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Portable Fire Evacuation Guide Robot System

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Abstract—**Robot technology is emerging for applications in disaster prevention with devices such as fire-fighting robots, rescue robots, and surveillance robots. In this paper, we suggest an portable fire evacuation guide robot system that can be thrown into a fire site to gather environmental information, search displaced people, and evacuate them from the fire site. This spool-like small and light mobile robot can be easily carried and remotely controlled by means of a laptop-sized tele-operator. It contains the following functional units: a camera to capture the fire site; sensors to gather temperature data, CO gas, and O_2 concentrations; and a microphone with speaker for emergency voice communications between firefighter and victims. The robot's design gives its high-temperature protection, excellent waterproofing, and high impact resistance. Laboratory tests were performed for evaluating the performance of the proposed evacuation guide robot system.**

I. Introduction

Recently, mobile robots capable of ubiquitous computing have become very popular ; these robots can be used at all times under all conditions. They can be widely used in areas such as military, the medical profession, and in various industries. However, for the deployment of robot systems in fire environments, a number of unsolved problems remain. The most representative examples of such problems are as follows.

1) Presently available robots are not able to function at high temperatures of over 1500°C, which occurs after flashover, and in the presence of water supplied by fire trucks, which would prevent firefighters from entering the site if a robot is being used. This implies that an evacuation robot needs to be equipped with temperature protection, waterproofing, and impact resistance mechanisms.

2) In general, when a fire or some other disaster is reported, firefighters are sent to the site in order to cope with it as soon as possible. Therefore, the evacuation robot also needs to be not only light weight but also easy to carry for rapid emergency response. Moreover, it is important that the firefighter can safely withdraw the deployed robots, because the efforts for withdrawing include additional dangerous activities in fire sites.

3) Due to the poor information regarding indoor space at fire sites, it is very difficult to decide when or how should firefighters enter a building. Therefore, the robot employed for evacuation purposes should be able to not only monitor the situation at fire sites but also report the gathered information to remote firefighters by using a manipulator.

4) In addition to the above drawbacks, there can be other unexpected problems that need to be addressed, such as poor vision in smoke-filled areas and limited RF communication channels.

In order to resolve these unsolved problems, many applications that use caterpillar and fire extinguisher equipment have been proposed [1] [2] [3]. However, they have several limitations due to their large sizes and high cost of maintenance. Therefore, the firefighters cannot easily carry or operate such robots in emergency situations.

In this paper, we report the design and development of a portable evacuation guide robot with various sensing systems that can monitor indoor disasters such as fire, or it can be used for victim detection and atmosphere observation. In addition, by using a voice communication module and LED guidance lamps, the robot can help in rescuing the victims. In order to cover large fire areas, several robots can be organized into a group, and they can transmit gathered information to the firefighter's controller at a remote site.

The rest of the paper is organized as follows. In Section 2, we review related work on robot systems such as fire field robots and portable mobile robots. Section 3 shows the proposed design architecture of the evacuation robot system and its implementation with user application. In Section 4, performance evaluation with a fire test-bed is described. Finally, in Section 5, concluding remarks and ideas for future work are summarized.

II. Related Work

A. Robots with rescuing functions

In the past decade, several mobile robots have been proposed for rescuing people in fire sites such as buildings that have collapsed due to earthquakes or sites where fire has been caused by explosions. In order to tackle these requirements for disaster management, many robot designs have been proposed [4] [5]. However, they have been not developed or fielded for real fire environments. The first robot's trial for urban search and rescue took place during World Trade Center (WTC) disaster [6]. As more pragmatic approaches to robot rescue, various robotic systems are

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introduced as follows. BEAR [1] is a versatile, humanoid robot capable of lifting and carrying victims. Its main functions are casualty extraction, building evacuation, heavy lifting, searching, rescuing, etc. However, because of high development costs, affordable services are limited except for military or research purposes. Jet Fighter [2] is another fire-fighting robot introduced by the Tokyo fire department. This robot is operated by a remote user and performs fire-extinguishing activities after determining the origin of a fire. In addition, it provides monitoring services by a wireless communication system, and it also has obstacle avoidance mechanisms to enable autonomous driving. Fire Searcher [3] is a type of scouting robot for use in fire sites with high temperatures and poisonous gas. It monitors victims and the internal situation in a building and then transmits the acquired information to remote users by using an applied manipulator. Tehzeeb [7] is also a rescuing robot, which employs a laser scanner module along with a manipulator and map generation algorithms for localizing itself while exploring in lightless or dense smoke areas. Mobile robot system with wireless sensor network [8] is an autonomous exploring robot, which is equipped with Zigbee [9] wireless communication module to facilitate video or audio data transfer. It helps to track the location of the robot by analyzing signal strength of the wireless sensor network.

Although these robot systems are well designed for monitoring, driving, and firefighting in extreme fields, they are still too heavy and large to be transported by firefighters. Moreover, due to the high costs of large devices and systems, the robot maintenance costs and additional overheads such as user education and repair cost also increase, which is not conducive for the commercialization and popularization of these devices.

B. Portable robots with mobility

ROB-1 [10], developed by Sony-Ericsson, is one of the most representative of portable robots, with networking services and autonomous driving. Its weight is about 1 kg, and it has a simple architecture with 2 wheels, which makes it suitable for hand carrying. Despite its compact structure, it provides Bluetooth [11] communication with remote users using mobile phones. However, it is designed for entertainment purposes such as playing music and shooting images, which does not make it suitable for emergency purposes. Wever C1 [12] is another compact robot with two-wheel architecture, and its main purpose is for home security. When illegal entry is detected by face or voice recognition sensors, the robot reports the video information to a remote user. It is also controlled by mobile phone and remote internet. Although this robot has a compact size and deals with indoor security, it cannot be directly applied to rescue missions in extreme fire sites because of its nondurable construction. Jack and Cutter Robots [13] are developed for rescue operations by jacking and cutting the obstacles in disaster sites. However, they still have some drawbacks such as unfitness for high temperature fire environments and lack of wireless communication modules for remote monitoring. In this study, we resolve these limitations by adapting cost effective robot designs for applications in fire management.

III. EVACUATION GUIDE ROBOT

A. Expected scenario and application

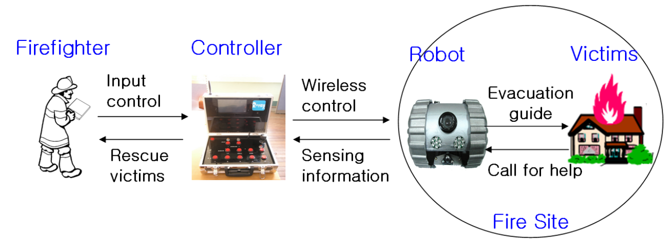

Fig. 1. Application scenario for the evacuation robot.

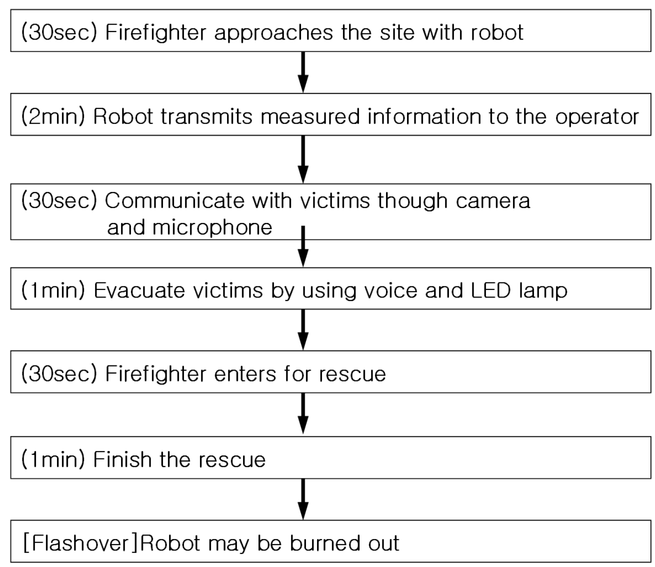

Fig. 2. Activity flow chart of expected scenario

As mentioned in the introduction in Section 1, the ordinary expected scenario for disaster robots would include several objects such as firefighters, a remote controller, a manipulator, victims, and the robot itself. This scenario is depicted in Figure 1. Because the most important task is to rescue victims in danger as soon as possible, the robot and the controller act as arbitrators between the firefighters and the victims, and they help them to communicate with each other. Furthermore, in such a situation, the inopportune entrance of firefighters would result in significant injuries to both the rescuers and the victims. Therefore, the deployed evacuation robot can be considered to be an avatar of the firefighter. The comprehensive robot application scenario sequence is represented in Figure 2. First, after fire detection, firefighters or rescuers arrive at the fire site carrying robot systems, which may take approximately 30s. Then, they deploy their evacuation robot by throwing it into the fire site directly, and the robot starts to gather the internal information by using various sensors such as those for temperature, CO, O_2, and gas. All the gathered information, including video and voice data, is forwarded to the remote firefighters using wireless channels. If the firefighters detect victims by using the robot's camera module, they can direct the victims to the emergency exit by using the microphone and speaker system on the robot, or they can directly enter the building for further rescue operations. This simple example of the rescue procedure takes approximately 5 min, which is the most important period for surveying the indoor space and rescuing victims before flashover occurs in which the temperatures exceed 1500°C. Therefore, the monitoring of information by the robot in this time has considerable influence on the rescue decisions made by the firefighters. Furthermore, the early operations by the robot, before firefighters are committed, are quite helpful for the safety of firemen as well as the victims.

B. Design overview of the robot system

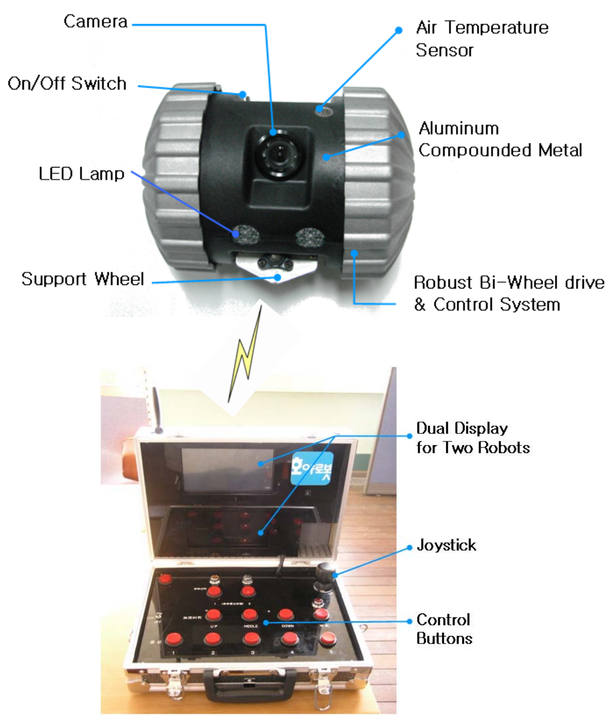

Fig. 3. Overall architecture of the evacuation robot with remote controller

One of the main purposes of our evacuation robot is easy portability, which would help firefighters to easily carry the tiny robot and allow quick movements. To satisfy this requirement, the robot has a spool-like round shape, dimensions of 120 mm × 120 mm × 150 mm, and weight of 2 kg, which makes it easy to carry. These specifications are listed in Table 1. Another advantage of this tiny design is that the manufacturing cost is low enough to make the robot expendable, so that it if need be, it can be destroyed by the fire after finishing its duty. Thus, the firefighters do not have to withdraw the used robot, which could result in another high risk, additional efforts, as well as additional maintenance costs. The main body of the evacuation robot consists of two DC motors, a RC servomotor, a camera, sensors(Temperature, CO, O_2, gas, compass, etc), a speaker, a microphone, an LED-set lamp, and separated wireless RF modules for video, voice, and sensing data. It also has a main controller based on an embedded OS (operating system) and an external body case, which is designed for thermal resistance, waterproofing, and impact resistance. The overall design architecture of the evacuation robot with the remote controller is shown in Figure 3, and the internal section of the evacuation robot is shown in Figure 4.

TABLE I. HARDWARE SPECIFICATIONS OF THE ROBOT

Category	Specification
Voltage range	6–9 V
Electric current (operation mode)	200 mA
Electric current (standby mode)	50 mA
Battery type	Lithium polymer
Maximum movement speed	282 mm/sec
Weight	2 kg

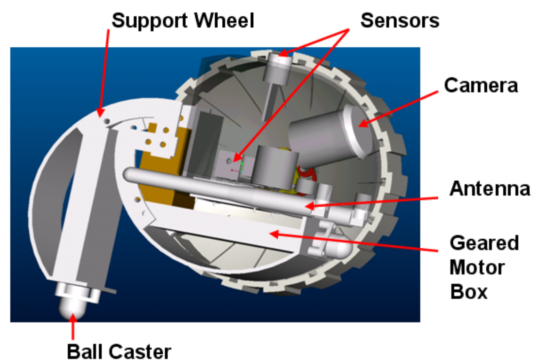

Fig. 4. Vertical section through the evacuation robot

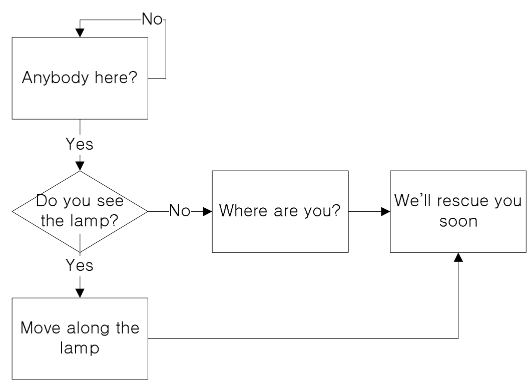

Fig. 5. Voice communication scenario for rescue

As shown in Figure 3, all control functions are executed by the remote controller after the robot is thrown. The joystick on the remote controller offers basic movement in all directions. In addition, there are assistant wheel buttons that direct three operations (up, down, and middle position control) and provide motion control to the round support wheels for stable driving and positioning. When the robot drives and navigates along the road, the two main wheels alone are not sufficient to keep the robot balanced. Even though the robot may be directed in any direction by the firefighter, the support wheel is able to keep the robot in balance and within position, with motions similar to a tumbling doll, which include kicking and rolling operations on the ground. In addition, when the robot climbs a slope, the support wheel acts as a prop for continuous driving as well as dynamic steering. Another feature of the support wheel is that it can be folded up to a small size so that the device can be easily carried by firefighters. All operations of the support wheel are controlled by a dedicated sub-motor. The vertical section of the wheel is illustrated in Figure 4.

There are 5 buttons on the control box, which are used to generate the user's prerecorded voice to communicate with victims in need. Figure 5 shows the sample voice communication scenario to be used with victims; however, the firefighter may generate and record his own voice with the microphone on the remote controller for further rescue operations. The reason why the robot offers prerecorded voice is to minimize the communication time since the entire rescue procedure should be completed in 5 min, as mentioned in Section 3.1.

C. Temperature protection and waterproofing

In general, a fire is classified into the following two stages: before and after the flashover. When the fire reaches the flashover point, most of the smoke changes into flames and the temperature exceeds 1500°C. In this case, most of the robot's materials and devices are burnt along with the entire building. In the other state of the fire, i.e., the one before the flashover, the temperature is between normal and 500°C. Therefore, the pre-flashover stage is the optimal period for rescuing victims by using the evacuation robot. However, since the fire usually reaches flashover in 5 min after the start of the fire, the robot should resist temperatures of up to at least 250°C during this period. To achieve this, we used an aluminum compound metal with Teflon wiring for the internal circuit and the external body, which enables the robot to survive up to approximately 250°C.

In fire and disaster sites, probable water spraying operations are performed by either the firefighters or the building sprinkling facility in order to extinguish the fire, which implies that the robot should have waterproofing mechanisms as well as thermal resistance. Therefore, most electronic circuits including the camera, motor, antenna, and sensor modules are inserted into the inside of the robot's body and the entire outer case is composed of waterproof epoxy adhesive. In addition, the rounded body design of the robot not only lets the falling water spread on the surface but it also distributes external impact, which is described in Section 3.4.

D. Impact resistance

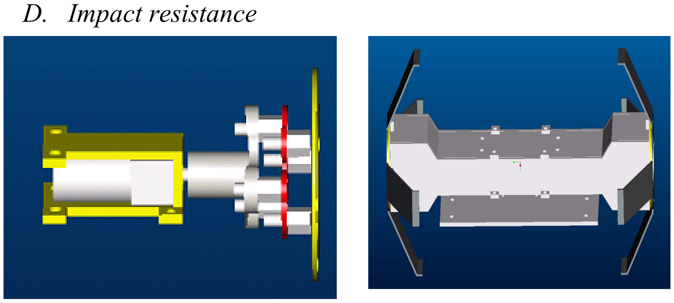

Fig. 6. Leaf spring and impact distribution frame with side bolster

Another feature of the evacuation robot is a crash cushion mechanism for impact resistance, which may prevent the cracking of the frame axis when the robot is thrown by the firefighters. To achieve this, we have inserted leaf springs inside the gears of the robot's wheels. The leaf spring, by using its internal coil, alleviates the outer impact from the vertical direction. In addition, the frame axis of the round wheel distributes the diagonal external impact over the entire body of the robot by using the side bolster. Therefore, irrespective of the direction in which the robot is thrown, it can resist and distribute the external impact. For example, once the robot is thrown in the diagonal direction, the side bolster distributes the first impact, and then, the inside leaf spring absorbs the remaining impact. Figure 4 illustrates the leaf spring and the distribution frame for external impact resistance.

E. Communication system for indoor monitoring

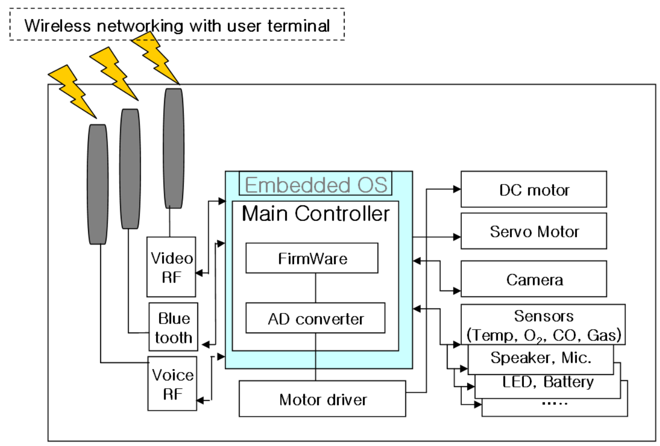

Fig. 7. Internal components of the evacuation robot

After the robot has been thrown, its first mission is to measure parameters such as the temperature and density of CO, O_2, and poisonous gas in the atmosphere within the building, using its many sensors. When other sensing data is needed for specific environments, the sensor board of the main circuit offers compatible interfaces for replacements, which implies that the robot can be used anywhere with any equipment and at low cost. The gathered information is transmitted to the remote user terminal by dedicated Bluetooth wireless channels, and the user transmits control packets to the robot for its use. The Bluetooth technology is a suitable solution for the evacuation robot because its RF devices are light in weight and have a low overhead profile, appropriate for the robot's portable size. Moreover, the Bluetooth antenna is also small enough to be integrated into the robot's frame. Although Bluetooth offers an efficient wireless networking mechanism for small networks, it is unable to deal with voice and video traffic because of its limited bandwidth and high error rate. Therefore, we inserted two additional dedicated RF interfaces with 2.4 GHz frequencies for voice and video processing, respectively. They use frequency modulation (FM) with transmission power of 17 dBm. In addition, several robots can be organized into a group by WPAN [14] for cooperative monitoring and guidance. Because the first robot may be destroyed in the fire, an additional backup robot is needed to complete the rescue mission started by the previous one. Different robots have independent RF channels in order to prevent signal interference between them, and they directly transmit sensing data to the remote controller, which implies that they do not support wireless multi-hop networking. When we adopt multi-hop capabilities, the error-prone wireless channel with limited bandwidth is not stable enough to manage seamless channel connections essential for delay-sensitive traffic such as video and voice during the robot's handover procedure. Therefore, by not using multi-hop relay procedures, the robot is able to minimize the transmission delays, which are a characteristic of multimedia traffic. The internal components of the robot with three RF interfaces for video, voice, and control data are shown in Figure 7.

F. GUI design for remote controller

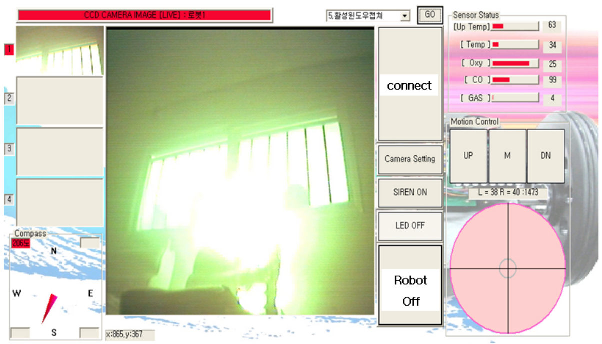

Fig. 8. GUI in the remote controller

The evacuation guide robot is mainly designed for rescuers or firefighters who are rarely familiar with electronic devices. This fact requires that the GUI of the remote controller for the robot should be designed to be user friendly, and it should be easy to carry. Therefore, we designed the following two types of GUIs. The first is a control box type, shown in Figure 3, which uses a joystick and a button-based remote controller, which enables firefighters to easily operate the robot while wearing thick thermal protection gloves. The other type is designed for hand held devices that use touch-screen manipulation on the monitor, and it is easy to carry and move in emergency situations. The overall GUI architecture of the remote controller is illustrated in Figure 8 and the layout can be described as follows. At the center of the screen, the visual information obtained from the robot's camera is shown. The reason why the color of the fire is white in Figure 8 is that the camera module automatically switches to the infrared picture mode in lightless environments. On the left side of the screen that shows the camera input, there are 4 small screens that display the other robot's visual information. When the user handles multiple robots, these separate display monitors not only display their monitoring statuses but also offer separated control services for robots by using separated wireless channels. By clicking the robot switch button in the control box or by touching the small screen in the handheld device, the operator is easily able to control the other thrown robots. In the upper right side of the GUI, there are several control bars that represent numeric values of various gathered data such as CO, O_2, gas, and temperature. On the left lower side of the GUI, an electronic compass is located and it displays the driving direction of the robot.

IV. Performance Evaluation

A. Impact resistance and waterproof test

We have designed a real fire test-bed with a container house and have evaluated the performance of the evacuation robot. The size (L × W × H) of house is 9m × 3m × 2.3m and the experiment sequence is as follows. First, we verify the impact resistance by throwing the robot and measuring the threshold value at which the robot cracks, as shown in Figure 9. The robot is thrown to the earth by increasing the falling height gradually until it shows external cracks or any functional disorders. The maximum falling height is about 3.5m, which is robust enough to be thrown by firefighters. Then, we operate the robot under falling water by using spring cooler facility, as shown in Figure 9. We verified that our robot can execute every predefined operations during shower in accordance with the IP22 standard criterion.

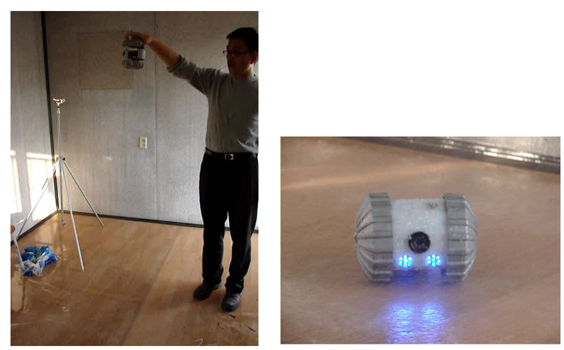
Fig. 9. Impact resistance and waterproof test

B. High temperature protection test

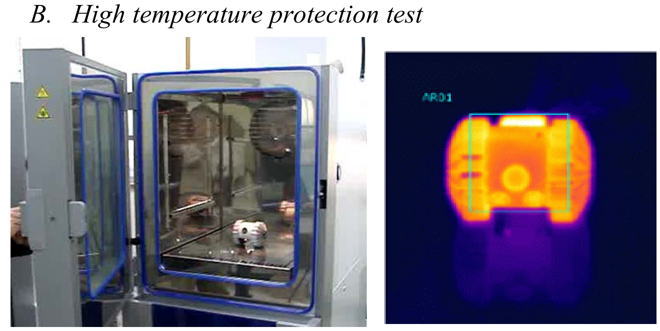
Fig. 10. Experiments with electronic oven

We carried out a high temperature protection test in both the laboratory and the house with real fire, as shown in Figure 10 and Figure 11, respectively. For the accurate measurement of temperature resistance, we use an electronic oven in which the robot tries to communicate with a remote controller until the temperature reaches maximum degree of robot's robust operations. Finally, we created a fire environment in a building and executed the entire rescue scenario shown in Figure 2. Table 2 summarizes the performance results of the evacuation robot, obtained in the experiment. From the results, we can note that the evacuation robot is suitable for monitoring fire sites and rescuing victims in the early stages of a fire before the temperature reaches flashover.

Fig. 11. Experiments with fire in container house

C. *Experiment of Multiple robots*

The situation of fire site is various and the firefighter may want to monitor several places for prompt rescue operations in fire building. Thus, we have used two robots with one remote controller to test cooperation between multiple robots in the building, as shown in Figure 12. Each robot entered the building with different directions and we turned on the remote controller. After each robot received wireless signals from the controller, they made WPAN topology by using separated Bluetooth channels. However, because the controller has only one joystick, the firefighter can manipulate only one robot at this moment. Thus, the other robot explores the building with simple autonomous navigation algorithms such as driving with obstacle avoidance and turning around the room. In this case of multiple robot operations, the maximum number of robots that the firefighter can operate simultaneously is 4.

Fig. 12. Experiments of cooperation between multiple robots

TABLE 2. PERFORMANCE STUDY

Parameter	Unit	Value
Video Rate	Fps	20
Data Rate	Kbps	56
Radio Range	Meter	50
Impact Resistance	Kgf-cm	200
Waterproof	IP	IP22
Voice Output	dB/mW	80/12
Transmission Delay	msec	100
Max. Temperature	°C	250
Height Overcome	cm	3
Survive Time	Min	15

V. CONCLUSIONS AND FUTURE WORK

In victim rescue operations at fire sites, which are one of the many applications of field robots, many environmental problems arise such as high temperatures, falling water, external impact, and limited data communication. In this paper, we present the design and implementation of a portable evacuation guide robot system with a remote controller, which overcomes these limitations. The robot is designed with aluminum compound metal for thermal resistance with waterproofing and an impact distribution frame for impact resistance. In addition, it offers various multimedia networking services such as video, voice, and sensing data transmission between the firefighters and the victims, based on separated wireless channels. The performance evaluation illustrates that our robot is well designed for providing monitoring services and rescuing victims at fire sites.

For future work on evacuation robots, we plan to develop an optimal multi-hop networking module for multimedia traffic, as well as dynamic topology management schemes for mobile environments. Then, we need to explore experiments for real victim evacuation guidance, which needs more caution and careful operations for dealing with victim's life.

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