Teleoperation of all-terrain robot using continuous acquisition of three-dimensional environment under time-delayed narrow bandwidth communication

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Abstract — Mobile rescue robots used in search and rescue missions must be able to navigate in unknown environments and map these environments. In such situations, three-dimensional (3D) data obtained by a laser range finder is very useful for supporting teleoperation of robots to locate victims and aid rescue crews in devising rescue strategies. However, when using conventional scanning systems to obtain such 3D data, the operators must wait for a few seconds and halt the operation of the rescue robot. To solve this time-loss-problem, our research group proposed a continuous acquisition system for acquiring 3D environment data for tracked vehicles using the 3D odometry with gyroscope. In locomotion issues, actuated subtracks, attached at the front and the back of the main body to improve stability of the robot, are commonly used to navigate on rough terrains, overcome large obstacles, and maneuver up or down stairs. However, managing actuated subtracks is difficult for the operator because only a small amount of information about the robot pose and environment is available. To assist the operators, our research group developed an autonomous control system based on the terrain data obtained using laser range finders for actuated sub-tracks. In this study, on the basis of the above systems, we developed a teleoperation system for mobile robots that functions effectively under conditions of time-delayed and narrow bandwidth wireless communication. In this paper, we introduce our teleoperation system and report the results of experiments performed to validate the system.

Keywords: *Teleoperation, All-terrain robot, 3D map*

I. Introduction

During natural or human disasters such as the great Hanshin Earthquake or the sarin gas attack in a Tokyo subway, rescue crews who search for victims may be injured during potential secondary disasters. In such cases, remote-controlled mobile robots (called rescue robots) can be used for searching missions in place of rescue crews in dangerous environments. However, it is not always possible to use high-speed wide-bandwidth communication to control rescue robots in such environments. In general disaster situation, conventional network infrastructure like mobile phone network cannot be used by breakdown or network congestion. Furthermore, if these rescue robots can be operated from distant locations, they will be additional assistance in search missions in the absence of rescue crews. Our research objective is to develop a teleoperation system that uses time-delayed and narrow bandwidth communication such as satellite communication for rescue robots.

During conventional teleoperation of rescue robots, operators use visual data obtained by cameras mounted on the robots to discern the surrounding environment of the robots. Moreover, speed control is typically used in the teleoperation of robots. Both these strategies pose problems when time-delayed and narrow bandwidth communication is used.

To solve the issues related to narrow bandwidth communication, we use three-dimensional (3D) range data obtained by a laser range finder as a representation of the surrounding environment of the robot during continuous navigation [1]. Although the size of 3D data is typically large, the data can be transmitted intermittently. In order to solve the issues related to time-delay, we use a teleoperation system based on indication of waypoints. In this method, an operator transmits the xy coordinates of the waypoint, instead of track speeds, to the rescue robot. This makes the method robust to time delay in communication. Since we cannot manually control actuated subtracks under time-delayed communication, we apply an autonomous control system for actuated sub-tracks [2].

In this research, we integrated the abovementioned teleoperation methods in our rescue robot Kenaf, which is shown in Figure 1. Then, assuming the failure of conventional communication infrastructure, we performed teleoperation experiments using the data obtained from the Engineering Test Satellite-VIII (ETS-VIII) launched by Japan Aerospace Exploration Agency (JAXA). In this paper, we describe the system integration for teleoperation and report the results of experiments performed to validate our teleoperation method.

II. Task definition and critical problems

As described in the previous section, we cannot always use high-speed wide-bandwidth communication to control rescue

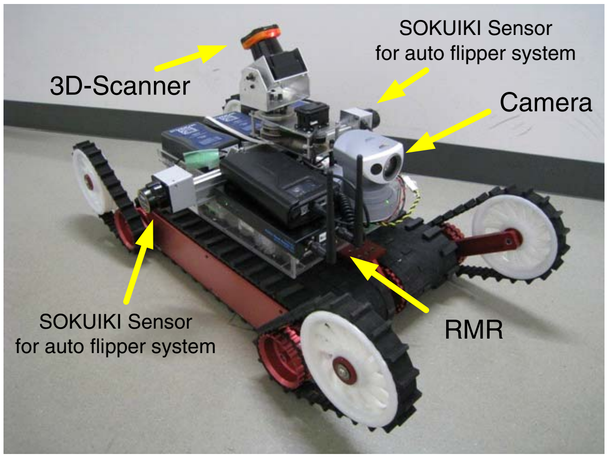

Fig. 1. Rescue robot Kenaf

robots in disaster environments. In the absence of rescue crews, teleoperation from distant locations can be of additional assistance in search and rescue missions. Therefore, we define our research task as the investigation of teleoperation of an all-terrain robot under time-delayed and narrow bandwidth communication.

In the conventional teleoperation of rescue robots, visual data obtained from cameras mounted on the robots is used to discern the surrounding environment of the robot. For this purpose, the following issues must be solved, (as described in the following sub-sections).

Issue 1: Two-dimensional (2D) Visual data

Typically, conventional cameras mounted on robots provide 2D images. In order to control the robots, operators extract 3D information regarding the environment from a series of 2D images for. This is a difficult process.

Issue 2: Narrow field of view

The robot body is not included in the field of view of the camera. Hence, the position of the robot relative to its target environment cannot be easily discerned. To estimate the pose of the robot, Shiroma et al. proposed an operating interface in which a virtual image of the robot is superimposed on the camera view [3]. This interface uses the previous images of the robot to estimate its current position and pose. Using this interface, operators can easily estimate the status of the robot relative to its environment. However, quantitative estimation of the distance between the robot and other objects in the environment is still difficult. In this method, we cannot choose an arbitrary view point; moreover, this method cannot be applied for teleoperation of the robot on a rough terrain.

Issue 3: Teleoperation of robot on rough terrain

To reduce the possibility of tipping over of rescue robots through rough terrains, such as obstacles and stairs, general rescue robots apply a stability function that uses subtracks mounted at the front and the back. The popular Packbot produced by iRobot and many tracked vehicles that participate in Robocup Rescue League [4] use such subtracks. Highly skilled operators are required for teleoperation of sub-tracks, which requires additional actuator control. Recently, some approaches for the autonomous control of subtracks to reduce the load on the operator were proposed. One approach is to use a contact sensing system that can detect the contact between subtracks and the ground [5]. Our recent approach is to use laser range finders that scan the terrain to obtain information about it [2].

The following issues must be solved in order to use time-delayed and narrow bandwidth communication such as satellite communication for teleoperation:

Issue 4: Narrow bandwidth

Usually, visual data is transmitted to an operator via continuous video streaming. This implies that a large amount of data is transferred even for a low-resolution image. Furthermore, streaming video may become unstable because radio quality varies depending on the position of the robot and the environment. Therefore, some of the frames may be dropped during narrow bandwidth communication, thus drastically decreasing the operativity of the robot.

Issue 5: Time-delayed communication

Typically, the time delay in satellite communication with mesh network is longer than that observed in a conventional wireless network. For example, the time delay of data transmission in satellite communication using ETS-VIII is approximately 600 ms. The time delay in the mesh network increases with the number of relay stations. This makes it difficult to constantly control the speed of the robot using a joystick.

To develop methods to compensate for the time delay, some teleoperation experiments were performed on an orbital manipulator for ETS-VII [6]. These experiments were jointly conducted by JAXA and Tohoku University in 1999. In these experiments, to improve an operator's maneuverability, the pose of remote manipulator for the operator's display was estimated by historical data of joystick control and a virtual model of the manipulator. The teleoperation system worked fine, and it verified a validity of such teleoperation method of manipulators. However, in case of a teleoperation method of mobile robots, estimation of the robot position is more difficult than that of manipulator pose because of the uncertainty involved in environment sensing.

Issue 6: Small wireless coverage area

The maximum output power of conventional wireless communications is limited to 10 mW by the Japanese Radio Law, and it causes that the maximum range of conventional wireless communications becomes from 50 m to 100 m in typical. Mesh networks are being actively researched to expand the wireless communication area. Recently, we successfully performed the long-distance navigation of tracked vehicles using a combination of wired network and wireless mesh network [7].

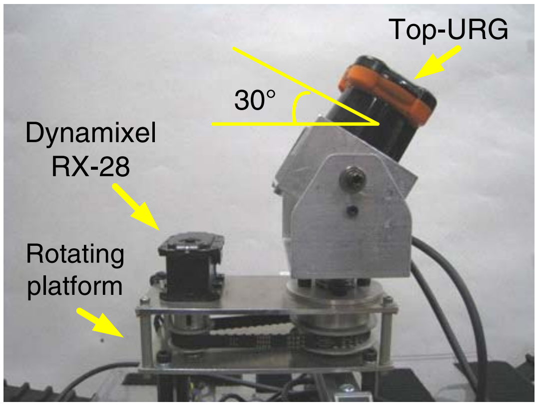

Fig. 2. 3D range finder

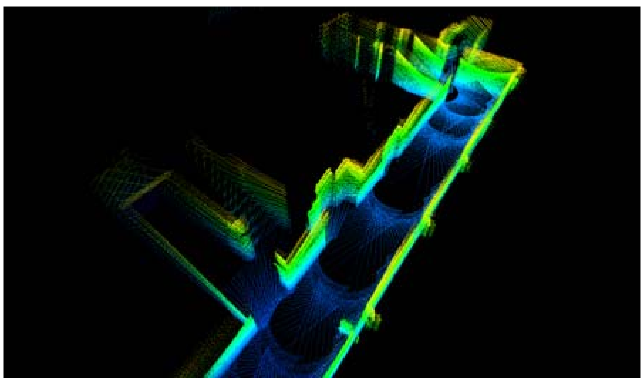

Fig. 3. A scanned image obtained using continuous acquisition system

III. TELEOPERATION OF ALL-TERRAIN ROBOT

To realize the teleoperation of all-terrain robot under time-delayed and narrow bandwidth communication, issues 1-6 must be solved. Therefore, we integrated five elemental systems, (1) a continuous acquisition system for acquiring 3D environment data, (2) a display system for the 3D environment model, (3) a teleoperation system based on indication of waypoints, (4) an autonomous control system for actuated subtracks, and (5) a satellite communication and mesh network system. Each elemental system is explained in the following subsections.

A. Continuous acquisition system for acquiring 3D environment data

To solve issues 1 and 2, we use a laser range finder to obtain 3D environment data, which is then transferred to the operators. The 3D environment data helps the operators discern the target environment. In the conventional teleoperation method, a robot remains stationary until the scan is completed. In our case, the scan time for 360^o view is typically less than 10 s. However, such time delay should be avoided in search and rescue missions. To reduce the time loss, we proposed the use of a continuous acquisition system for acquiring 3D environment data, in the last international workshop on Safety, Security, and Rescue Robotics (SSRR 2008) [1]. In this method, the xy coordinate of the robot is perfectly synchronized with the scan time. Therefore, the robot does not have to stop while the range data are being scanned. We have described this method in detail in [1].

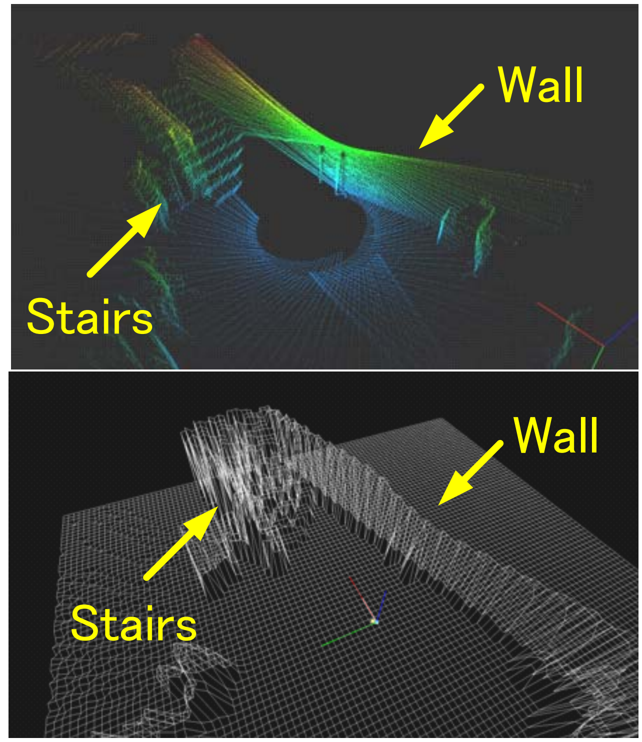

Fig. 4. Environment expression: Point cloud representation (upper image) and DEM (lower image)

Our 3D laser range finder is shown in Figure 2. It consists of a 2D laser range finder (UTM-30LX: Hokuyo Automatic Co., Ltd.), SmartMotor (Dynamixel RX-28: Robotis), and a rotation table. The scan surface is inclined at an angle of 30^o to the horizontal (Figure 2) to obtain the 3D range data of the environment. Figure 3 shows the image of a corridor obtained by continuous data acquisition without stopping the robot. This confirms the validity of our continuous acquisition system for acquiring 3D environment data. We used gyro-based odometry instead of the matching process.

B. Display system for 3D environment model

During narrow bandwidth communication, issue 4 becomes more significant than issues 1 and 2. For example, the upper image in Figure 4 is a 3D display obtained using point cloud data. This image is composed of 95,000 points, and the file size is 4 Mb in plain text style. To compress the image, we represented the environment using a digital elevation map (DEM) [8]. In DEM, each scan point is registered as data regarding the elevation from a base level and is stored in a lattice cell on the xy plane. The lower image in Figure 4 displays a DEM, which includes height data in 100 times 100 of the 2D array. The file size of the DEM data is 25 kb. Features of the environment are recognizable even if the 3D images are of poor quality; thus, issue 4 can be solved using DEM.

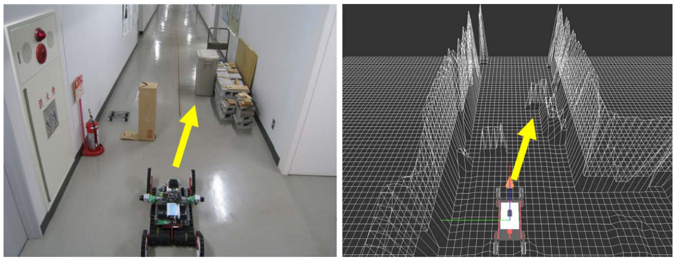

Fig. 5. Teleoperation system based on indication of a waypoint (lower image) and the corresponding real-world scene (upper image)

The DEM effectively represents an uneven environment, but it cannot be used to discern areas overlain by other objects. In case of existence of a ceiling, DEM is filled by the height of the ceiling. This is because only the highest scan point is registered. In this research, we set a proper threshold value of the maximum height to eliminate ceiling data.

C. Teleoperation system based on indication of waypoints

Operators obtain environment data for teleoperation from the 3D display system. However, the time delay (issue 5) in communication prevents smooth teleoperation by speed control. The operator must control the speed of the robot based on its past position and the past environment shown on the display.

To solve the abovementioned problem, we use an indication command that indicates waypoints instead of the speed control command. Using the indication command, an operator specifies the waypoint on the DEM. The robot follows the line between its current position and the next waypoint. This method is very robust to time delay in communication. If a next waypoint is updated before the robot arrives there, the robot is smoothly diverted along the new line that leads to the updated waypoint. However, if a large obstacle is suddenly inserted between the robot and the next waypoint, the robot may collide with the obstacle. Therefore, a waypoint should be set less than a few meters from the robot. Figure 5 shows an example of a teleoperation display (lower image) and the corresponding real world scene (upper image). The operator indicates the position of the arrowhead in the DEM using a mouse or any other input device, and the robot moves toward the corresponding a waypoint in the real world.

The above teleoperation system was inspired by the research conducted by Maeyama [9]; however, his approach was based on video images instead of a DEM.

D. Control of actuated subtracks for teleoperation

As mentioned in issue 3, highly skilled operators are required for teleoperation of actuated subtracks. Furthermore, manual control of subtracks is almost impossible during teleoperation based on indication of waypoints. This is because the robot controls its own speed. Therefore, we applied autonomous control system, which was developed by our research group [], for actuated subtracks. In this control system, information regarding a terrain and the posture of the robot is obtained by using laser range finders attached on either

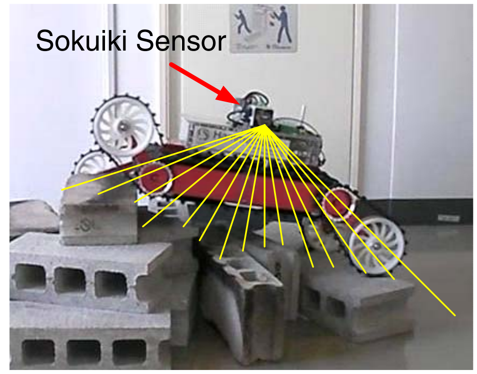

Fig. 6. Terrain sensing using laser range finder

sides of Kenaf. A gravity sensor and 3 degrees of freedom gyroscopes are attached to the center of the robot body. The robot generates motions of subtracks to improve stability of the robot based on the terrain data using a laser range finder, shown in figure 6.

E. Satellite communication and mesh network system

The disadvantage of using satellite communication is the narrow bandwidth and the long communication time delay. However it has a greater advantage given by the fact that the satellites are not damaged by the disasters on the ground. Although, such satellite communication terminals and antennas are sufficiently large, and it requires open sky, other wireless relay networks are required for communication between operators and robots. As described in issue 6, the maximum area covered by a conventional wireless LAN is limited. Therefore, to enhance communication area, we use a wireless mesh network in the disaster area. In this system, a robot places mesh relay nodes by itself in a target environment or some robots can be movable mesh relay nodes to maintain constant communication.

IV. Experiments

A. Target environment

To confirm the validity of our teleoperation system, we performed some experiments on long-distance teleoperation. In these experiments, the Sendai Astronomical Observatory building was considered as the disaster environment, and our laboratory at Tohoku University was considered as the operation room. The distance between these places was approximately 8 km. Inside the observatory, an open space on the first floor was used for conducting basic teleoperation experiments; the first and second floors were used as exploration area. Figure 7 shows a portion of the target environment in the observatory (left) and the operation room (right).

B. Tracked vehicle Kenaf

We used our tracked vehicle Kenaf (Figure 1) during our experiments using the teleoperation system shown in the previous section. The testbed was designed for a project on development of component technology for advanced robots, "Mobile RT Systems in Disaster Buildings," supported by

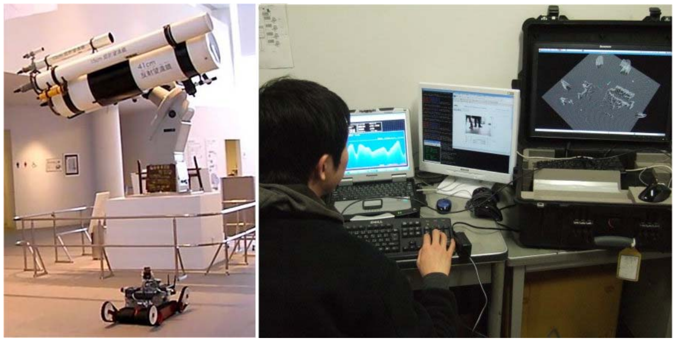

Fig. 7. Experimental environments

NEDO, Japan. The basic mechanism and controls of Kenaf are described in [9]. Kenaf has two main tracks at the bottom of its body and four subtracks to enable terrain-reflective motion. Two short-range laser range finders are attached to either sides of the robot body to obtain terrain data; a 3D long-range laser range finder and a pan-tilt camera are used to obtain 3D environment data and visual data, respectively. Rokko Mesh Router (RMR) (Thinktube Co. Ltd.) is used to enable communication between Kenaf and the ground station (in the simulated disaster environment) via the wireless mesh network.

C. Satellite communication and mesh network

We used ETS-VIII to enable communication between the ground station and the operator site. This satellite was launched into the target geostationary orbit on December 18th, 2006 at 146^{o}E.

We used satellite dish antennas with a diameter of 1.2 m at both the sites–the disaster environment and the operation room. This enabled bidirectional communication up to 768 kbps. From our preliminary experiments, we measured the bandwidth to be 704 kbps in 768-kbps mode and 352 kbps in 384-kbps mode; the average time delay was approximately 560 ms.

Inside the simulated disaster environment, we first introduced six RMR to construct the wireless mesh network. The maximum time delay in three-hop communication was approximately 250 ms, and the typical time delay under the same condition was approximately 160 ms. The throughput of the mesh network part in 3 hops is over 3Mbps, and is larger than the satellite network part. The mesh network was connected to the satellite network through a standard LAN connection.

Figure 8 shows an overview of the network configuration used in this experiment.

In this experiment, the following data were transmitted:

- Video streaming data obtained by mounted network camera (AXIS 213 PTZ : 352pixels $\times$ 240pixels, 80% compression, 10 fps) mounted on the robot
- DEM data (100$\times$100, approximately 25 kb in every 5 s)
- Control command (reference track speeds or xy coordinates of waypoints).

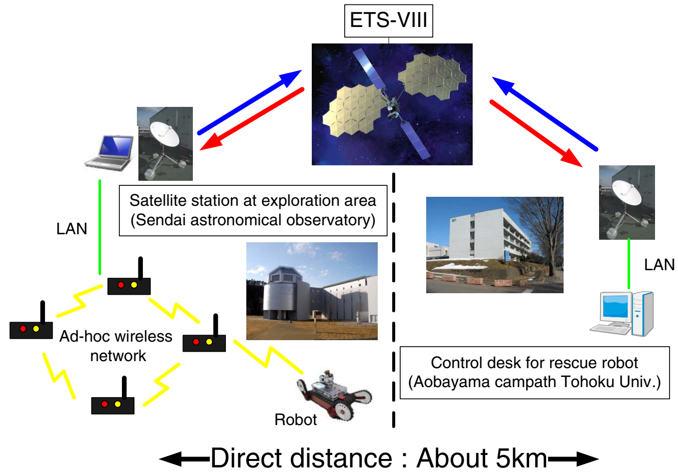

Fig. 8. Network configuration

D. Experiment 1: Teleoperation in slalom course

To confirm the validity of our system, we created a simple slalom course for teleoperation. We placed three pylons at the 5-m intervals on a flat ground. The mission was as follows: Each operator had to navigate Kenaf along the specified course and to return it to its initial position. Owing to the time constraints, trials were performed with expert operator and inexpert operator under the following conditions:

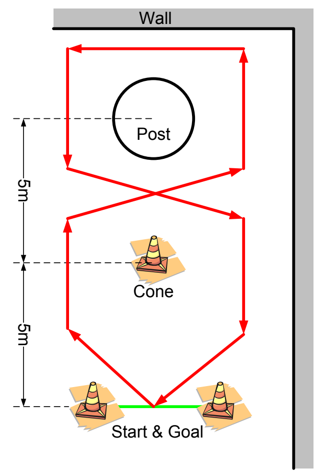

Fig. 9. Target course for oeprators

1) Teleoperation based on speed control using data obtained from a single camera
2) Teleoperation based on speed control using data obtained from a single camera and DEM data
3) Teleoperation system based on indication of waypoints using data obtained from a single camera and DEM data.

Fig.9 shows the target course for operators.

We performed the abovementioned teleoperations at two communication speeds, 768 kbps and 384 kbps. Table I shows the experimental results. Both the operators succeeded in returning to the initial point only under the third condition, regardless of the difference in the skill of the operator and the communication speed. This experiment proved that teleoperation of mobile robots based on speed control is very difficult, and that the teleoperation system based on indication of waypoints functioned efficiently under the abovementioned conditions. In addition, during communication at 384 kbps, vision-based control was difficult because of periodic freezing of the video image. However, the transmission of DEM data every 5 s was stable even at narrow bandwidth communication. This proves the advantage of our system.

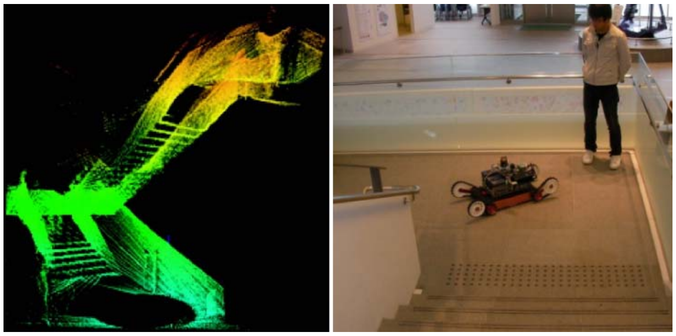

Fig. 10. Image obtained using point cloud data (left) for the stairs (right)

E. Experiment 2: Long-distance navigation

To validate our proposed system qualitatively, we demonstrated long-distance navigation using this system. The navigation course included flat surfaces, stairs, and narrow gaps, shown in the Fig.11. Although the operators were aware of the target position and the rough terrain, the details regarding the paths were not conveyed to them. The path length was about 150 m from the initial to the target positions. The trials were also performed at both the communication speeds, 768 kbps and 384 kbps.

At both the abovementioned communication speeds, the operators successfully reached the target position and returned to the initial point. This experiment proves that the proposed teleoperation method is practicable in actual search and rescue missions. The actuated subtracks (described in section III-D), in particular, were effective in maneuvering Kenaf up or down the stairs. Figure 10 shows an image obtained using point cloud data while Kenaf maneuvered the stairs.

V. Conclusions

In this research, we integrated the following elemental systems into our teleoperation system under time delayed and narrow bandwidth communication for Kenaf : (1) a continuous acquisition system for 3D environment data, (2) a display system for 3D environment model, (3) a teleoperation system based on indication of waypoints, (4) an autonomous control system for actuated subtracks, and (5) satellite communication and mesh network system. As seen from the experiments in which we used the data obtained from ETS-VIII, our teleoperation system worked effectively under time delayed and narrow bandwidth communication. Thus, the validity of our teleoperation system under these conditions was established.

TABLE I

Experimental results of teleoperation in slalom course

	Expert operator		Inexpert operator	
	768kbps	384kbps	768kbps	384kbps
Speed control using camera only	×	×	×	×
Speed control using camera and DEM	○	×	×	×
Waypoints control using camera and DEM	○	○	○	○

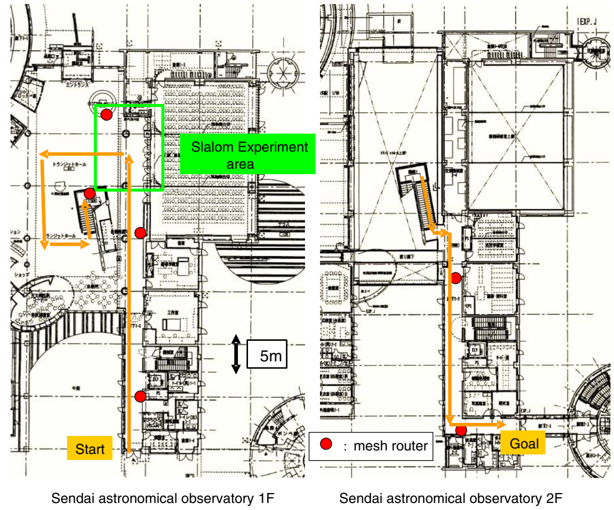

Fig. 11. The target environment in Experiment 2

In our future research, we shall consider introducing a path planning assist system in our teleoperation system, which suggests a reasonable path of the robot based on sensing data, to reduce the load on operators.

Acknowledgement

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