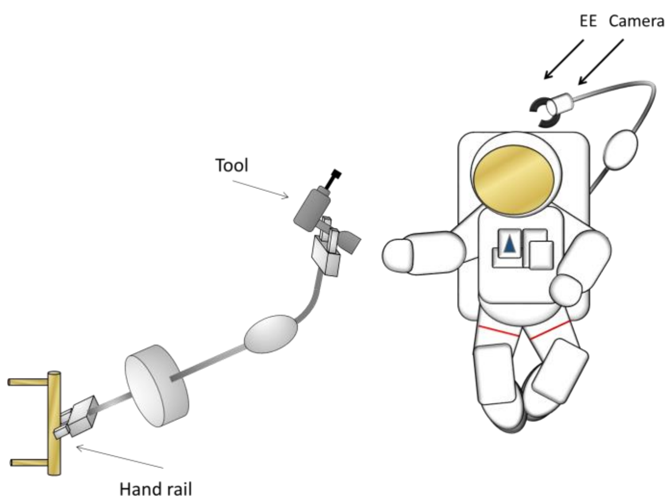

Fig.3 Application example 1
(Recording astronauts working and Passing a tool to an astronaut outside a space station)

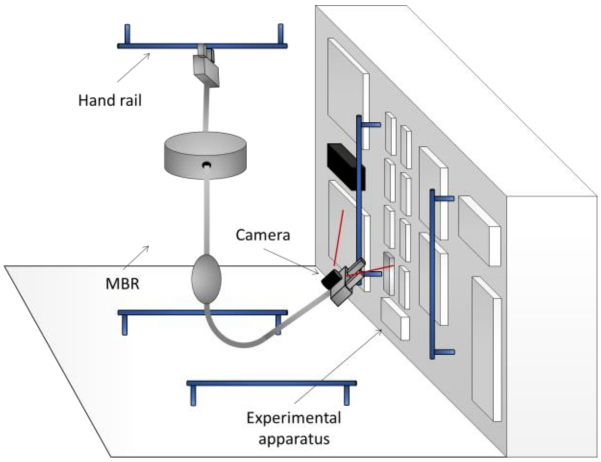

Fig.4 Application example 2
(Inspection and recording experimental equipment inside a space station)

2.2 Requirements

MBR is required the following functions to accomplish tasks.

(1) Working capability
Kinematic conditions such as beam length and DoF which can determine the EE's position and attitude.
Dynamic and static conditions such as stiffness and momentum to grip and move tools or things.

(2) Moving capability
Robot can move from a few meters to tens of meters in only one action.

(3) Cognitive capability
Robot can measure position and attitude of EE and itself inside/outside a space station.

(4) Size
Robot can be stored small.

(5) Safety requirement
Robot could make no damage to astronauts or structures if it would make a collision to them.

2.3 System

MBR consists of the following subsystems to meet the objective and the requirements.

(1) Morphable Beam
A beam structure which can be changed its shape by applying a force and can keep the shape. It is needed to select the length.

(2) Shaping system
It moves on Morphable Beam and changes the shape by bending and reshaping. Shaping system consists of 2 components shown in Fig.5. The right side of the system is called Beam Shaper (BS) and the left side is called Moving Mechanism (MM).

(3) Extension system
It changes the beam length.

(4) End effector
Robotic hand, camera, light, display, etc.

(5) Measurement system
It measures beam shape, as well as position and attitudes of the shaping system.

(6) Electric system
It supplies power to, communicates with, and controls each subsystem.

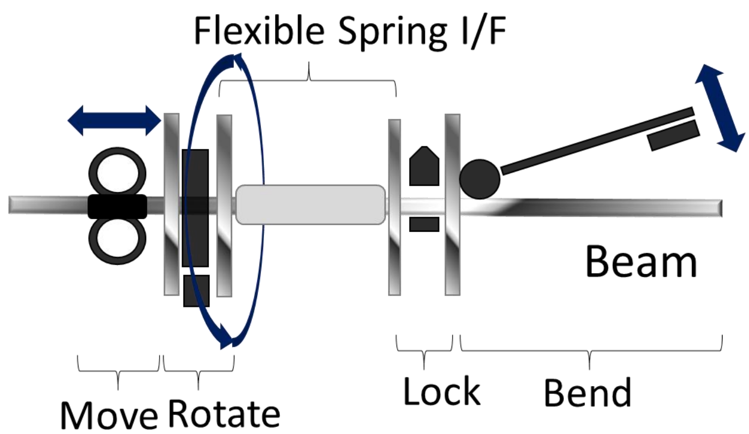

Fig.5 Shaping System configuration

3 Shaping System

3.1 Requirements of Shaping System

This subsystem is an equipment for beam changing. It can shape, reshape, and move on the beam. For shaping and reshaping, the determination of the relative position and attitude to the beam and fixation of it are required. In addition, this subsystem should be small if possible. To meet these requirements, SS consists of 2 components for kinematic reasons of the beam. They are Beam Shaper (BS) and Moving Mechanism (MM). BS has bending/reshaping and locking functions. MM has moving and rotating functions.

4 Beam Shaper

To realize beam shaping which a user want to do, beam shaping method, mechanical and engineering conditions are very important. In this section, studies of a beam bending method and the design process are described.

4.1 Beam shaping method for MBR

At first, the requirements for the BS is summarized. They can be divided into two levels, requirements from the SS and engineering requirements.

(1) Upper level: Requirements from the SS
These requirements are very simple, beam shaping and reshaping. Here, shaping is defined as bending the Morphable Beam to control the EE position and attitude. Reshaping is defined that BS can make the beam straight.

(2) Lower level: Engineering requirements
Machinery, material, actuator, and driving system is required to apply a force which is needed to change the beam shape. Number of revolutions must be controlled correctly. Position and attitude of EE and the beam shape must be measured. BS have to work outside the space station correctly and have radiation, electromagnetic, and launch vibration tolerance are needed.

4.2 Beam Shape design

To realize the requirements as described before, BS was designed. It has two points. The first point is how to apply a force to the beam. It is combinations of fixation and force applying point. The simplest case is 1 fixation and 1 force applying point. Selection of the number and position of each point is very important. The second point is how to describe the shaping. Beam shaping can be described by using a frame. 2 or 3 dimension, Euclidean frame or polar coordinate system, and so on.

According to these considerations, the simplest combination should be selected because it can meet the requirements of SS. Thus, BS consists of 1bending and 1 fixation points and beam bending is described as Euclidean frame, and this combination can realize large and accurate bending, small number of actuators, small size structure, and simple control method.

Each machinery is placed on a plate, and this plate can connect MM. One side is a bending part and another side is a locking part. To reduce back drive, a worm gear is used in a driving system. Each function is controlled by rotation quantities of motors.

4.3 Beam Shaper Bread Board Model (BBM)

To confirm BS's specifications and the assumptions, we developed the BBM and got information from some experiments. Fig.6 is a picture of BBM. To change the driving system, it can increase bending quantities.

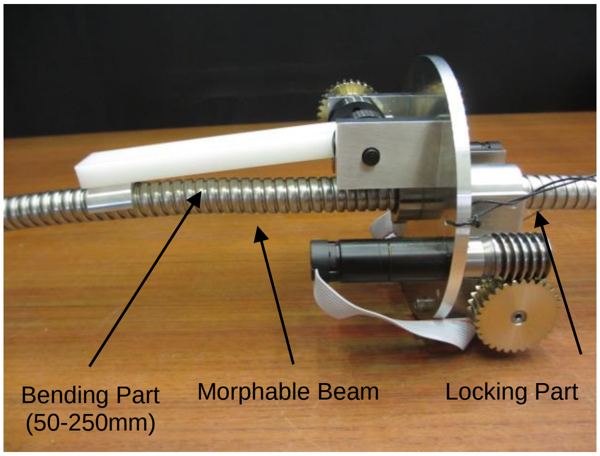

Fig.6 Beam Shaper BBM

5 Moving Mechanism

5.1 Shaper's moving method for MBR

(1) Upper level: Requirements from the SS
Moving mechanism have to meet 2

requirements. “Shaping system can move on the beam when the beam is straight and bending.” “When it is not driven, the system prevents moving and rotating.” To meet these requirements, the following requirements are needed to meet.

(2) Lower level: Engineering requirements
We should study engineering requirements to realize functions. Machinery, actuator, and driving system is required to apply a force which is needed to change the beam shape. Number of revolutions must be controlled correctly. Position and attitude of SS must be measured. MM have to work outside the space station correctly. These requirements have to be applied to the design.

5.2 Moving Mechanism design

There are some mechanisms which realize moving on a pole, a rod, or a beam structure. For example, a tree climbing robot, Treebot at Shenzhen Institute of Advanced Technology [4] and snake-like robot at Carnegie Mellon University (CMU) [5] exist. Treebot climbs a tree by changing grasping positions by using 2 grippers. CMU snake-like robot moves a branch by winding and twisting many points of DoF. These mechanisms have to apply momentum to a structure and have a possibility of bending Morphable Beam. Thus, these methods are not appropriate for a moving method of Morphable Beam. To realize moving on the beam without bending it, how to apply force and torque is very important. However, it is impossible without applying any force on the beam. Thus, all the force has to be applied at one point. In addition, the number of force is also important. Thus, not to run off the beam, at least 3 forces are required. For these reasons, we selected to use wheels to move.

To confirm mechanism functions, we developed functional verification model shown in Fig.7. We moved moving and rotating functions manually. Moving function consists of 3 wheels. From our study, more than 2 driven wheels are needed to move on the beam. In addition, diameter connecting wheels and the beam is changeable to determine the best diameter. From this study, we found that the diameter is required to be smaller than 0 to -1 mm the beam diameter.

From the study of shaper’s moving method, the moving function is consisted of 3 wheels. All wheels are driven by a motor and a worm gear to reduce back drive. This function is used to decide a position on the beam. In addition, shaping system is required to determine the attitude by rotating BS. For this function, MM can rotate BS by gears, and BS and MM is connected by a spring because the working area that is limited. The spring is chosen to follow the beam shape when the shaping system is moving.

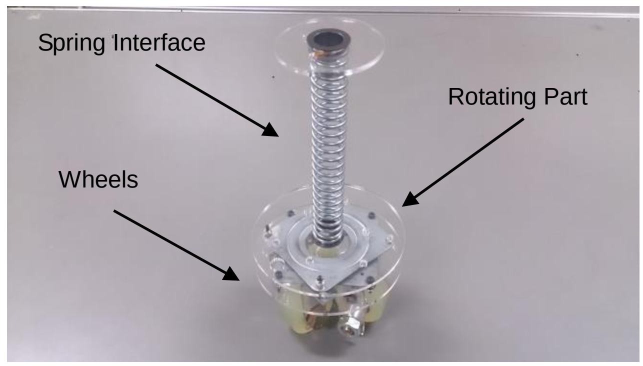

Fig. 7 Functional verification model of MM

5.3 Moving Mechanism BBM

Moving Mechanism BBM is shown in Fig.8.

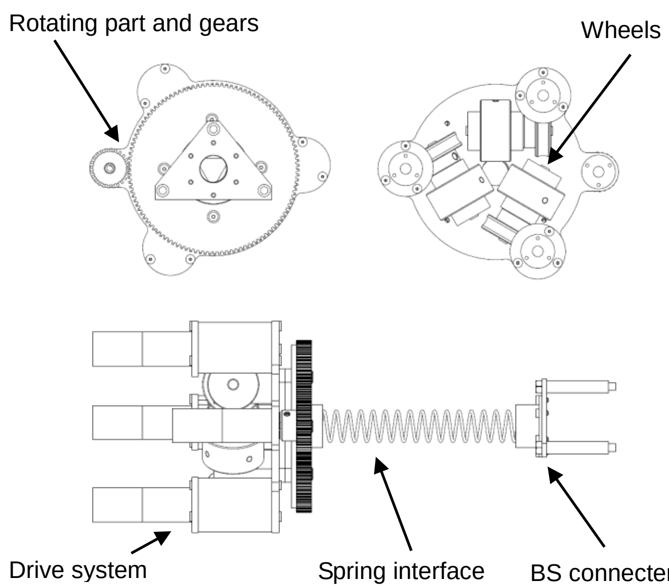

Fig.8 Moving Mechanism BBM CAD model

6 Experiment

6.1 Different lengths of beam bending parts experiment

In this experiment, we confirmed the difference of bending behavior when a length of shaper's bending part is different. This experiment aims to find the best design of BS. Lengths are 50mm, 100mm, 150mm, 200mm and 250mm, and shaper bends the beam until the beam becomes maximum position and attitude. Fig.9 shows the experimental setup and an x-y plane. BS is hung from the aluminum frame for gravity cancel. We measured position and attitude manually. Fig.8 shows results of the x-y position. In this experiment, input attitudes means angles of beam bending part, and 0 degree shows it parallels y axis.

Results of this experiment are shown in Fig.10 and Fig.11. Fig.10 shows the relationship between input and output attitude of a tip of EE. Input attitude is determined from motor's rotating value.

Short length like 50mm needs large attitude volume before shaper pushes the beam. Thus, input attitude is large, but output attitude is much smaller than any other lengths. Compared to short lengths, long lengths (200mm and 250mm) output attitude and position become smaller than the results of 150mm. This behavior happens because the bending part fit the beam and stops bending.

From these results, the best length of the bending part is 150mm for this beam. It is because it can bend maximum position and attitude in all lengths.

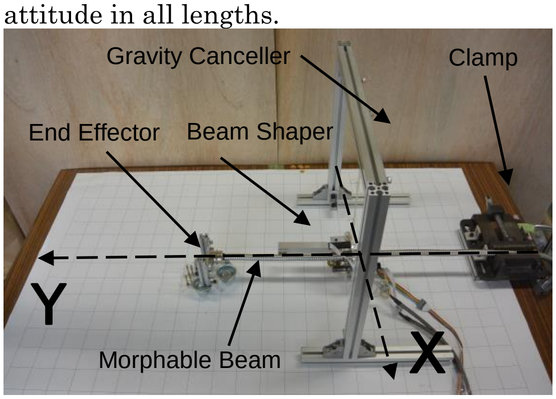

Fig.9 Experimental setup and an x-y plane

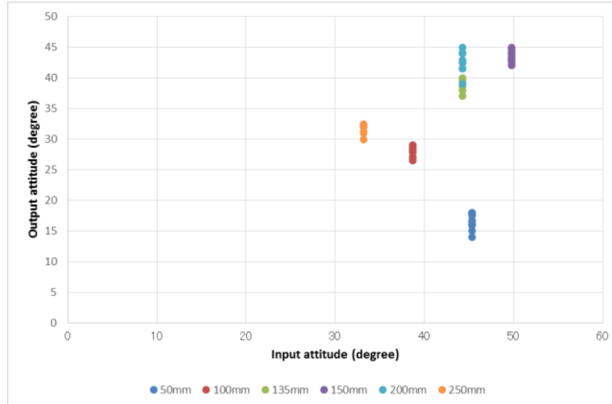

Fig.10 Relationship between input and output attitude of each length parts

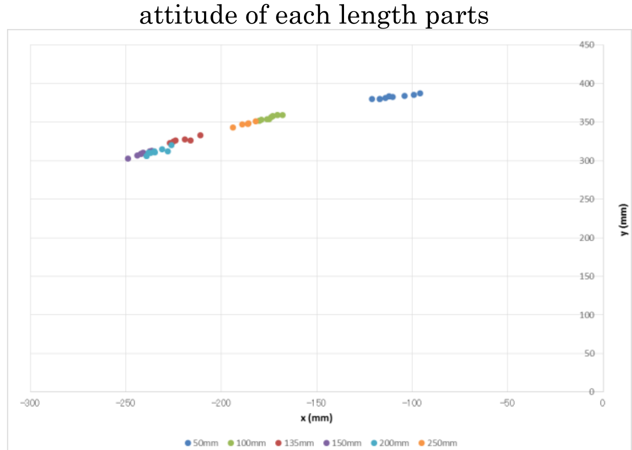

Fig.11 Position result of different lengths of bending parts.

6.2 Bending experiment of 150mm part

The best length of a bending part is 150mm from the last section. In this section, behavior of different input attitude is described.

In this experiment, we inputted different attitudes and measured the position and attitude of the tips of EE. Input attitude were 3.3, 8.8, 11.6, 14.3, 17.1, 19.9, 22.7, 25.4, 36.5, and 42.0 degrees after bending parts fit the beam. Each input angle experiment is repeated 5 times. Experimental setup and measurement method are same with the last experiment.

Fig.9 shows some examples of 3.3, 22.7, and 42.0 input degrees. Fig. 13 shows the relationship between input and output attitude. Fig. 14 shows position results on the x-y plane.

From this experiment, position and attitude increased if we inputted large input attitude angle. The relationship between input and output attitudes shows linear increase. This result was found by an improvement of driving system of BS. For this improvement, BS can bend large angles.

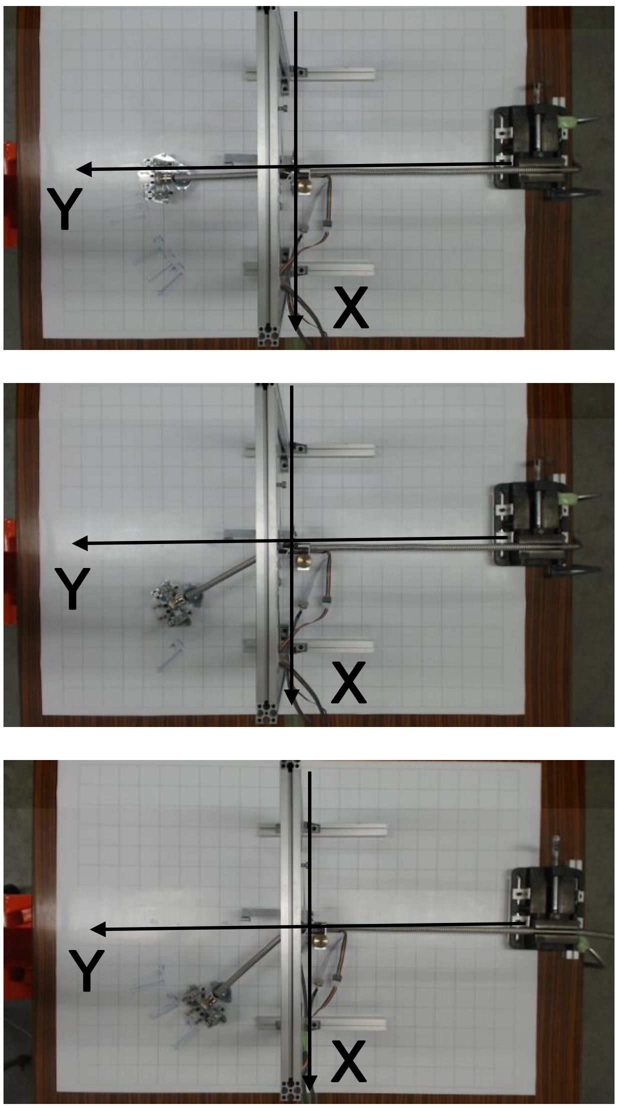

Fig.12 Beam bending by 150mm parts (Upper: input 3.3 degrees, Middle: input 22.7 degrees, Lower: input 42.0 degrees)

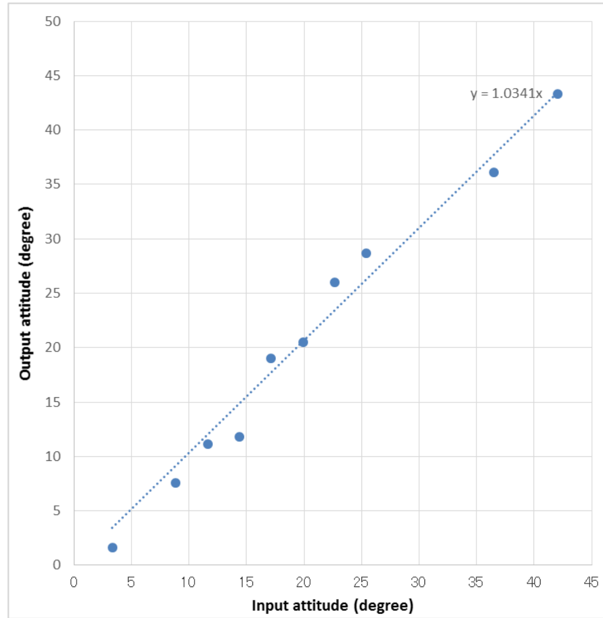

Fig.13 The relationship between input and output attitudes and its approximate line.

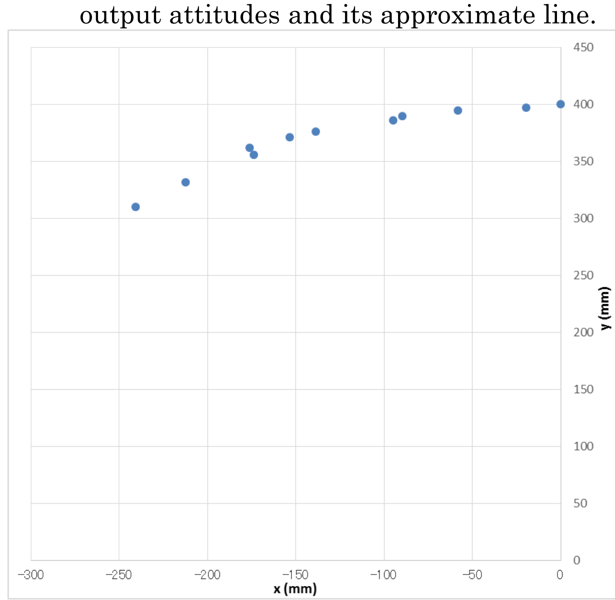

Fig.14 The experimental results of position on x-y plane

In addition, the beam backs a few to 10 mm or under 2 degrees when the bending part releases from the beam because of the beam's elasticity. We found that input attitude becomes larger, back volume become larger. This relationship is shown in Fig.15.

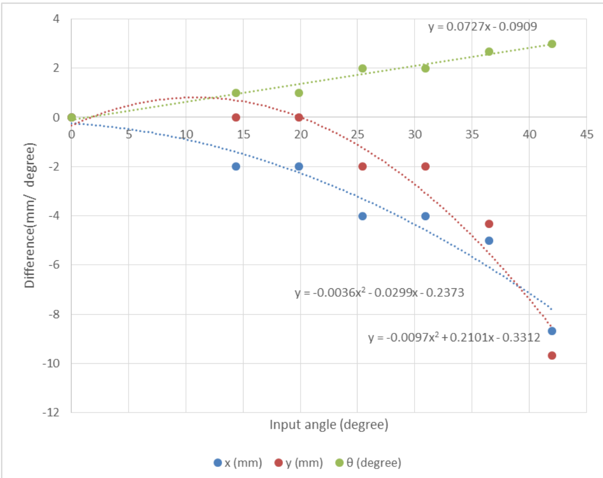

Fig.15 Back volume and its approximate line after releasing of BS from the beam.

6.3 Reshaping test of 150mm part

At last, reshaping feasibility is described. Not only bending, reshaping is needed for MBR. We confirmed reshaping from a maximum bending. Fig.16 shows a beam shape after reshaping. As it is shown in this picture, the beam become straight after reshaping.

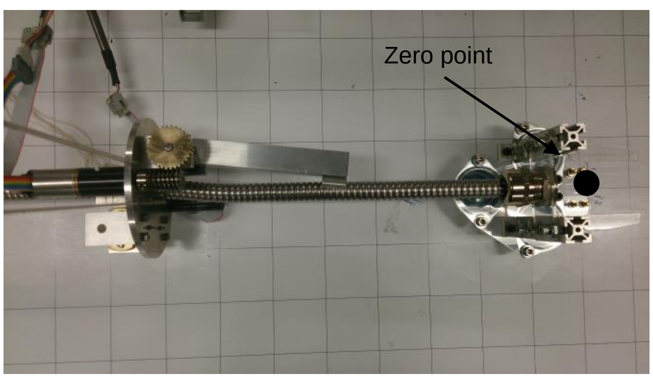

Fig.16 Reshaping experiment

7 Conclusions

In this paper, we described the design method and the specification of a mechanical system to realize super multi DoF space robotic arm, as well as some experimental outputs.

For future tasks, we have to confirm specifications of MM and generalization of each function by making mathematical models. In addition, we'll confirm the feasibility of real tasks such like inspection or pick and place.

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