Small modular robot with self-disassembly function for intra-vehicular supporting system

*Kenichi Tamamushi, Naohiro Uyama, Tomohiro Narumi, and Shinichi Kimura

(Tokyo University of Science)

Kimura Laboratory, Tokyo University of Science, Japan
e-mail: tamamushi@kimura-lab.net

Abstract

We propose a modular manipulator for an intra-vehicular crew support robot that ensures the safety of astronauts in the event of an unexpected collision by disassembling itself if an astronaut comes into contact with the robot. Because the robot consists of modules, it can be stored compactly in limited intra-vehicular space and can be assembled into various structures and utilize various types of end effectors for various purposes. In this paper, we describe how we reduced the size of the robot and improved its connection mechanism to achieve disassembly for safety in response to a weak impact.

This paper describes the small modular robot and presents its specifications and the results of an evaluation of its performance.

1 Introduction

With the expansion of space utilization, the work load of astronauts has been drastically increasing. To reduce this work load, robotic technologies, especially robots that support intra-vehicular activities, are expected to play important roles in future space missions. The design of an intra-vehicular supporting robot must address several issues. The first and most important issue is collision safety. The robot should have reliable collision safety features to prevent injury to astronauts and damage to on-board equipment. Because an unexpected collision may occur regardless of how attentive astronauts are, the robot itself must be designed for safety in the event of an unexpected collision. The second issue is the size of the robot: it must be small enough to be used in limited intra-vehicular space. Therefore, the robot must be as compact as possible when stored. A small size is also advantageous in operation. The third issue is the adaptability of the robot to various situations and utilizations. An intra-vehicular support robot must be able to perform various tasks using the same system. In other words, a single robot must be versatile enough to meet various demands.

We propose a modular manipulator for an intra-vehicular crew support robot that ensures the safety of astronauts in the event of an unexpected collision by disassembling itself if an astronaut comes into contact with the robot [1][2]. Because the robot consists of modules, it can be stored compactly in limited intra-vehicular space, it can be assembled into various structures, and it can utilize various types of end effectors for various purposes.

We developed a prototype model for a modular robot based on this concept [1], but the prototype model needed some improvements in its size and its connection mechanism. The prototype model required a mover 1 meter long for a manipulator with six degrees of freedom. This size may constrain the use of the robot in a limited space such as that on the space station. In addition, the connection strength between the modules of the prototype were stronger than we expected because we used mechanical connectors to ensure connection. Unfortunately, this mechanism slightly decreased the collision safety of the prototype by increasing the force of the impact necessary to cause disassembly. To increase the reliability of the robot and its safety in the event of an unexpected collision, we decided to improve on the prototype and develop a new modular robot that would be smaller in size and would disassemble in response to a weaker impact.

To achieve small size and small-impact disassembly, we improved the modular robot in the following three ways.

First, we improved the decentralized controller unit to increase its capability and reduce its size. A joint mechanism called a "cross-gear universal joint" was developed for the modular manipulator to provide two degrees of freedom in one joint. However, in the prototype model, one controller controlled one degree of freedom. Using this control architecture, two controllers and two batteries would be needed for one joint, and we could not take advantage of the compact nature of the cross-gear universal joint. Therefore, the decentralized controller unit was improved to control two degrees of freedom in one control unit using a small high-performance micro controller. In addition, the size of the controller unit was reduced.

Second, we changed the connection mechanism from a mechanical contact system to a magnetic contact system. The prototype model employed a claw mechanism to increase the positioning accuracy and inertial support of the end effector. However, using a mechanical contact system slightly impedes the flexibility of the disassembling process and increases the force of the impact needed to cause disassembly. Therefore, we changed the connection mechanism from a claw-type mechanical joint system to a magnetic connection system. This improvement not only reduces the impact force required to cause disassembly but also increases the flexibility of the system.

Third, we increased the variety of shapes and structures that can be formed using the modular robot. The ability to assume various shapes and configurations is one of the most unique features of a modular robot. In the prototype model, the joint mechanism and controller/link structure were designed as one simple module, so it was rather limited in the number of shapes it could assume. To increase the variety of shapes and structures possible, the joint module and link module were separated in the new, smaller modular robot. Using separate structures, various types of joint mechanisms can be utilized in the same modular scheme.

In summary, based on the considerations described above, we improved upon the prototype model in the following three ways in the development of a new, smaller modular robot.

(1) Improvement of the control architecture to reduce the system size.
(2) Use of a magnetically jointed connection mechanism to reduce the disassembly impact.
(3) Separation of the link modules and the joint modules to allow the robot to assume various shapes and configurations and perform various movements.

In this paper, the basic concept of the modular robot for intra-vehicular support and the details of the new, smaller modular robot are described briefly. The results of tests conducted to assess the performance of the robot with respect to the disassembly impact are also described.

2 Modular manipulator for use on the space station

2.1 Concept

The basic concept of the modular manipulator is “self-disassembly.” For safety, the robot must disassemble itself if it comes into contact with an astronaut.

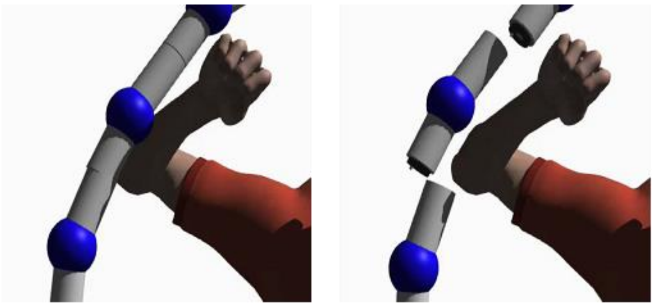

Figure 1: Modular robot with disassembly mechanism

The modular manipulator is composed of various types of modules that have a variety of functions. Some examples of these modules and functions are shown in Figure 2.

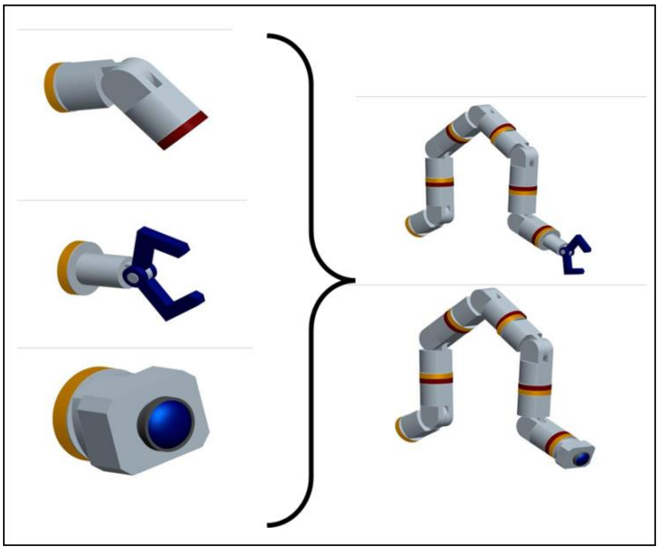

Figure 2: Changing the modular robot’s structure

In Figure 2, the modular manipulator is shown as being composed of one joint module, one hand module, and one camera module. We have developed this modular manipulator to function as a working robot on the space station.

Details of the module manipulator prototype model

Table 1: Specification of module manipulator

Number of joint modules	3
Degrees of freedom	6
Maximum value of the angular velocity	9.76 [deg/sec]
Maximum turning angle	80 [deg]
Mass of one module	755 [g]
Length of one module	445 [mm]
Outer diameter	55 [mm]
Inner diameter	50 [mm]
Torque	10.8 [Nm]

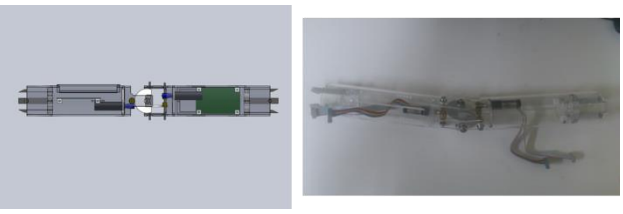

Figure 3: Modular manipulator

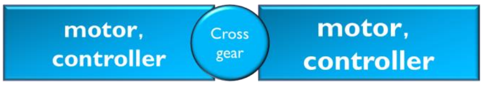

Figure 4: Mounting element

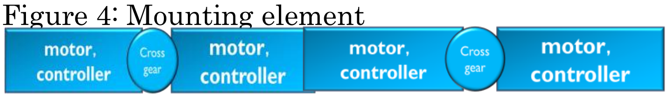

Figure 5: Jointed assembly

The module manipulator uses one controller for each motor and, therefore, two controllers per module.

2.2 Contact Mechanism

The module manipulator has a “self-disassembly” system. The module manipulator disassembles itself if the robot comes into contact with an astronaut. The self-disassembly system is shown in Figure 6.

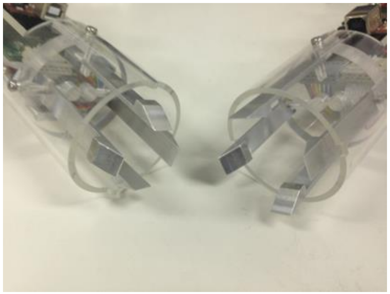

Figure 6: Self-disassembly system

This system is designed for heavy work. Therefore, the system does not disassemble itself easily in cases other than emergencies.

3 The new modular robot

The new modular robot is shown in Figure 7.

Figure 7: The new modular robot

Figure 8: Joint module

Figure 9: Link module

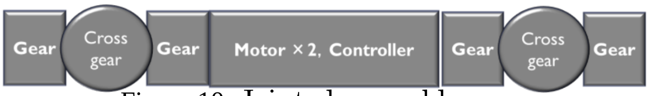

Figure 10: Jointed assembly

In Figure 7, the robot is shown in a configuration that combines one link module and one joint module.

The internal structure of the link module and the joint module are shown in the diagrams in Figures 8 and 9, respectively. A block diagram of the resulting combination of the modules is shown in Figure 10. The miniaturization achieved is made possible because one controller controls two motors.

3.1 Details of the link module

The link module is shown in Figure 11, and its specifications are summarized in Table 2.

Figure 11: Link module

Table 2: Specifications of the link module

Weight	402 g
Length	445mm
Outer diameter	55mm

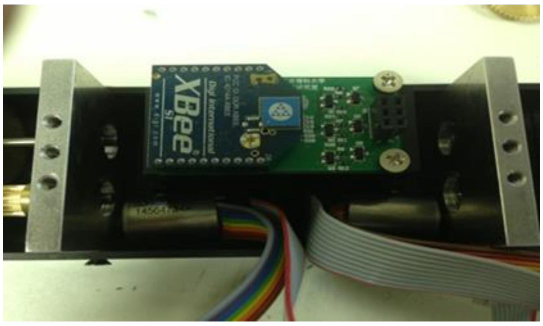

Figure 12: Interior of the link module

The link module has all of the drive and control elements required, including a motor, circuit board, communication module, and battery.

3.2 Details of the joint module

The joint module is shown in Figure13, and its specifications are summarized in Table 3.

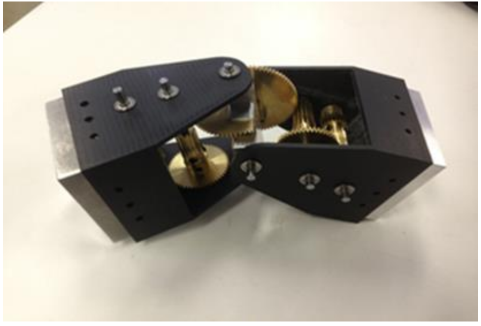

Figure 13: Joint module

Table 3: Specifications of the joint module

Weight	255 g
Length	130mm
Outer diameter	48mm

The joint module's mounted devices are gears. Therefore, the development of a new joint module is easy, and the robot can easily be configured in a variety of ways. In addition, a new mechanism called a cross-gear universal joint that we have developed has been adopted for the joints.

3.2.1 Cross-gear universal joint

This system was developed by our research team. The key feature of the cross-gear universal joint is that this joint can achieve two degrees of freedom at one point [3].

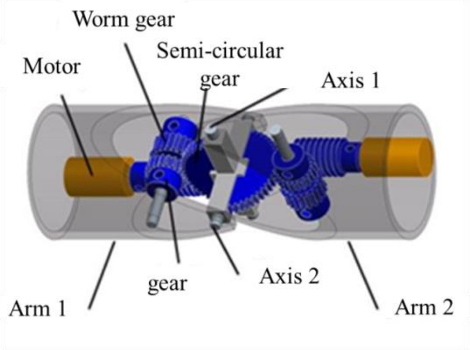

Figure 14: Cross-gear universal joint

This mechanism is an application of a rack gear. Figure 15 shows how the cross gear compares to a rack gear.

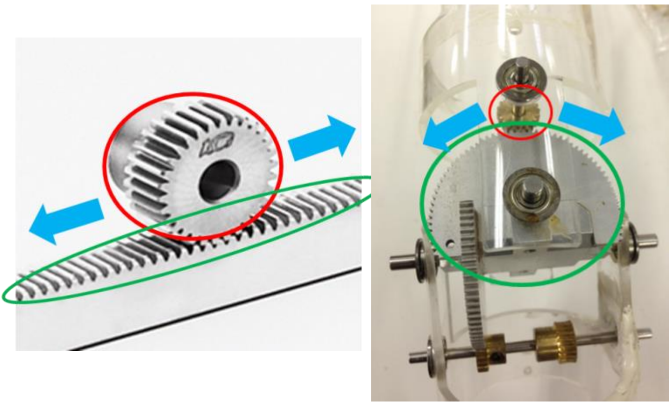

Figure 15: Cross-gear universal joint

The part encircled in red in the image on the left-hand side of Figure 15 corresponds to the part encircled in green in the image on the right-hand side. The part encircled in green in the image on the left-hand side is called the "rack gear," and the part encircled in red in the image on the right-hand side is called the "cross gear." The parts encircled in red in the images on the left-hand and right-hand sides are called "drive gears." Each link is moved by a drive gear driving the cross gear. In other words, a variety of movements can be achieved by changing the shape of the cross gear.

4 Self-disassembly system

The central design concept of the modular robot is that the safety of astronauts is ensured by the modular robot disassembling itself in the event of an unexpected collision. The self-disassembly system that we developed for the robot makes use of permanent magnets, as shown in Figure 15.

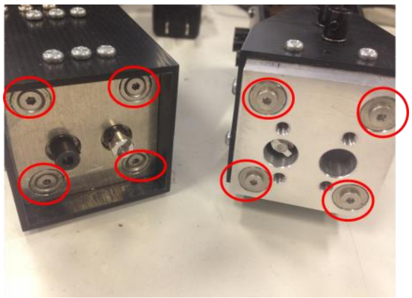

Figure 16: Self-disassembly system

This system is designed to separate upon application of a relatively weak force. The parts encircled in red are embedded magnets. Each of the modules are connected by the forces induced by these magnets.

In the study described in this paper, we divided one module into a link module and a joint module. The link module contains the motor, but the joint module does not have any actuator. To move the module robot, the power of the motor must be transmitted to the joint module. We have developed a transmission system called a “collar connection system.” Figure 16 shows the parts of the set collar connection system.

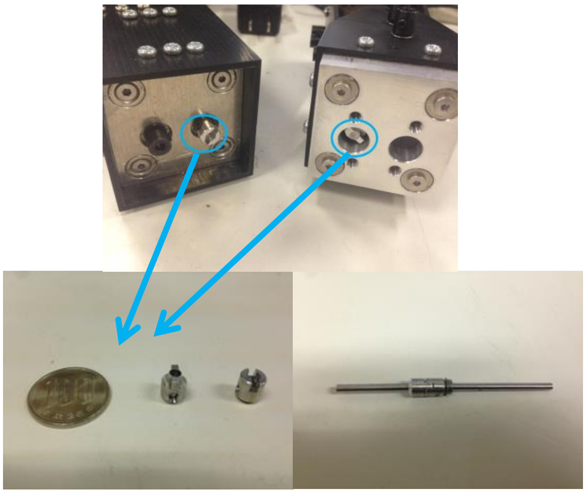

Figure 17:Set Collar connection system

The parts encircled in blue are parts of the collar connection system. When the link module and joint module are connected, the collar system connects the turning shaft and transmits the power of the motor.

5 Safety verification

We verified the safety of the robot by means of the experiment described in this section.

5.1 Experiment setup

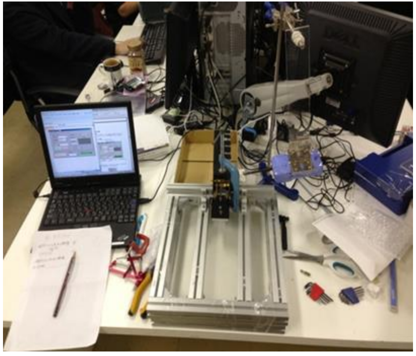

Figure 18: Experiment setup

Figure 19: Digital force gauge

To measure the ability of the robot to self-disassemble, we measured the contact force required to make the robot disassemble itself.

Experimental procedure

The force gauge was pressed against the robot 3, 6, 9, 12, and 15 cm from the point of attachment of the modules. We measured the force on the robot when it disassembled.

Experimental results

We obtained the results shown in Table 6.

Table 6: Measured values

The Pressing point from attachment (cm)	Measured value (N)	Measured value (N・m)
3	47.4	1.422
6	25.3	1.518
9	20.3	1.827
12	16.4	1.968
15	12.5	1.875
Average value		1.722

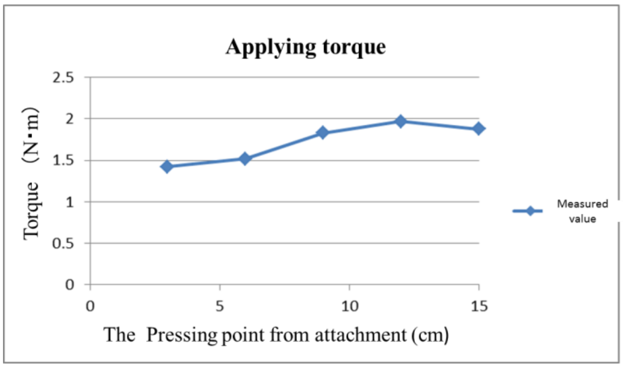

Figure 20: Torque applied versus distance from the attachment

Verification

We verified that the results we obtained from the experimental tests were appropriate through the calculations described below.

It was assumed that the centers of the link modules of the tip of the robot came into contact.

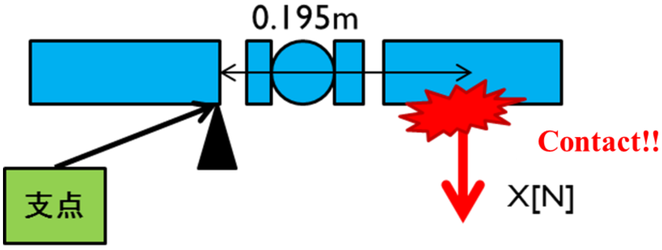

Figure 21: Contact condition

The contact force was calculated as the average applied torque determined from the measured values.

0.195 [m] × X [N] = 1.722 [N・m]
∴X = 8.83 [N]
8.83 [N] ÷ 9.8 [m/s^2] = 0.9 [kg・f]

Verification result

Based on the above results, we determined that this modular robot disassembles itself when a force on the order of approximately 900 [g] is applied. This is a sufficiently weak force to ensure safety when this modular robot comes into contact with people.

5 Summary

In this paper, we describe how we reduced the size of the modular robot that we have developed and verified its safety. We also describe how we changed the configuration of the entire robot to reduce its size, improve its safety, and increase the variety of configurations in which it can be used.

In the future, we will develop a new joint module to make various other configurations possible. In addition, we want to develop an innovative system for autonomous distributed control. We hope that the modular robot developed in this research can be applied to uses in various fields.

References

[1] S. Kimura, M. Yamauchi, and Y. Ozawa, “Magnetically Jointed Module Manipulators: New Concept for Safe Intravehicular Activity in Space Vehicles,” *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 47, No. 3, 2011, pp. 2247-2253.

[2] Naohiro Uyama, Takehiro Matsunaga, Takashi Kurose, Tomohiro Narumi, and Shinichi Kimura, “Dynamics and Performance Evaluation of a Modular-Type Space Manipulator Guaranteeing Collision Safety for Intra-Vehicular Use,” *The 29th International Symposium on Space Technology and Science (29th ISTS)*, June 2-9, 2013, Nagoya, Japan, 2013-d-41.

[3] Shu Yamauchi and Shinichi Kimura “Cross Gear Universal Joint – A New Approach for Module Type Manipulators” 1 2012.