Field Experiment on Multiple Mobile Robots conducted in an Underground Mall

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Abstract Rapid information gathering during the initial stage of investigation is an important process in case of disasters. However this task could be very risky, or even impossible for human rescue crews, when the environment has contaminated by nuclear, biological, or chemical weapons. We developed the information gathering system using multiple mobile robots teleoperated from the safe place, to be deployed in such situation. In this paper, we described functions of the system and report the field experiment conducted in a real underground mall to validate its usability, limitation, and requirements for future developments.

Key words: Search and Rescue, Teleoperation, Field Robotics, Mapping

1 Introduction

Confined spaces such as underground cities, subways, buildings, and tunnels pose the maximum risk to first responders during urban search and rescue missions. Their advanced equipment and materials have the following objectives:

1. reduce the risk to personnel by using equipment instead of human for performing critical tasks;
2. perform tasks that humans can not execute; and
3. support personnel for rapid and sure execution of the task.

The responders will use robots and related technologies as advanced equipment to achieve these objectives.

The Ministry of Economy, Trade and Industry of Japan (METI) has investigated important issues that are required to be resolved in order to strongly promote robot applications, and they have designed a roadmap for the same.

In order to promote the development of disaster response robots, METI and New Energy and Industrial Technology Development Organization (NEDO) have set up

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"Project for Strategic Development of Advanced Robotics Elemental Technologies, Area of Special Environment Robots, RT System to Travel within Disaster-affected Buildings." The mission statement is as follows:

1. Gather information rapidly at the first stage of the disaster
2. Increase efficiency and accuracy of response by quick and distributed sensing.
3. Use RT (robot technology) in order to eliminate the risk of possible secondary disaster to human responders.

To meet the above demands, we have launched an industry-government-academia research project in collaboration with five universities, two national institutes, and three companies. The objective of the project is to develop an RT system for use in search and rescue missions; it consists of (1) highly maneuverable multiple robots, (2) a scalable communication system for long distance teleoperation of robots, (3) an intelligent remote control system for the robots used for assisting human operators, and (4) a 3-D mapping technology in no GPS environment and an environmental information management system for locating victims and aid rescue crews strategically. Disaster areas such as underground malls may be contaminated with nuclear, biological, or chemical weapons due to which they might be very dangerous for human responders during the initial stage of investigation. We have been developing the above RT system since 2005, which consist of multiple tracked vehicles, and have conducted a field experiment in an actual underground mall "Santica" located in Kobe, Japan. Fig.1 shows *Kenaf* moving toward simulated victims during the field experiment.

In this paper, we have described the RT system in brief. Then we have reported the results of the field experiment conducted to validate our RT system's usability and limitations, and identify requirements for future developments.

Fig. 1 Field experiment conducted in underground mall "Santica"

2 Fundamental functions

RT systems used in search and rescue missions are required to consist of highly maneuverable robots, teleoperating system, a positioning system, and a communication system. In order to integrate these systems and evaluate their performances, we have developed 10 tracked vehicles that serve as a research platform named "*Kenaf*." The fundamental mechanism and functions of *Kenaf* are introduced in the following sections.

2.1 Highly maneuverable mobile robots

Kenaf has a pair of full-body main tracks, and two pairs of sub-tracks (flippers) whose end pulley is larger than the hub pulley. Each flipper can change its orientation. It has a simple and tough ladder frame structure. The resulting total weight of the basic configuration is 20 [kg]. Heavy components such as batteries and motors

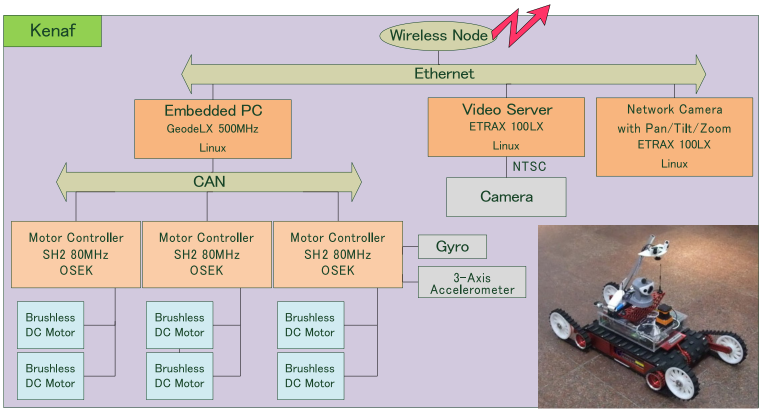


Fig. 2 Architecture of controller components

are placed in the lower position of the robots to maintain a low center of gravity. This, in turn, ensures that *Kenaf* with the basic configuration, does not fall over until its roll angle exceeds 80[°], in theory. The main tracks are driven by a 90[W] brushless DC motor with a dedicated dual channel motor controller. The orientation axis of each flipper is driven by a 50[W] motor. The maximum running speed is approximately 0.8 [m/s] when a standard gear reduction ratio is employed and it increases to 2.5 [m/s] with a high speed configuration of gear reduction ratio.

2.2 Control architecture

Kenaf has three Renesas SH2 embedded controllers as the motor controller and an AMD Geode-based low-power-consumption board computer as the main controller(Fig.2). Each motor controller is responsible for controlling the speed of the two motors. The controller used for the motor driving the main track employs 3D odometry (described in Section 2.4) and controls the trajectory of the robot so that it follows a given target line. The main controller coordinates with all the motor controllers by communicating over CAN. It has a certain degree of autonomy in terms of avoiding obstacles (Section 3.1), following the given path (Section 3.2), stopping in case of emergencies, and controlling the flippers (Section 3.3).

The main controller runs on Linux using a Gentoo Live CD that is highly customized for use with the PC installed on-board *Kenaf*. All read-only files are stored in a read-only filesystem (squashfs), and other files, including configuration files, log files, and some components of *Kenaf* are stored in tmpfs that is initialized and created from the read-only file on each boot. This configuration ensures that no permanent damage is caused to the filesystem in case of sudden power failure. A locomotion controller named *kenafLocoServer* accepts motion commands and status queries via CORBA. Status information used for executing on-board processes is also available on the shared memory to avoid communication overhead in CORBA.

2.3 Basic operator interface

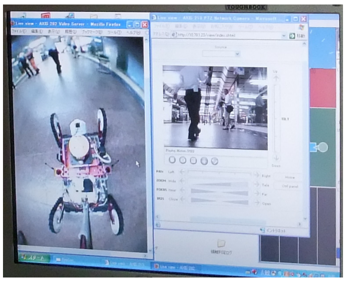


Fig. 3 Operator console with basic configuration

As a baseline remote control function, we have developed a basic operator interface that can be used to control each 6DOF motion of the robot using a simple game pad and it can be used to monitor parameters such as battery voltage, pressure, and temperature. The operator console and *Kenaf* communicate over an IP network, which can be unreliable. To avoid a critical situation wherein the operator can not transmit a stop command to *Kenaf*, the operator console communicates with a dedicated remote control server via UDP instead of CORBA IIOP. If communication is not restored within a certain time period, the remote control server will disables all the actuators on *Kenaf* for safety.

The operator makes decisions on the basis of *Kenaf*'s camera view and its tilt status. Even though some various camera configurations are available, the primary camera configuration employed for basic teleoperation consist of a wide-view-angle (134[°] vertical, 103[°] horizontal) look down camera placed on top of a pole(Fig.1). The operator can perceive not only the surroundings but also the condition of *Kenaf* using this camera. Fig.3 shows images observed at the basic operator interface using the look down camera, and front camera.

2.4 3-D odometry using 3DOF gyroscope

Generally, realizing an odometry system with tracked vehicles is difficult, because the turning motion of the vehicle generates positioning errors. Moreover, eliminating the positioning errors in our system is very important to transmit the position of the robot to the operator and to map the target environment. Therefore, we have proposed a novel odometry method for the position estimation of tracked vehicles with gyro sensors used in a 2-D environment tracking into account the slip characteristics of the tracked vehicle. The method is described in [7] in detail.

2-D odometry can not be used to provide accurate 3-D position information of our robots, and the temperature drift of the gyroscope is also a serious problem. Therefore, we have extended the above method for use in 3-D environments and have appended a drift cancellation function [8]. A preliminary experiment was conducted in an environment consist of standard stairs, and 60[cm] errors on an average were detected during 25[m] up-down navigation of the stairs. Other results were described in [8] in detail. These results are reasonable for our application, and this method was successfully implemented on all our robots.

2.5 Communication network

Remote control of the communication system in an RT system is one of the major challenges. In Japan, the antenna power of wireless LANs is limited to 10 [mW]; therefore, its coverage area is in the range of 50 to 100 [m]. Moreover, increased traffic causes network congestion in communication infrastructure such as cellular networks at the time of disasters. Using cables or wireless mesh networks are inadequate in such situations. Cables exhibit better performance in terms of bandwidth and latency as compared to wireless networks, but they hinder robot motion owing to their weight and tendency to coil up.

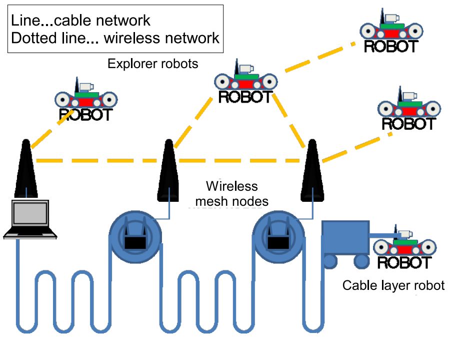


Fig. 4 Hybrid mesh network system

Therefore, we have designed and developed a hybrid mesh network system consisting of a cable network and a wireless mesh network (Fig.4). The traffic between the wireless mesh nodes of this system is controlled using the Rokko Mesh Router designed by Thinktube Inc., which also serves as a 50 [m] network cable reel. The physical layer of the network complies with IEEE802.11g in the case of the wireless network and 100base-TX in the case of the cable network. The mesh network is based on the AODV routing protocol. A cable deployment robot is used to deploy the cables and wireless mesh nodes every 50 [m]. The other robots are then connected to the operator via the hybrid mesh network.

3 Operator assistance functions

3.1 Obstacle avoidance function

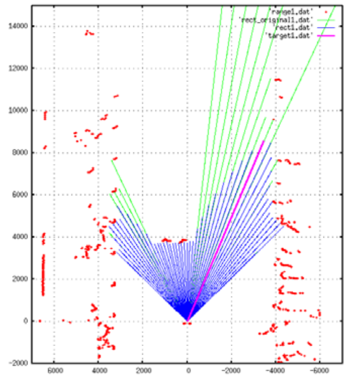


Fig. 5 Sensor data obtained by laser range finder and generated path

Using our RT system, operators manually control the robots on the basis of visual sensor data (described in Section 2.3). However, in situations where some evacuees obstruct the path of the robots, an autonomous obstacle avoidance function can prove advantageous for reducing the operator's work load. Therefore, we have appended a simple obstacle avoidance function on *Kenaf* which uses the sensor data acquired by a laser range finder (Top-URG UTM-30LX, Hokuyo Corp.). An important feature of the function is that it generates a path such that a certain distance is maintained from the moving obstacles for safety.

Fig.5 shows the actual momentary sensor data and the path generated in the case of a human standing in front of the robot at a distance of 4 [m]. First, the robot obtains 2-D range information (red dots in the figure). Then, possible paths for the robot are generated (green segments in the figure), and, finally, taking into account the boundary of the obstacles, the pink segment is selected as the robot's path. The autonomous obstacle avoidance function is run on a realtime basis by repeating the above procedure every 1/10 [s].

This obstacle avoidance function can anytime be replaced with conventional manual control.

3.2 Pointing navigation function

Teleoperating a mobile robot over long distances is a tough and tedious task for human operators. We have developed an operator interface for operating robots in flat and large areas, which reduces interaction between the robot and the operator. The interface accepts a target path expressed in terms of a sequence of waypoints, and the robot moves along the path autonomously. Thus, even in the case of long communication latency between the operator console and the robot, robot motion does not get affected.

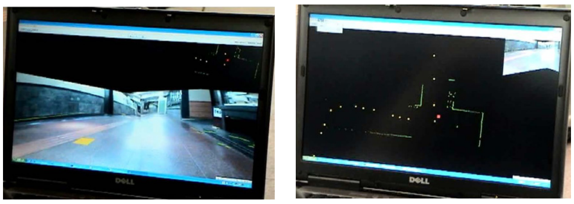


Fig. 6 Left: Robot's camera view. Right: Bird's-eye view.

We have setup two view modes for the operator. One is the local map mode that shows the sensor data obtained from a horizontal laser range finder(Fig.6, right), and the other is the camera video mode that shows images that are obtained from the on-board camera and that are superimposed by the sensor data(Fig.6, left). The operator can switch between these modes anytime during operation. Two cameras focused diagonally forward from left to right are used in addition to the standard look down camera for wide field of view. The operator clicks on these views to specify the waypoints.

The operator can interrupt the autonomous motion of the robot and switch to the manual control mode anytime during operation. Further, when obstacles are detected along the path, the operator can switch to the obstacle avoidance mode, which is described in the previous section.

3.3 Autonomous flipper control system for operator's assistance

Flippers (sub-tracks) greatly assist robots in traversing large steps and rough terrains. However, it is challenging for an operator, particularly for one who does not possess necessary skills, to control such flippers remotely without a direct view of the actual environment.

To assist the operation of the tracked vehicle "Kenaf," we have been developing two autonomous flipper control systems based on different approaches. The common strategy of both the systems is to control each flipper angle on the basis of the sensor data to traverse bumps on the ground. The operator is required to indicate the direction to the robot for navigation.

One approach is on the basis of the contact detection of flippers to the ground, and the gap detection under main tracks. The contact of flippers is detected by measuring each flipper's motor torque, and the gaps under main tracks are obtained from PSD range sensors attached to the front and rear of *Kenaf*. Details are described in [1].

The other approach is to use two laser range finders to obtain the terrain shape information [6]. The two laser range finders are located on both side of *Kenaf*. Their sensing surfaces are perpendicular to the ground so that the ground shape in the vicinity of the two front flippers can be perceived. Fig.7 shows the locations of the sensors used to obtain the terrain information.

Both systems have been successfully implemented on *Kenaf*, and some preliminary experimental results have validated the usefulness of both systems. Fig.8 shows *Kenaf* traversing steps using the former autonomous flipper control system.

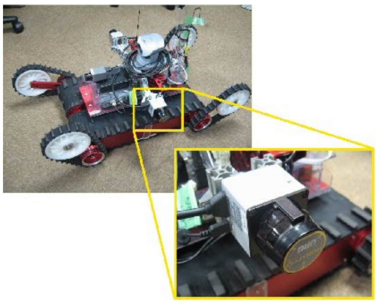


Fig. 7 Location of laser range sensors

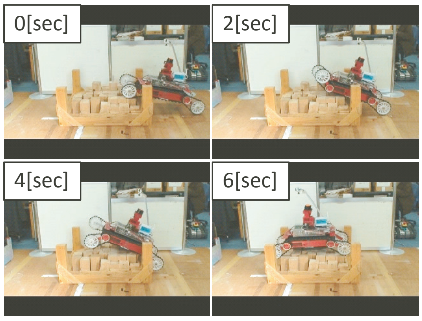


Fig. 8 Traversing random step fields under autonomous flipper control

4 Environmental information gathering functions

4.1 3-D mapping using laser range finder

3-D maps are very useful to rescue crews for strategizing. One of the features of a 3-D map is that it can be viewed in multiple modes, such as a bird's-eye view, which is a big advantage for strategizing rescue plans.

The simplest method to obtain a 3-D map using a robot is to fix a laser range finder on the upper position of the robot. It directed upward to obtain distance information leftward, upward, and rightward of its body. 3-D information is then obtained by moving the robot in the forward or backward direction. This is a very simple and effective method to obtain 3-D information. However, the quality of the map depends largely on the accuracy of the estimated position of the robot.

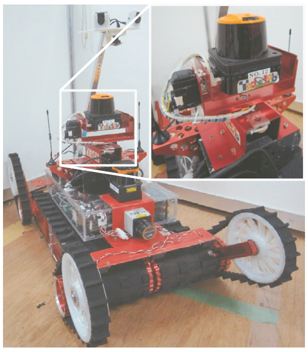
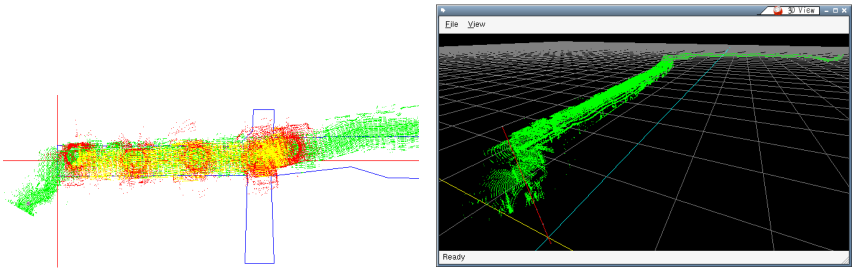


Fig. 9 3-D scanner named TK-scanner.

To obtain detailed 3-D environmental information, we have developed another small-sized, wide-view, and lightweight 3-D scanner named TK-scanner [2] (Fig.9) using a 2-D laser range finder and a pan-tilt mechanical base. The TK-scanner spun the tilted 2-D laser range finder to obtain a set of 3-D information in 10 [s]. To obtain a consistent 3-D information, the robot must keep still while TK-scanner is scanning.

4.2 Geographic information system

Information sharing is the most fundamental and important issue in managing rescue operations in case of disasters. Because mobile rescue robots and devices provide only fragments of information, we need a database system to store and integrate them. Further, because this information is location and time-sensitive, the database system should be similar to a geographic information system(GIS).



(a) 2-D view.

(b) 3-D view.

Fig. 10 Integrated sensor data of laser range finders installed on several robots

We used DaRuMa (DAtabase for Rescue Utility MAnagement) [5] as the GIS to gather and integrate the sensor data obtained from our robots. DaRuMa is one of the MISP (Mitigation Information Sharing Protocol) [3, 4] server implementation systems, and it serves as a database middleware. MISP provides functions to access and maintain a geographic information database over networks. The protocol consists of pure and simple XML representations; this facilitate the development of systems that can handle this protocol. The entire system based on MISP forms a client-server system wherein the server is the database and clients are data providers and/or data requesters. Client programs can communicate with DaRuMa using MISP, and all registered/queried data are transferred to/from a SQL server through DaRuMa. Our robots can directly transmit their sensor data to DaRuMa through the hybrid mesh networks.

5 System integration and field experiment

The experiment was conducted on 11/6/2008 at 2:30 AM in “Santica” underground mall located in Kobe, Japan, to validate the integrated system in a real environment.

The starting position of three of the *Kenaf* robots was set close to the operator station in front of several blocks of random step field which simulate uneven terrain. The fourth robot was placed at a distance of 550 [m] from the station. All the four *Kenaf* robots were teleoperated from the operator station.

Because we only had a limited time to use the site, the network infrastructure for this experiment was set up by human in advance, instead of using cable deployment robot. It was 12 wireless nodes connected by 50 [m] LAN cables in serial.

The first robot with the basic configuration was teleoperated to travel as much distance as possible. The second robot employs intelligent operator assistance functions, and it was used to explore the environment in the vicinity of simulated victims. This robot was normally teleoperated using the pointing navigation interface, and the operator switched to the obstacle avoidance mode or the manual control mode as and when required. All the other robots were teleoperated using the basic operator interface with the video stream obtained from the look down camera installed on each robot. To verify the reliability of the operator assistance functions, a group of people was used to simulate evacuees in the real environment.

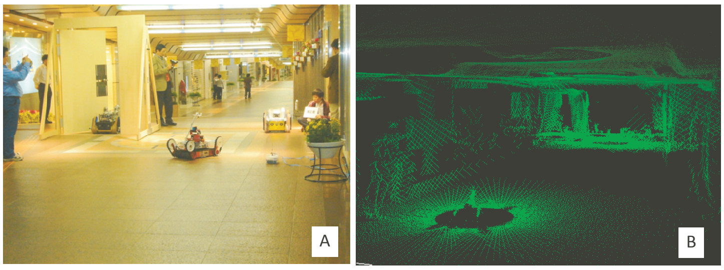


Fig. 11 The *Kenaf* with TK-Scanner in action and a resulting 3-D map.

The third robot which was equipped with TK-Scanner (Fig.9), also was used to explore and obtain detailed 3-D information regarding the environment in the vicinity of the simulated victims simulated victims. Fig.11 shows a resulting 3-D map obtained using TK-Scanner. All the 3-D data measured by each *Kenaf* robot was input to the DaRuMa server.

The role of the fourth robot was to monitor the first robot, and to add more traffic load on the network for network performance test. The reliability of the network system was verified monitoring the network traffic from these four robots.

In general, the experimental results indicate that the integrated system shows good performance. The first *Kenaf* robot traversed a corridor and reached a dead end at a distance of 683 [m] from the starting point. The hybrid network system successfully provided coverage even when each robot used 4 [Mbps] of bandwidth for transmitting the video stream and control signal. An automatic cable deployment was one of the key technology to succeed in our scenario, but it was not used in this experiment. We will apply our developing cable deployment robot in our future field experiments for setting up the network infrastructure.

The GIS system worked successfully in the case of the four robots. The robots were operated for approximately 1 [h], and the GIS system could register and integrate more than five million data points during this time. Fig.10-(a) shows the example point data around starting point registered by two robots. Fig.10-(b) also shows 3-D viewer application, called DaRuMa Viewer, viewing all data points which was obtained by a fixed laser range finder on the first robot. Anyone can explore and interact collected data in the DaRuMa server with this viewer even when the operators operate robots at the same time.

On the basis of the experimental results, we have found that the current version of the DaRuMa server does not scale well because the data entry process could handle only one registration request at once. The function used for registering and handling the data is required to be modified in the next version. All the information is registered on a coordinate frame designed for each robot. The relationship between each coordinate frame was configured in advance on the basis of the initial position of each robot. However, the accumulated positioning error of each robot caused distortion in the resulting 3-D map. Since each map from each robot are generated independently from other map from other robot, there were some inconsistencies in resulting united 3D map. We propose to use the SLAM technique to refine the resulting map in our future experiment.

The intelligent operator assistance functions were very helpful in a particular situation. In case the simulated evacuees moved toward *Kenaf* in walking speed, the obstacle avoidance function successfully avoided the collision of the robot with the evacuees. Nevertheless, when evacuees moved toward *Kenaf* in running speed, it failed in avoiding collisions. In reality, a more intelligent function may be required. The pointing navigation function worked well when there were only a few obstacles in front of the robot. However, in other cases, manual navigation was effective in controlling the robot. This was because the paths could not always be determined in advance. In case of moving or large number of obstacles, the operator has to determine paths using imprecise, and incomplete information, which is not easy or even possible. This problem might be solved if an advanced obstacle avoidance function is integrated into the pointing navigation function. The two flipper control systems were successfully integrated in two of the *Kenaf* robots. Both systems drastically decreased operator interactions in the presence of a stairs and random step fields.

6 Conclusions

In this paper, we have presented the results of a field experiment conducted using a remote controlled multiple mobile robot system as an advanced tool for assisting first responders during an urban search and rescue mission. Four mobile robots were simultaneously successfully operated using a realtime video stream of the environment. Data such as 3-D information of the environment, location of the victims, and trajectory of each robot was input to GIS DB server, and this data could be used to design a unified map. Further, we are attempting to enhance the hybrid network system so that it can operate 10 robots by using IEEE 802.11n.

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