Development of a remotely operated robot system for movement in narrow areas based on workspace characteristics

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***Abstract*— When several robots operate in the same workspace simultaneously, e.g., in nuclear decommissioning, it is necessary to consider their movement in narrow areas. In such environments, both autonomous navigation and manual remote operation are necessary because of the unknown operating conditions that may require human judgements. We develop and experimentally verify an enhanced remotely operated robot system that can freely switch between autonomous navigation and manual remote operation with a common communication protocol; its operating conditions can be changed according to the workspace characteristics. In the proposed system, a robot could move in narrow areas by specifying the workspace and automatically changing its obstacle detection distance. Furthermore, it showed that two robots could pass-by each other without any coordination by appropriate conditions. We will investigate additional parameters, such as movement speed and priority using inter-robot communication for nuclear decommissioning and other applications.**

I. INTRODUCTION

Various remotely operated robots are used for nuclear decommissioning tasks at the Fukushima Daiichi nuclear facility (1F) [1]-[5]. Such tasks are unpredictable and require decision-making during the process of performing them. Thus, work efficiency can be improved when multiple robots operate in the same workspace simultaneously because the 1F area is narrow and contains debris. Consequently, coordination among robots is required to avoid robot damage and ensure that a robot does not block the movements of other robots. In this study, we propose a control system that enables a remotely operated robot to move without getting stuck, even in narrow areas. The proposed system can control several types of robots using a common communication protocol and the same graphical user interface (GUI) [6],[7]. In particular, robot movements are based on workspace characteristics to improve the performance of the system. Additionally, our system is considered to design for "easy to understand and operate".

II. REMOTELY OPERATED ROBOT SYSTEMS BASED ON WORKSPACE CHARACTERISTICS

Several concepts, such as spatial intelligence [8], information-structured environment, and "Kukanchi" [9]-[11], have been proposed for robots operating to communicate with environmental characteristics. In this study, we develop such a robot system with easy-to-understand operations. These operations are increasingly important considering human error and work efficiency. In workspaces requiring detailed operations, the speed of robot movement must be reduced; in narrow workspaces for robots, the distance required for obstacle detection and avoidance must also be reduced. In contrast, in large workspaces, the speed of robot movement and the object detection distance must be increased. Additionally, the level of noise produced by robots must not disturb the surrounding work. By acquiring information on the robot's operating conditions from its workspace, human operators are not required to perform complicated adjustments on the robot's operating parameters such as movement speed or obstacle detection distance. Furthermore, operators may be confused if a robot makes decisions and modifies its operating conditions autonomously; it is easier for them to understand robot operations based on the workspace.

III. ROBOT MOVEMENT IN NARROW AREAS

In this study, we examine robot movements in narrow areas where a robot blocks or narrowly avoids the movement of another robot. Mobile robots are usually equipped with an obstacle avoidance function to avoid collisions. The obstacle detection distance is usually set larger than the size of a robot, except in emergencies, when path planning and deceleration must be considered. Strictly speaking, the distance between detecting an obstacle and stopping needs to be considered. In addition, when the paths of two robots intersect, it is desirable to minimize the obstacle avoidance distance. In this study, we consider two robots that can avoid each other when operating in a narrow workspace. If this is impossible, priorities must be applied. For example, such priorities can be based considering the time each robot enters the workspace or the importance of tasks. In the first case, robots can be controlled by a high-level control system, which manages the status of robots in the workspace and makes the necessary decisions. In cases where

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the control system cannot decide on priorities or the disconnection from the high-level control system, the robots should make their own decisions. Navigation robots usually use self-positions and maps for their navigation, so they will be able to exchange information to determine their priorities. Robots with low priority can wait near the entrance or exit of a narrow area and let another robot with higher priority move first. In such cases, robots can decide their movements autonomously. Significant research has been conducted on multiple mobile robots moving autonomously in narrow areas, such as warehouses, to avoid collisions. Additionally, research and development has been conducted on communications among robots performing collaborative tasks [12]-[14] such as semiautonomous remotely operated robots employed in maintenance work in nuclear power plants. However, the existing research on robots operating in concrete working environments is limited. Therefore, new methods for robots employed in nuclear decommissioning are urgently required to enable them to operate smoothly in narrow areas.

IV. Remote Control System Using Robot Service Network Protocol (RSNP)

We have developed a remotely controlled robot system, operating via the Internet based on the robot service network protocol (RSNP). The developed system is shown in Fig. 1 [6]. RSNP, which was proposed and developed by Robot Service Initiative (RSi) in 2004, is a commonly used protocol for service robots. RSNP can link various service robots and allows service providers to provide the same service regardless of the type of robot they use. However, RSNP does not operate in real time; thus, a robot must be operated via command control [15],[16]. Blue line to RSNP Server in Fig. 1 shows the RSNP communication. It is possible to be an independent unit as an RSNP Unit, dotted block in Fig. 1, for easy connection with existing robots. RSNP transmits movement commands to various robots, acquires data from various sensors, and has been widely applied. We believe that by additionally applying remote control, the field of applications can be significantly expanded. So far, several applications have been developed [17]-[20]. Nuclear decommissioning using remotely operated robots is also an important field of application because data obtained from various sensors enable robots to operate autonomously and remotely.

In our remotely operated robot system, we implemented navigation control using the robot operating system (ROS) [21] and communication via the Internet using RSNP. Message queuing telemetry transport (MQTT) was used for communication between RSNP and ROS. MQTT communication is commonly used to easily connect a system (i.e., a robot and its surrounding environment, such as elevators, sensors, automated doors, etc.) to IoT. The developed GUI allows operators to remotely control a robot, without being aware of teleoperation or autonomous controls.

The GUI used in our system which is shown in Fig. 2; it controls a robot-mounted camera for the timely selection and display of images and an overhead camera installed in the workspace. GUI also features arrow keys, which are used for robot manual operation, and function keys for reproducing robot positions and movements registered in advance. The mobile robot creates a map of the workspace, moves to positions registered on the map via a RSNP server PC, located at another site, connected to the Internet, avoids obstacles using autonomous navigation, and can be manually operated to correct its position. For path planning, the user can select a time elastic band (TEB) or a dynamic window approach (DWA) planner in ROS system.

Furthermore, the system was designed so that the operator can instruct the robot to do specific tasks, rather than being aware of functions such as autonomous and remote control. Specifically, GUI controls the start/stop, autonomous control, and teleoperation state transitions, as shown in Fig. 3. Here, avoidance means the obstacle avoidance function. This allows the operator to freely switch between autonomous navigation and manual remote control via GUI. Pressing the arrow keys enables manual operation, whereas pressing the function keys enables autonomous navigation. Here, we have newly added the function which can change the object detection distance based on the environmental characteristics as shown in Fig.1.

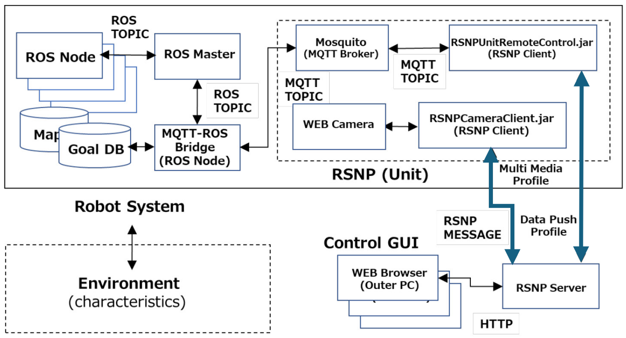

Figure 1. Control system of the developed remotely operated robot system using ROS, RSNP, and environmental characteristics

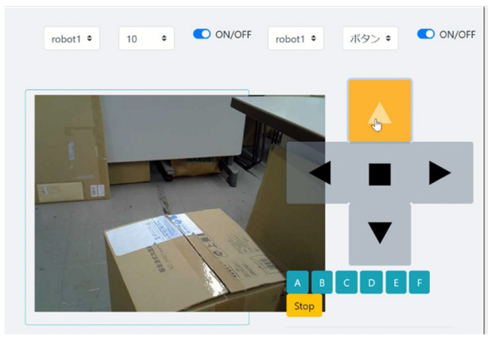

Figure 2. GUI for robot control

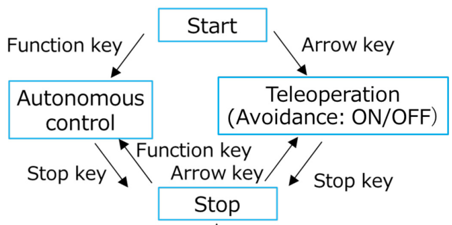

Figure 3. State transitions of the remotely operated robot system

V. Robot Behavior Based on Workspace Characteristics

We conducted a basic experiment by initially varying the object detection distance for obstacle avoidance by a robot in the workspace. This was implemented in the ROS system to enhance the RSNP remotely operated robot system. We mapped the workspace in advance and added a function to vary the obstacle detection distance inside and outside the workspace.

(1) Detection distance variation (from a wide space to a narrow space)

The variation in the detection distance is shown in Fig. 4. The detection distance (referred to as mod in the figure) was specified as mod_op, mod_na, and 0 for a wide space, a narrow space, and a stuck robot, respectively. Here, the values of these parameters for the robot were set to 0.7 m, 0.3 m and 0 m, respectively. Thus, mod can be used in a unified control manner. These parameters are not based on the actual environmental needs; however, they are used to verify the validity of the proposed function.

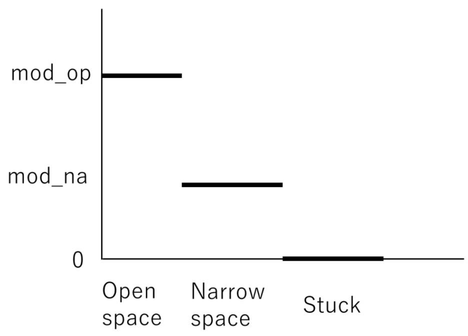

Figure 4. Relationship between detection distance and workspace

(2) Movement in a narrow area

The object detection distance was varied, even during manual remote control. In a previous study [7], the detection distance was set to 0 m as an escape from a stuck robot situation; however, in a poor visibility environment, a collision avoidance function allows safe operation. In especially narrow areas, four points (A–D) were specified on the map in ROS visualization tool Rviz, and the obstacle detection distance was varied inside and outside the specified area.

VI. Experimental Results and Discussions

6-1 Experimental setup

The experiment was conducted in the space with a narrow area (A-B-C-D), as shown in Fig. 5. The diameter of the robot was about 0.5 m, the aisle width was 1.2 m as a specified narrow area, and the obstacle size was 0.3 × 0.3 m. The obstacle detection distance was set to 0.7 m in the wide space outside the narrow area and to 0.3 m inside the narrow area.

6-2 Obstacle avoidance using variable obstacle detection distance in a narrow area

The system was tested via RSNP for autonomous navigation by placing two obstacles in the narrow area and setting the target position at a point outside the narrow area, as shown in Figs. 5–8. Fig. 6 shows the stuck (mod = 0.7) and passing-by (mod = 0.3) cases. Fig.7 shows the robot trajectories for mod = 0.7 and mod = 0.3. In the trajectory with mod = 0.7, the robot moved while back and forth, stopping on the way. Fig. 8 shows the Rviz view for each case. The planned path is shown by the blue line in the center of Fig. 8 right (mod = 0.3). These figures show the case of the robot passing through a narrow area. For mod = 0.7 m, the robot could not pass through the narrow area and it got stuck; however, for mod = 0.3 m, the robot successfully passed through. This result verifies the importance of setting an appropriate obstacle detection distance. Additionally, it was verified that the robot could pass through via manual remote control using the same settings when stuck.

6-3 Passing-by experiment using two robots

After checking the control system of the standalone robot, we conducted an experiment using two identical robots, as shown in Figs. 9 and 10. As shown in Fig. 9, autonomous navigation was employed for Robots 1 and 2 in the same environment as Fig. 5 to move them to positions 2 and 1, respectively. Fig. 10 shows that the robots were able to move to their target positions without getting stuck or colliding with each other; however, they sometimes collided with each other in the narrow area. The detection distance was set to 0.3 m in the narrow area for both robots.

Fig. 10 shows the case of the robots passing each other, where only the obstacle avoidance and navigation functions were employed. We observe that in Fig. 10 (1), the robots face each other; in Fig. 10 (2), Robot 2 backs off to allow Robot 1 to pass through (Fig. 10 (3)); in Fig. 10 (4), Robot 2 passes through.

In this experiment, the robots were able to move without receiving any instructions from the high-level control system. Although TEB was used as the planner, we need communication between the high-level control system and robots or between robots to ensure reliable and speedy movements. For example, a robot hands over the passage to a robot with a higher priority.

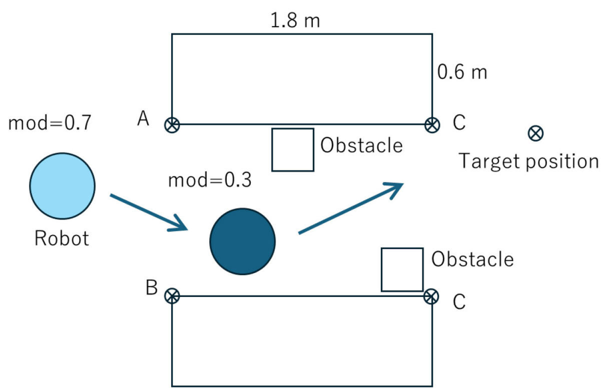

Figure 5. Experimental setup for robot navigation

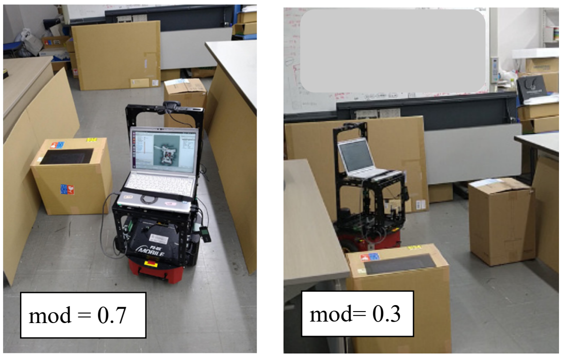

Figure 6. Experimental scenes in autonomous navigation (mod = 0.7 on the left and mod = 0.3 on the right)

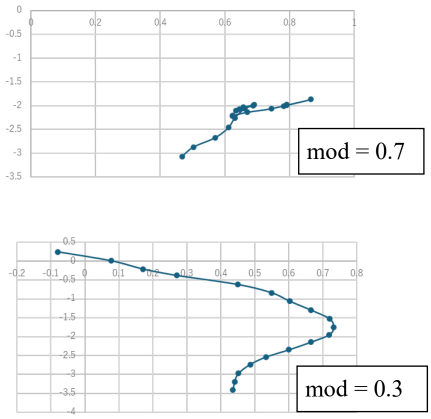

Figure 7. Trajectories of a stuck and a passing-by robot

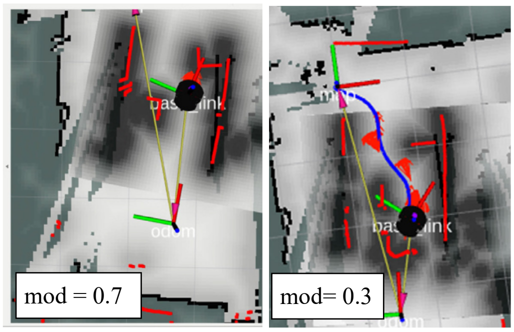

Figure 8. Rviz views of a stuck (left) and a passing-by (right) robot

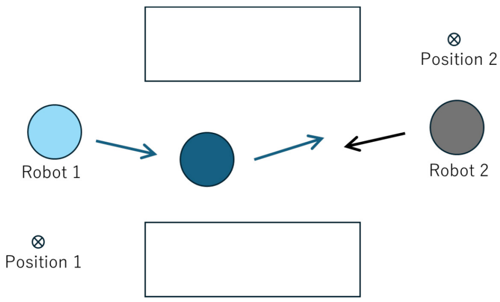

Figure 9. Experiment involving two robots moving in a narrow area

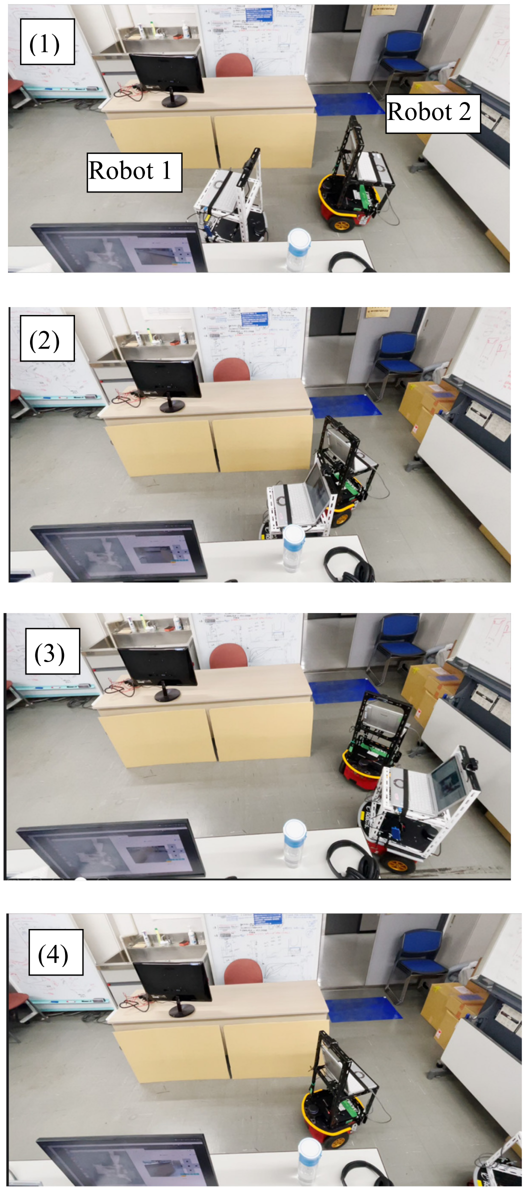

Figure 10. Experiments involving two robots passing by each other

VII. Conclusion

When several robots operate in the same workspace simultaneously, e.g., in nuclear decommissioning, it is necessary to consider their movement in narrow areas. In such environments, both autonomous navigation and manual remote operation are necessary because of the unknown operating conditions that require human judgements. In this study, we developed a remotely operated robot system using RSNP. The system can freely switch between autonomous navigation and manual remote operation. Additionally, to enhance the operation system, the function has newly been developed that the robot movement conditions are variable based on the workspace characteristics. The experiments verified that the robot could move in a narrow area by specifying the space and changing the obstacle detection distance. Furthermore, we demonstrated that it is possible for two robots to move past each other by appropriate conditions. The control parameters etc. are to be reflected according to the actual environmental needs. In the future, we will investigate robots' movement speed and priority for smooth coordination using inter-robot communication for nuclear decommissioning and other applications.

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