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FULL PAPER

Development of a separable search-and-rescue robot composed of a mobile robot and a snake robot

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In this study, we propose a new robot system consisting of a mobile robot and a snake robot. The system works not only as a mobile manipulator but also as a multi-agent system by using the snake robot's ability to separate from the mobile robot. Initially, the snake robot is mounted on the mobile robot in the carrying mode. When an operator uses the snake robot as a manipulator, the robot changes to the manipulator mode. The operator can detach the snake robot from the mobile robot and command the snake robot to conduct lateral rolling motions. In this paper, we present the details of our robot and its performance in the World Robot Summit.

Keywords: separable robot; snake robot; mobile robot; urban search-and-rescue; multi-agent system

1. Introduction

Robots often need to be used for search-and-rescue operations in large-scale disasters. Studies have been conducted on the research and development of various disaster-response robots [1][2][3]. Remote-controlled mobile robots driven by crawler mechanism is the majority of disaster response robots. Most of them equip robotic manipulators to handle objects and sensors to recognize surroundings [4][5]. Several types of snake robots are also proposed as disaster response robots. Snake robots are expected to investigate narrow and complex environments [7][6]. However, it is difficult to prepare a versatile robot that can be used in different type of disasters because the environment at each disaster site is different, and the tasks required for the robots are also diverse.

One solution to address the problem is to use a multi-agent system. For example, in [8], the researchers proposed a system for searching the inside of a damaged building by using grouped rescue robots. The system consists of robots, sensors, a network, a communication protocol, user interfaces, and database management systems. In the study, the researchers developed two types of mobile robot platforms in which robots could construct a network infrastructure and investigate the interior of a building. In [9], the researchers described an architecture for human–robot teaming for search-and-rescue activities; they describe a multi-agent system infrastructure that includes two types of robots, a simulation environment, and an approach to the sensor fusion and interface design for effective robotic control. In these examples, the role of the mobile robot is independent.

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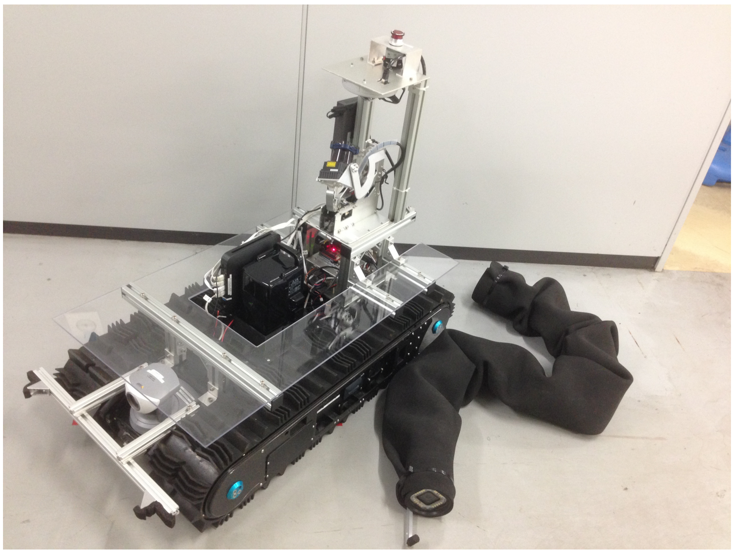

Figure 1. The two robots: the mobile robot and the snake robot

In this study, we focus on the possible multi-functional use of snake robots. Snake robots can be manipulators as well as mobile robots. Several kinds of snake robots have been developed for use in the real world [10]. A concept of a robot system composed a mobile robot and a separable manipulator [11], and a robot with dual-use arm for manipulation and locomotion [12] are previously proposed. However, snake robots still have room for improvement as remotely operated disaster response robots. For example, to maintain the feature of a snake robot, the robot should keep its long and thin structure. That gives constraints to the design of installing batteries in the snake robot, and operating time of the snake robot would be limited relative to ordinary mobile robots. In addition, locomotion speed of a snake robot is typically lower than an ordinary mobile robot.

In this study, we demonstrate a new robot system composed of a mobile robot and a snake robot. It works not only as a mobile manipulator but also as a multi-agent system by having a snake robot that separates from the mobile robot. This configuration complements the features of snake robots and mobile robots: the snake robot investigates a narrow space where the mobile robot cannot enter, the mobile robot can operate longer time and move faster than the snake robot. In this paper, we describe the details of the robot and its performance in the World Robot Summit.

2. Design of a separable robot

In this paper, we propose a combination of a mobile robot and a snake robot. A typical search-and-rescue robot is a remote-controlled mobile robot with sensors. Such mobile robots usually adopt a crawler mechanism to move on uneven terrain, and a few such robots have manipulators to handle objects. Disaster site often have very narrow spaces where ordinary mobile robots cannot enter. Snake robots have the possibility of examining narrow spaces. The snake robot can function as a manipulator when it is on a mobile robot, and the snake robot can detach from the mobile robot for examining narrow spaces.

Each robot needs to be an independent remote-controlled robot, that is, each robot needs to have a battery and a wireless communication device in addition to having sensors for remote control. Consequently, the robot can be operated as a separable search-and-rescue robot. In this study, we developed a mobile robot and a snake robot, as shown in Figure 1. The details of each robot are described in the following sections.

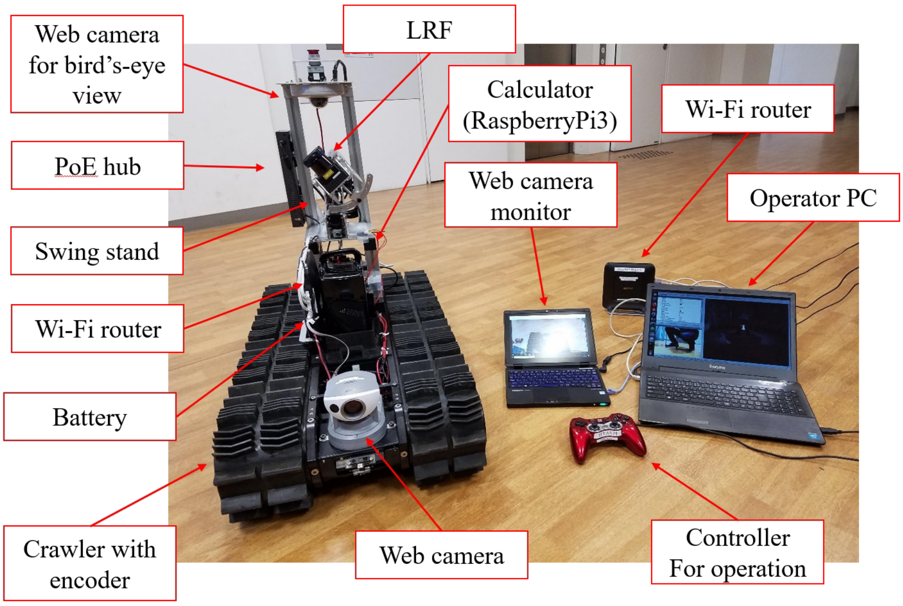

Figure 2. Hardware components of the mobile robot system

2.1 *Mobile robot*

2.1.1 Hardware of the robot

We developed a mobile robot, as shown in Figure 2. The robot is typical skid-steer-type mobile robot. The driving mechanism of the robot is an ordinary crawler mechanism with an order-made crawler belt. The robot has two web cameras. One pan, tilt, zoom camera (AXIS 213 PTZ) was located in the front of the robot so that it could look forward. The other camera (Canon VB-S30D MkII) was located at the rear top to monitor the surroundings of the robot; this provide a bird's-eye view. A calculator (Raspberry Pi 3) was installed in the robot and was connected using an operator personal computer (PC) via Wi-Fi routers. The images of the web cameras were also transmitted via the Wi-Fi routers, and they were displayed on the PC monitor. A laser range finder (LRF) (HOKUYO UTM-30LX-EW) was mounted on the robot to measure the distance from the robot to the environments. The LRF was mounted on a swing stand to obtain three-dimensional data. The mechanism and algorithm to transform the coordinate system are described in [13]. In addition, we attached a transparent board for mounting a snake robot. The total size of the robot was (approximately) 0.95 m in length, 0.45 m in width, 0.78 m in height. The approximate weight of this robot was 44.5 kg. A battery (Panasonic, Lithium-ion battery, 25.2 V, 13.2 Ah) of the robot is mounted at the center of the robot. We confirmed that the robot can drive its motors for 4 hours 50 minutes. The maximum speed of the robot is 0.276 m/s.

2.1.2 Remote operation of the robot

The mobile robot program was developed by using the robot operating system (ROS), which was installed in the operator PC and Raspberry Pi 3. The operator watches a video image using the web cameras on the PC monitor, and also watches the three-dimensional point cloud measured by the LRF displayed on the PC monitor. The operator inputs commands to drive the robot and to change the orientation of web cameras by using a joypad controller. In addition, the software to automatically read the QR code is installed in the robot system. We used ZBar (open-source library) and zbar_ros (package of ROS) for the software to read the QR code.

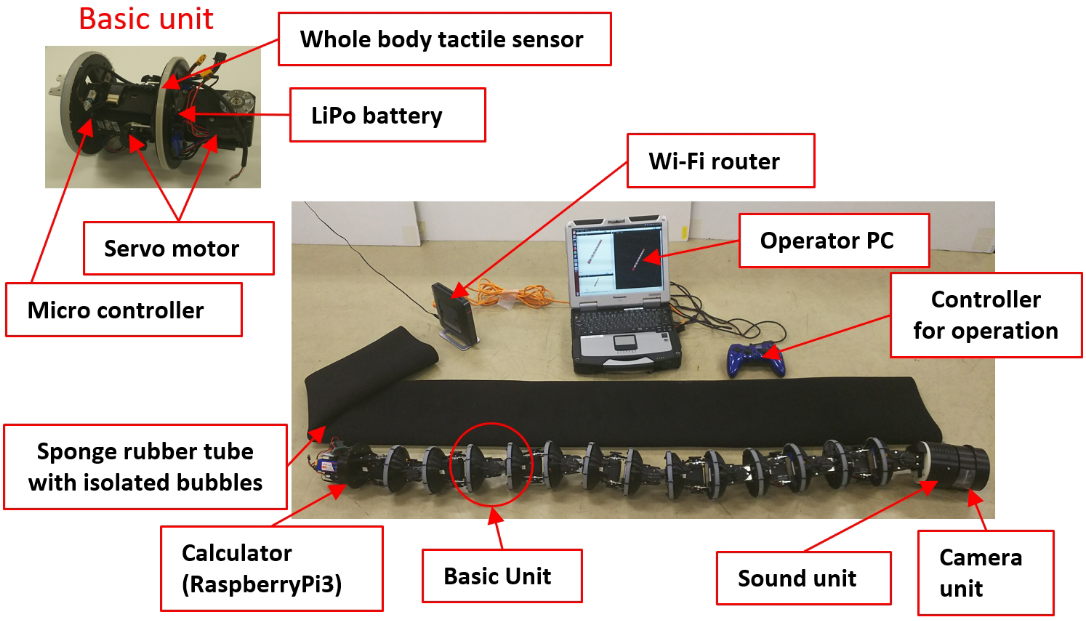

Figure 3. Hardware components of the snake robot system

2.2 *Snake robot*

2.2.1 Hardware of the robot

We developed a snake robot, named YATSUME, as shown in Figure 3. YATSUME was constructed by connecting the pitch axes and the yaw axes alternately to obtain three-dimensional motion. The robot had a total of 14 joints. For driving joints of servo motors, we used Dynamixel MX-106 manufactured by ROBOTIS Co., Ltd. We designed a basic unit consisting of two servo motors (a pitch axis and a yaw axis), a battery (Hyperion, Lithium-polymer battery, 11.1 V, 850 mAh), a microcontroller, and tactile sensor. In the head region of the robot, we installed a camera unit including an action camera (GoPro HERO 4 Session), an LED light, and a sound unit. In addition, we optionally attached a small hook on the head region to manipulate an object. At the tail part of the robot, we installed a calculator (Raspberry Pi 3), which was connected using an operator PC via a Wi-Fi router. The body of the robot was inserted into a sponge rubber tube made of an isolated bubble to make it waterproof and dustproof. The total length of the robot was approximately 1.5 m in length; its diameter was approximately 0.14 m, and its weight was approximately 8.5 kg. The maximum speed of the robot is 0.057 m/s in the pedal wave locomotion. The robot can continue the locomotion for 50 minutes.

The tactile sensor and the sound unit were not used in the World Robot Summit competition described later in this article; however, they were used for the inspection of the pipe interiors.

2.2.2 Control and motion of the robot

The the snake robot program was also developed by using ROS, which was installed in the operator PC and Raspberry Pi 3. The operator inputs a command by using the joypad controller. The status, such as the shape of the robot, was displayed on the monitor of operator PC by utilizing ROS visualization.

Initially, the snake robot was mounted on the mobile robot in the carrying mode. When an operator would like to use the snake robot as a manipulator, the carrying mode is changed to the manipulator mode. The carrying mode and manipulator mode are shown in Figure 4. When the snake robot changes to the carrying mode, it deforms gradually from the joints of the head so that it dose not fall down. After the deformation, an operator controls the position of the

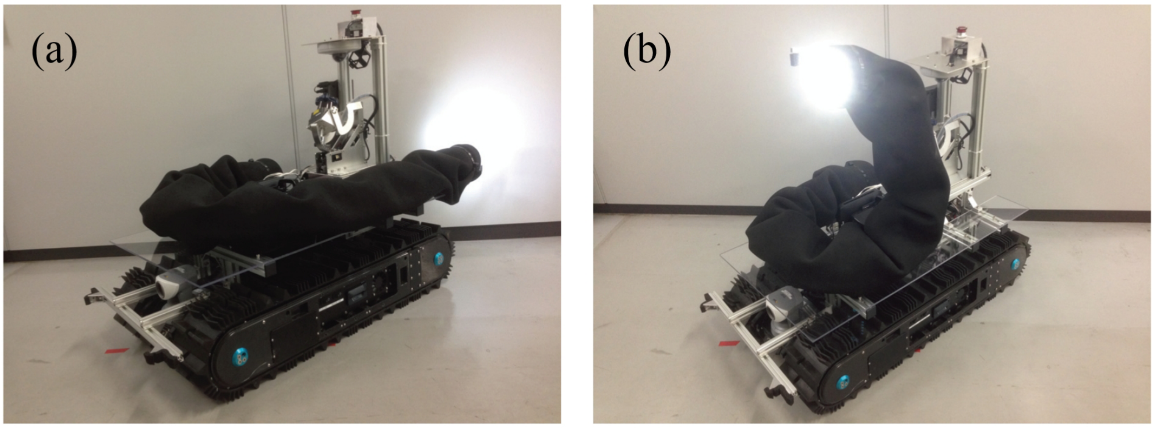

Figure 4. The combined robot; the snake robot is mounted on the mobile robot. (a) Carrying mode and (b) Manipulator mode.

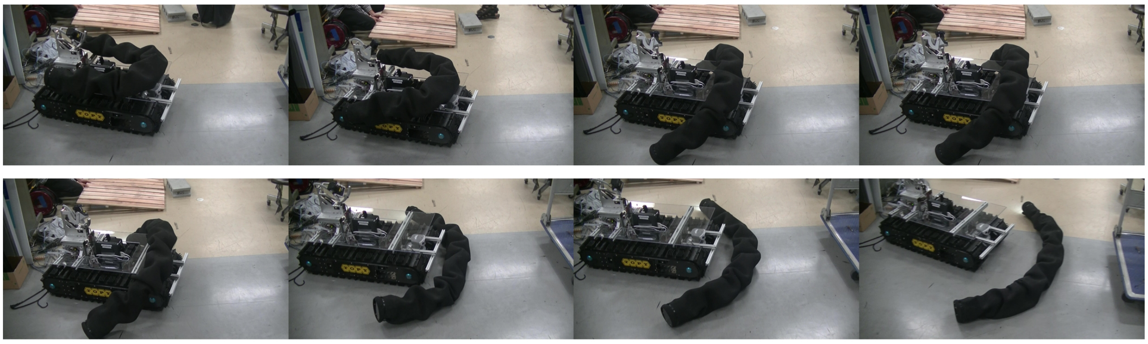

Figure 5. The snake robot detaches from the mobile robot by using a lateral rolling motion.

head portion by using the joypad controller.

Two control modes were implemented to the snake robot in the manipulator mode. One mode could change the position of the head keeping orientation of the camera. The other mode could change the angle of joint independently, each joint motion corresponded to the button of joypad controller.

2.3 *Preliminary experiments*

2.3.1 Detach the snake robot from the mobile robot

When an operator would like detach the snake robot from the mobile robot, the operator commands the snake robot to perform a lateral rolling motion. The details of the lateral rolling motion of a snake robot are described in [14] and [15]. Consequently, the snake robot moves on the mobile robot and finally detaches itself from the mobile robot. The detaching motion is shown in Figure 5. After the snake robot detaches itself from the mobile robot, the snake robot moves on the environment by itself. We implemented some motions of the snake robot, such as the helical rolling motion, the sidewinding motion, and the pedal wave motion, which have already been proposed as motions of a snake robot in [16][17].

In the current, it is not possible to mount the snake robot on the mobile robot again after the snake robot detached from the mobile robot. In our future work, that point will be improved by proposing a new motion of the snake robot to climb the mobile robot, so that the snake robot can be reused.

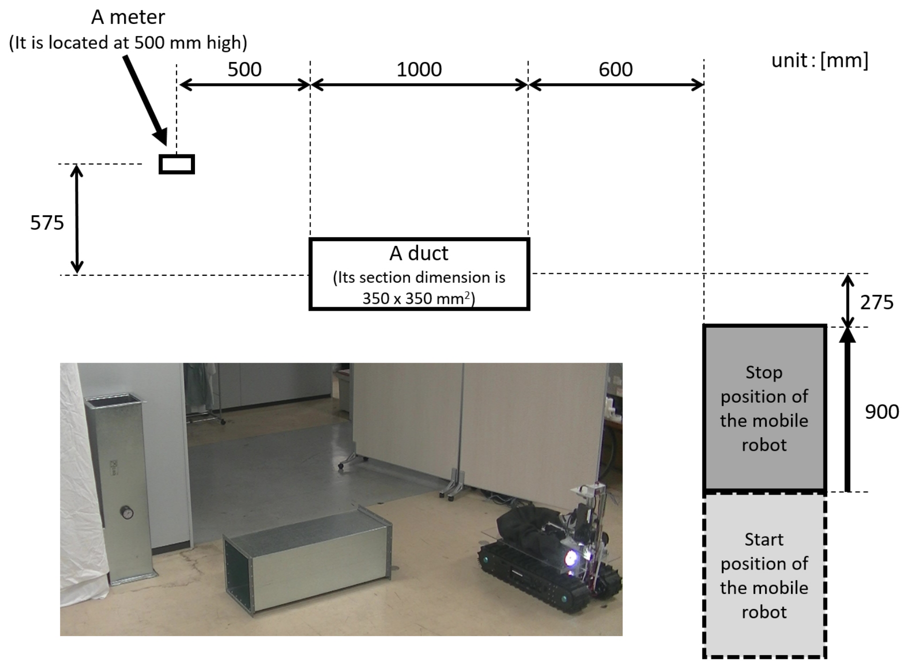

Figure 6. The layout of the experimental environment

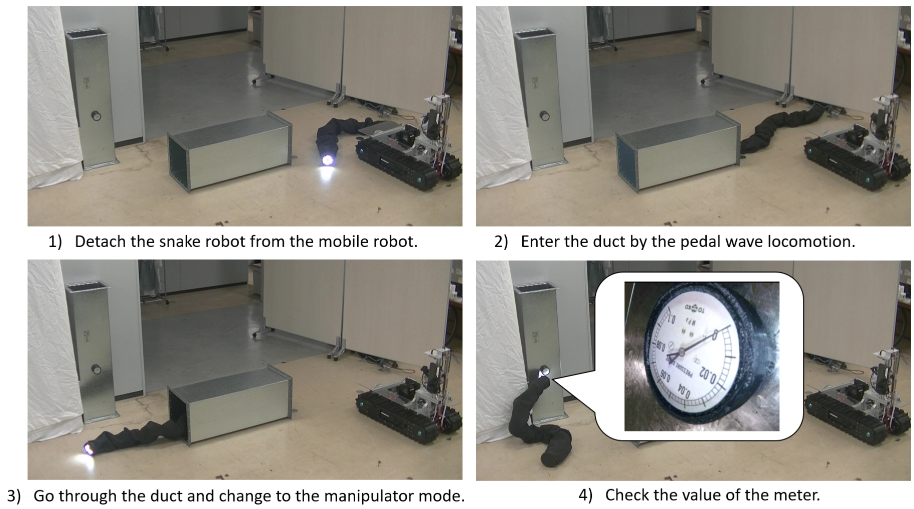

Figure 7. The sequential snapshot of the preliminary experiment and the final image captured by the head camera of the snake robot.

2.3.2 Investigation after going through narrow space

In this section, a demonstration to show the effectiveness our proposing system is shown. Figure 6 shows the layout of the experimental environment.

In this preliminary experiment, the target meter was located on the far side of the narrow space (a duct of which section dimension is 350×350 mm^2). The mobile robot can not reach the front of the meter because the size of the duct is smaller than the size of the mobile robot. The mobile robot carried the snake robot at the front of the duct, then the snake robot was detached from the mobile robot. After that, the snake robot entered the duct alone by using the pedal wave motion. The snake robot changed its mode to manipulator mode after going through the duct. Finally, the operator checked the value of the meter (which is located at 500 mm high) by using the camera on the snake robot. The sequential snapshot of the experiment and the final image captured by the camera is shown in Figure 7.

This demonstration shows that the our proposing system can achieve the task that is impossible in the case of a single mobile robot manipulator.

3. Performance at the World Robot Summit

The effectiveness of the separable robot was demonstrated in the World Robot Summit competition. We participated in the challenge of Standard Disaster Robotics in Disaster Robotics Category of the World Robot Summit. The Standard Disaster Robotics has several missions that evaluate robots for urban search-and-rescue activities [18]. Our team (called Oshinobi) tried most of the missions except for MOB1 (including the climbing of stairs) and SEC1 (including the manipulation of an object in uneven terrain); these missions were very difficult for our robot.

Figures 8, 9, 10 and 11 show how these missions are conducted. Figures 8 shows the DEX2 mission (including the manipulation of L-shaped object). In the mission, the snake robot was used to pull and push the object as a manipulator and use camera images from the head of the snake robot to look for the object. Simultaneously, the bird's-eye view camera on the mobile robot was used to observe the remote operations. Figure 9 shows the EXP1 mission (including the large-area inspection of a wall). In the mission, the PTZ camera on the mobile robot was used to detect the QR codes on the wall. In addition, the robot was able to conduct the tasks for the other missions by using the following functions of the robots: MAN1 (including the running through a relatively narrow space), MOB2 (including moving on the Grating/Checker plate), EXP2 (including the investigation in a duct), and DEX1 (including the reading of meters and manipulating valves). In particular, in the DEX1 mission, the snake robot was used to read the value of the meter by using the head camera on the snake robot, and it was also used to rotate the valve by utilizing the hook on the head region for manipulation, as shown in Figure 11. Our team was ranked 7th among 19 teams the participated.

It was not necessary to detach the snake robot from the mobile robot throughout the entire mission to earn points for the competition. However, we demonstrated how to detach in the MOB2 mission before ending the task. The detachment was conducted successfully in the mission, as shown in Figure 10. When the snake robot was not separated, it did not fall off the mobile robot even when the mobile robot shook a lot. In particular, in MOB2, the mobile robot sometimes shook greatly because of continuous slope running down a slope; yet, the snake robot did not fall off even through it was not fixed to the mobile robot. Servo was applied to each joint of the snake robot, and the snake robot was placed on the mobile robot in a certain shape. The snake robot was covered with sponge rubber; therefore, there was a large amount of friction between the mobile robot and the snake robot. Therefore, the snake robot did not fall off the mobile robot when external force was applied. In addition, this demonstration showed an example of the utility of the mobile robot: the mobile robot moved fast and long distance in the mission. The snake robot was able to save the power before it was detached from the mobile robot because the snake robot did not need to move long distance by itself.

4. Discussions

In this section, we summarize the merits and demerits of the proposed system and the lessons learned by participating in the World Robot Summit.

One merit of our system is that even in the development of robots, the mobile robot and the snake robot could be completely separated from each other. By separating a large system into subsystems, each subsystem can be independently developed and maintained. One advantage of the separation into subsystems is that while one team was debugging a robot, another team could

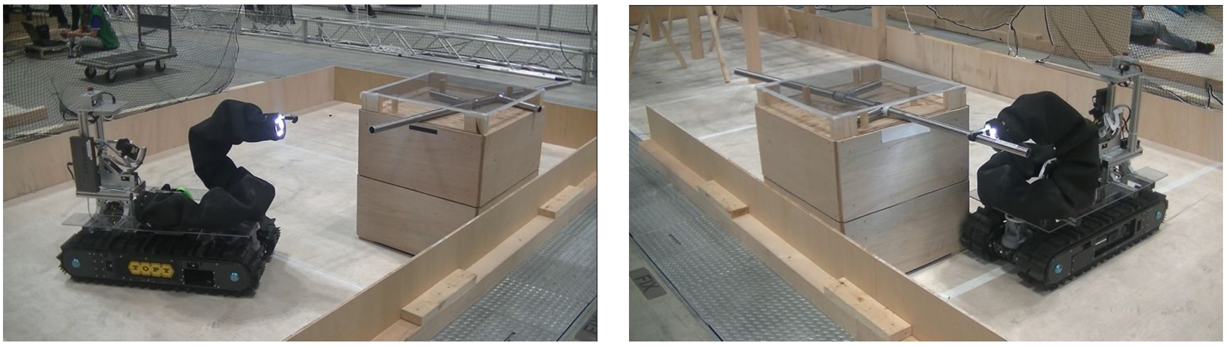

Figure 8. The snake robot performing the DEX2 task at the World Robot Summit. Left: Looking for a bar, Right: Manipulating the bar.

Figure 9. The mobile robot searching the wall in EXP1 task of the World Robot Summit.

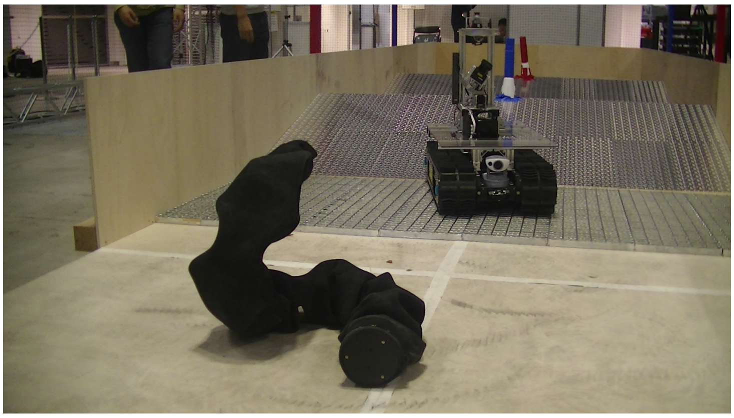

Figure 10. The snake robot looking at the mobile robot after being detached from it in MOB2 task.

develop and train the other robot. However, the separation of the robot has certain disadvantages. Two robot systems were completely separated, and the operations to be performed were complicated. According to the World Robot Summit rules, only one operator can operate the robots at one time. Therefore, it was necessary for the operator to master the operation systems of both the robots. In our team, we used the strategy of changing the operator by controlling the main robot depending on the mission. We need to develop a better operation interface for remote operations and for better integration of the ROS.

In the World Robot Summit, our system performed quite well; we could conduct several

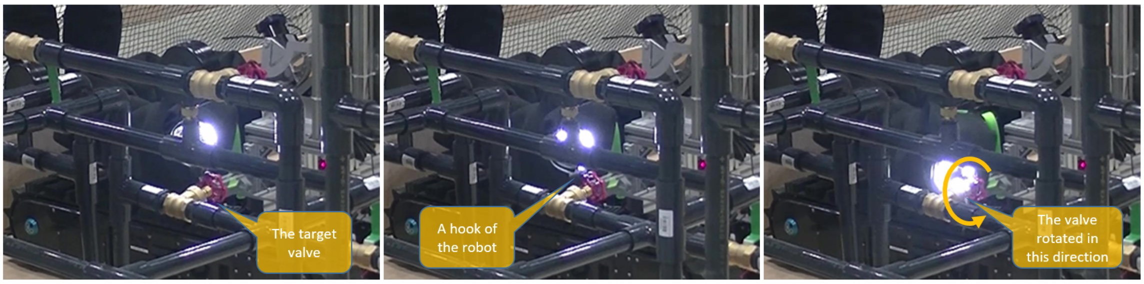

Figure 11. The snake robot manipulating the valve in DEX1 task.

missions in the competition by using the mobile robot along with the snake robot. However, each robot was not designed specifically for the mission; therefore, the performance of our robot was not the best. For example, if we had designed the mobile robot with a flipper arm, its mobility would have improved further in the missions that required the climbing of stairs. The snake robot had only a small hook, but if the gripper mechanism was attached to the head, the manipulating function could have been improved. To use the robot in a real disaster situation, we need to improve the functions of each robot.

In addition, we could not demonstrate the true value of our proposed system in the World Robot Summit. The advantages of our robot system design would have been evident for a task in a very narrow space where only a snake robot could enter. Nevertheless, our team achieved a relatively good performance because our robot was able to perform each task quite well. It is not always necessary to perform all the tasks using a perfect robot, such as a mobile robot with a manipulator. For example, our mobile robot could travel easily in a relatively flat environment without any problems, and it could scrutinize a wall by using the web cameras of the mobile robot. In this case, there was no need for a manipulator (i.e., a snake robot). We assumed that depending on the tasks required on the site, the mobile robot may be equipped with another robot that was not a snake robot. In the future, we propose to make the system more flexible by combining the subsystems based on the situation.

5. Conclusion

In this paper, we describe our robot as a separable robot consisting of a mobile robot and a snake robot that was mounted on the mobile robot. The snake robot functions as a manipulator and a mobile robot. The effectiveness of the separable robot was demonstrated in preliminary experiments and in the World Robot Summit. In our future work, we will focus on improving the robot system such that the remote operating system of the mobile robot and the snake robot can be combined. In addition, we propose to develop a new motion of the snake robot that of mounting on the mobile robot by itself after the snake robot detaches itself from the mobile robot.

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