

Design and Implementation of User-Friendly Remote Controllers for Rescue Robots Used at Fire Sites

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Abstract— Many robotic applications have been developed for rescue operations during disasters; these applications involve the use of different types of robots such as fire-fighting robots, rescue robots, and surveillance robots. In this paper, we propose two novel wireless remote controllers that not only offer a user-friendly operating interface but also enable easy control of a robot. The handheld controller can be easily carried by firefighters and the joystick-based controller allows more accurate and rapid control for specific tasks in emergency situations. Both controllers are designed to gather situational information such as video feed and temperature and gas concentration data. We analyze the efficiency of the two controllers by carrying out a performance evaluation. To determine the usefulness of these controllers to firefighters, a questionnaire survey was conducted. Based on the opinions of firefighters, we suggest scenarios in which both controllers may be applicable at expected fire sites.

I. INTRODUCTION

The popularity of robot-related technology has grown recently because of their numerous pragmatic applications in various fields such as military, medical, and industrial fields. In search-and-rescue applications, devising an efficient rescue robot that can safely rescue displaced people in extremely dangerous situations has been a challenging issue, despite recent work in this area [1–3]. Most previous research only focuses on performance enhancement for the robot platform and does not, to the extent necessary, consider the interface between the robot and the remote user—an interface that is required for safe operation at fire sites. Although there are a number of open observable problems with regard to the remote controller, the most recent design issues for rescue robots may be summarized as follows.

1) In general, one of the most important design issues is safety—primarily for the victim and the firefighters and also

for preservation of the robot. When the firefighter enters an actual fire site, unexpected obstacles may be encountered, such as falling rubble and hazardous water leakages. Thus, for safe operation, the rescue-robot controller must be compact and should allow flexible movement on the part of the firefighters.

2) At extreme fire sites, firefighters must devise an appropriate rescue strategy and finish the operations as fast as possible so as to avoid additional casualties. Thus, rapid control of rescue robots by the remote user is another important issue for the remote controller.

3) When a rescue robot enters a fire site instead of firefighters, the robot is frequently not visible to the remote user, which could lead to misuse of the control board or imprecise manipulations of the robot. In addition, the numerous dangerous obstacles such as those mentioned above may disturb the intended operations of the firefighters. Thus, the controller must minimize control errors and maximize the accuracy of robot manipulations.

4) In addition to the above issues, unsolved problems remain to be addressed, such as the lack of information-gathering ability that could give firefighters a view of the situation in smoke-filled areas or ergonomic aspects of the remote controller that would lead to more efficient control.

To tackle these challenging issues, we designed and implemented two types of user-friendly remote controllers. The first type of remote controller is a touch-screen-based handheld controller that may be easily carried by firefighters and offers rapid operation of the robot. The second type of remote controller is a joystick-based controller that offers not only a user-friendly interface but also more elaborate control operations than the handheld controller. Both control platforms use two separate wireless communication channels; one to exchange control messages and the other for video data processing.

The rest of the paper is organized as follows. In Section 2, we review several related works on remote controllers for rescue robots and explain our motivation for improving their performance. Section 3 illustrates the design specifications we propose for user-friendly remote controllers, which are based on the requirements of firefighters; we implement these specifications within suitable application scenarios. In Section 4, we evaluate the performance of an existing rescue robot system. Finally, we conclude and describe future works in Section 5.

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II. RELATED WORKS

Many proposals have been put forward to explore efficient control architecture for rescue robots in various environments. Entire windows-based graphical user interfaces (GUIs) [4] constitute a representative architecture for remotely controlled rescue robots. Such a design reduces the unnecessary operation latency that results from user-attention shifting and maximizes the controller display size by removing the redundancy control panel. However, this contribution only concentrates on the attention latency of users and does not address the behavioral pattern of the firefighter who is the expected user at fire sites. For safety considerations, an ergonomic operating board [5] has been developed to reduce the risk caused by disturbances at rescue sites. This system analyzes general foreseeable misuses and proposes a wearable-type controller that offers flexible movement in uneven terrains. The wrist-mounted display [6] is another wearable controller that offers virtual visualization. This system allows the user to quickly detach the system, which may help rapid rescue operations in emergency situations. The joypad-based controller [7] is another proposition that offers relatively intuitive and familiar operation to nonspecialized operators.

Although these remote control systems offer advantages in some applications, such as those involving security and rescue, they do not fully consider the characteristics of firefighters who need more accurate and safe controls at real fire sites. For example, although the control board discussed in [5] proposes ergonomic safety specifications, it suffers from a lack of rescue functionality because it does not present detailed operations related to firefighting or rescue. The controller discussed in [6] still has some limitations in that it neglects wireless networking for information gathering in rescue fields, and the joypad in [7] is not suitable for elaborate control such as tilting, turning, rotation, etc. In this study, we analyze the core requirements of firefighters and propose effective control architectures that consider both safety and functionality.

III. PROPOSED REMOTE CONTROLLERS FOR RESCUE ROBOTS

A. Design requirements and basic architecture for remote controller

As mentioned in the previous section, there are a number of requirements that must be satisfied in designing a robot system for rescue operations at real fire sites. To deal with these requirements, we note that designing the rescue robot platform is important because it deals with actual rescue processes such as approaching victims and guiding evacuation to the nearest exit. However, to safely manipulate the robot system in a remote manner, we need an efficient remote controller that can also aid firefighters in devising the appropriate subsequent functions for further rescue processes. Thus, based on these factors, we summarize the key requirements as follows:

- 1) The firefighter who controls the robot system must safely finish the rescue mission.
- 2) The remote controller should be useful for rapid controls, be easy to use, accurate, and error free.

In this section, we propose two types of remote controllers that take these requirements into account. The first type is based on an ultramobile personal-computer (UMPC) platform and the second type is a joystick-based platform. Although these two platforms are designed to be applied to different rescue scenarios, the basic architecture is similar, as shown in Figure 1.

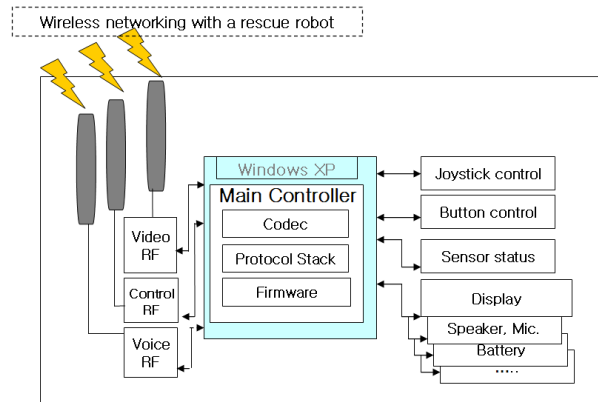


Fig. 1. Basic architecture of remote controllers

In general, when the entire remote control system, including the rescue robot, is deployed to a fire site, the communication between the robot and the controller begins by using wireless channels. From the many wireless networking schemes adapted for various purposes, we adopt two dedicated 2.4-GHz radio frequency (RF) interfaces for video and voice transmissions and a Bluetooth/Zigbee [8, 9] interface for control data. The reason we use separate wireless channels is that this architecture provides not only low signal interference but also fast data transmission for prompt robot control. However, when we deploy multiple robot systems to support multihop networking, we need other RF solutions such as WLAN [10] and Wi-MAX [11] with appropriate routing protocols. However, discussion of these solutions is beyond the scope of this paper and is thus left for the future work.

B. Design of UMPC-based remote controller

At real fire sites, firefighters are required to execute many missions, including extinguishing the fire, removing obstacles, rescuing victims, etc., so they want both their hands free for these operations. Thus, the remote controller should allow the firefighter to simultaneously execute other tasks with the free hand, for example, controlling the robot system with one hand and holding the water hose with the other. Thus, we designed a UMPC-based remote controller that includes a simple, compact touch-screen interface with a display of approximately 7" (see Figure 2). The specifications of this controller are summarized in Table 1. This platform is easily

gripped with a single hand or can be mounted on the wrist if the firefighter wants to perform other rescue operations.

Moreover, Bluetooth and Zigbee, which are used for the networking module, are suitable solutions for handheld-sized devices. Although this proposed controller is fully compatible for any rescue robot system that uses a Bluetooth/Zigbee module, we choose the mobile evacuation robot [12] as the target application. Figure 4 illustrates the robot architecture, which consists of two wheels with one support wheel, a light-emitting diode (LED) lamp for evacuation guiding, a camera module for visual monitoring, and various sensors for measuring the density of poisonous gases in the atmosphere. All information gathered from the robot is immediately transmitted to the remote controller over the wireless channel.

As shown in Figure 2, the video information is presented at the center of the screen and the touch panel for robot manipulation is located at the bottom-right side of the screen. The firefighter can easily drive the robot in a desired direction by touching the circular panel. For example, if the user touches the upper, bottom, left, or right side of the circle, the robot makes a forward, backward, left, or right turn, respectively. In addition, the user can easily increase or decrease the robot's speed by varying the distance between the touch point and the center of the circular panel, as depicted in Figure 3. Because this UMPC-based platform is small enough to be carried by in one hand, we believe that it provides more safety for firefighters, which is one of the main requirements given in Section 3.1.

Size	W × H × D mm	190 × 120.8 × 30.3
Weight	kg	0.78
Operating system	Software	Windows XP
CPU	GHz	1.2
Memory	MB	768
Display	Resolution	1,024 × 600
Data rate	Kbps	56
Video rate	Fps	20
Radio range	Meter	50
Battery capacity	mAh	3,900

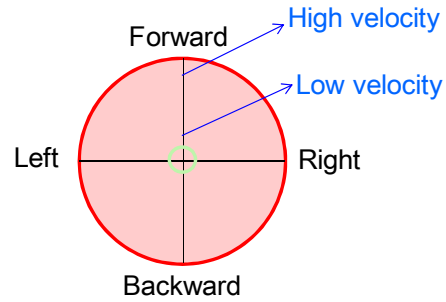


Fig. 3. Robot manipulation panel on controller

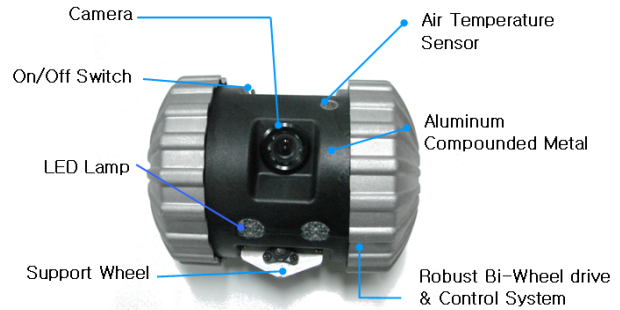
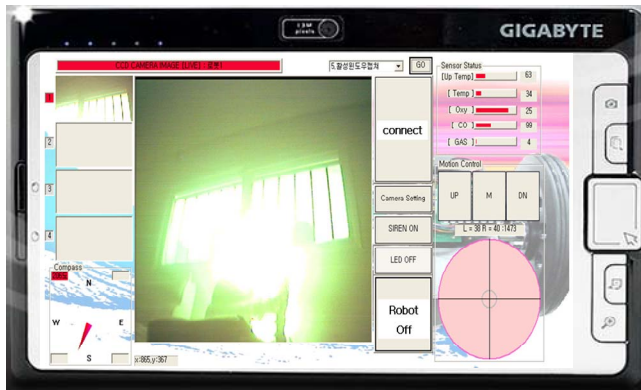


Fig. 4. Evacuation guide robot



(a) Feature with GUI display



(b) Use of controller

Fig. 2. UMPC-based remote controller

C. Design of joystick-based remote controller

As discussed in the previous section, the UMPC-based remote controller is well suited for safe rescue operations by virtue that it leaves firefighter's hands relatively free. However, for the following reasons its compact size also introduces some limitations: For example, when the firefighter wears the thick gloves that are required to execute specific tasks, it becomes very difficult to make accurate touch input due to the small size of the touch-based display, which may result in unexpected risks such as robot collisions, misguidance for victims, etc. Second, the small battery capacity of the UMPC controller may not be sufficient to last the entire rescue operation, which means sudden system failure and service interruption is possible in emergency situations.

To research these limitations, we designed and developed an efficient joystick-based remote controller that is shown in Figure 5, and whose specifications are summarized in Table 2. One of the major advantages of the joystick platform is that most firefighters are very familiar with this type of platform. This means that the joystick allows more stable and accurate manipulations when compared to the touch-screen based platform. Another advantage of the joystick platform comes

Table 1. Specifications of UMPC-based remote controller

Specification	Unit	Value
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from the control-button based architecture as an input mechanism whereas the UMPC-based controller only provides touch-screen based methods, which are more error prone for firefighters. Moreover, the entire control component including buttons, switch, and joystick, can adopt waterproofing materials, which enables firefighters to manage operations that involve water while controlling the robot system.



Fig. 5. Joystick-based remote controller

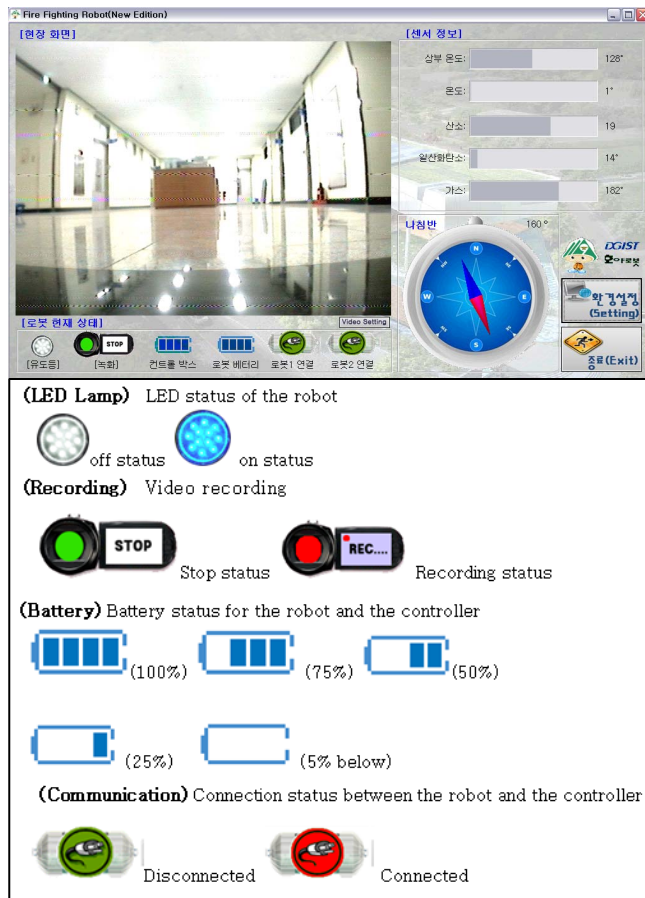


Fig. 6. GUI information display of joystick-based controller

As shown in Figure 5, the main distinguishing feature of the joystick-based architecture is its large size and mass (baggage type: 45(W) × 35(H) × 18(D) cm, 7 kg). Although this large size enables firefighters to easily control and

monitor the robot with high accuracy and efficiency, it is more difficult to transport than the UMPC-based handheld device, which is one of the main drawbacks of the joystick-based system. However, by adopting the baggage type joystick, other advantages such as high battery capacity and impact resistance, including waterproofing, are provided. In addition, it also allows simultaneous robot monitoring by using dual displays when the firefighter uses two robot systems for cooperative purposes. However, since the controller has only one joystick, the firefighter can control only one robot at a time. To switch control to another robot, the firefighter must push the robot-select button located below the display, and the necessity of this extra manipulation may represent another drawback. Thus, we conclude that there is a tradeoff involved in choosing between the joystick-based controller and UMPC-based controller in operational performance.

Table 2. Specifications of UMPC-based remote controller

Specification	Unit	Value
Size	W × H × D mm	450 × 350 × 180
Weight	kg	7
Operating system	Software	Windows XP
CPU	GHz	1.33
Memory	MB	1024
Main & Sub Display	Resolution	800 × 600
Data rate	Kbps	56
Video rate	Fps	20
Radio range	Meter	50
Battery capacity	mAh	5,400

The other functional features of the joystick-based controller are similar to those of the UMPC system, except that the GUI components of the UMPC system present more information both about the robot and about the controller status (e.g., LED lamp, video recording, battery status, and communication connectivity). Figure 6 describes the proposed GUI architecture.

IV. PERFORMANCE EVALUATION

A. Experimental environment

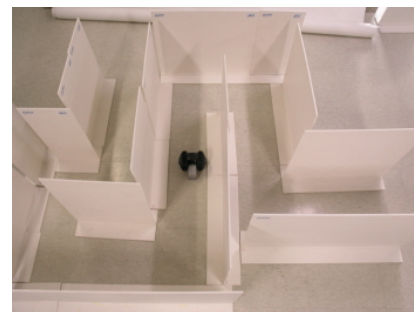


Fig. 7. Experiment with maze course

To evaluate the performance of the proposed remote controllers, we designed two driving courses for the rescue robot, which are shown in Figure 7 and Figure 8. The first course is a maze course, and the second course is an S-shaped course. In the maze course (170 × 170 cm²), the robot travels along the course between the entrance and the exit gate by

making 90° left and right turns. In the S-shaped course (200 × 150 cm²), the robot drives to the exit gate by making a smooth curve. To negotiate these courses, the robot operators are asked to use the two remote controllers that are proposed in Section 3, and we then compare the operational performance of the two platforms under four different scenarios: (a) UMPC with the maze course, (b) joystick with the maze course, (c) UMPC with S-shaped course, and (d) joystick with S-shaped course.

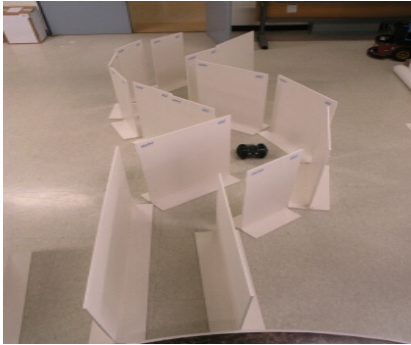


Fig. 8. Experiment with S-shaped course

B. Experiment result

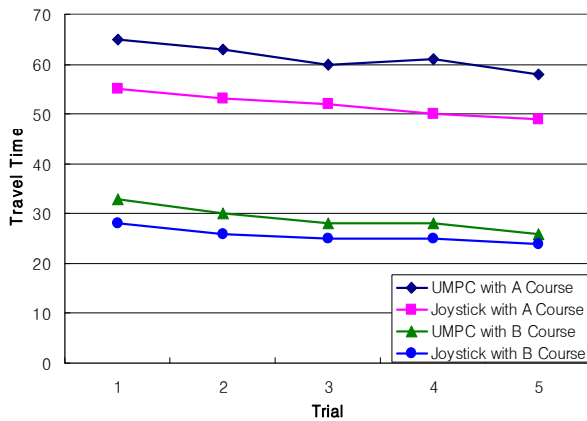


Fig. 9. Movement delay of robot

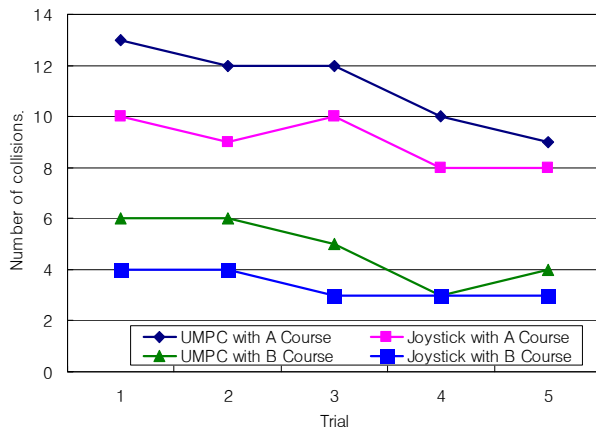


Fig. 10. Number of collisions during movement through courses

Figure 9 shows the robot traversal time between a start

point and a destination point. As shown in the figure, the robot in the maze course suffers more traversal delay because this course has more turns than the S-shaped course. The UMPC controller causes more traversal latency than the joystick controller because of the difficult manipulations required by the former, whereas the joystick controller provides faster operations.

Figure 10 compares the number of collisions for the different courses between the two control platforms. The result corroborates those of Figure 9 in that the joystick-based controller performs better than the UMPC controller in both courses. We conclude that the joystick controller provides more stable operation and that the error rate for manipulation by the UMPC controller is higher than for the joystick controller.

Finally, Table 3 compares time required by a user that runs 100 m in a straight line holding each controller (one at a time) to describe an emergency situation. As shown in the reduction ratios of 12% and 12.5%, the UMPC-based controller offers better mobility performance because it is 6 kg less massive than the joystick platform. This means that firefighters may benefit from significant freedom of movement during the rescue procedure when they use UMPC-based controller.

Table 3. Comparison of time required while running with each controller held

Method	1st trial	2nd trial
UMPC with A Course	15.8 s	15.9 s
Joystick with A Course	17.7 s	17.9 s
Reduction Ratio	12%	12.5%

C. Questionnaire result

The proposed robot controllers to operate rescue robot systems are intended to be used by firefighters at real fire sites. Therefore, before distribution of the proposed systems to firefighters, we performed a questionnaire survey of more than 100 firefighters in Daegu, Korea [13]. After the system trials, we asked about the degree of usefulness and the ease of manipulation for the two proposed controllers. The questionnaire results for the joystick-based controller and the UMP- based controller are given in Figures 10 and 11, respectively. As shown in the figures, 36% of firefighters rated the use of the joystick as "good" or "excellent," whereas only 13% responded "good" or "excellent" regarding the use of UMPC-based controller, and these results are similar to those of the laboratory experiments described in the previous section. Thus, we conclude that the firefighters are more satisfied with the joystick platform than with the UMPC-based one platform.

In addition to the performance questionnaire of proposed controllers, we also asked incumbent firefighters about general requirements regarding the efficiency of remote controllers in the real fire environment, and the results are shown in Table 3. We found that 43% of the firefighters responded that "stable controls for intended operations" is the most important factor. In addition, 73% firefighters responded similarly when they were allowed to give two important factors. However, the requirement of "fast movement" is the third most important factor for firefighting

operations, which means that many incumbent firefighters prefer the joystick-based controller over the UMPC-based controller.

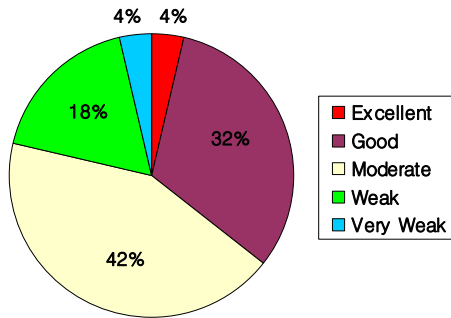


Fig. 10. Ease of manipulation for joystick-based controller

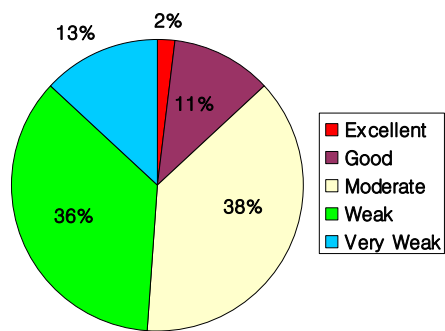


Fig. 11. Ease of manipulation for UMPC-based controller

Table 3. Requirements for efficient remote controllers

Importance factor	1st requirement	1st + 2nd requirement
Stable controls for intended operations	48.3%	73%
Accurate video information in fire sites	23.2%	55.9%
Fast movement	14.8%	23.2%
Stable wireless networking	5.3%	22.8%
Control for Obstacle avoidance	3%	4.9%
Fast boot time	1.1%	5.3%
Thermal resistance and waterproof	1.1%	1.1%
Wide display	0.8%	1.9%
Monitoring temperature/gas data	1.5%	9.2%

D. Expected application scenarios for proposed controllers

Similar to what we find in the performance experiments, choosing between the two proposed controllers involves a tradeoff between stable controls and prompt reactions. Thus, it is very important to use these platforms in appropriate rescue scenarios by considering how their functional features match expected fire-site conditions (even though the fire environment is often unpredictable). The UMPC-based controller should be very useful for a firefighter that performs an entire rescue operation, such as search and evacuation, because this situation requires a more prompt reaction because of the manpower shortage. However, the joystick-based controller should prove very useful when firefighters search for victims and are required to digest information from, for example, a large underground pipeline

or holes, because these operations require more accurate manipulations to maintain victim safety and to preserve sensitive equipment.

V. CONCLUSION AND FUTURE WORK

The rescue robot platform plays an important role in performing efficient rescue operations. However, to safely and stably manipulate the robot system from a remote site, a user-friendly wireless remote controller that helps firefighters devise appropriate subsequent strategies for further rescue processes is required. In this paper, we have presented the design of two remote controllers: the first is of an UMPC-based type and the second is of a joystick-based type. The UMPC type combines easy transportation with portable size, whereas the joystick type allows more stable manipulations of the robot.

The experimental results show that tradeoffs are involved in choosing between these two controllers; namely, one must choose between prompt reaction and accurate operations. In addition, we also discuss expected application scenarios for our proposed controller by considering their system functionalities.

In future work involving the proposed platforms, we will combine the advantages of the two controllers and use the resulting system in various rescue robot systems. Furthermore, we plan to distribute the proposed platforms to fire stations for further functional feedback.

VI. ACKNOWLEDGEMENT

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