Development of a Networked Robotic System for Disaster Mitigation
— Test Bed Experiments for Remote Operation Over Rough Terrain and High Resolution 3D Geometry Acquisition —

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Summary. In this paper, a newly initiated project of networked robotic system for disaster mitigation is introduced. In this project, multiple robots are coordinately operated through ad-hoc wireless communication network, including satellite-based IP communication link, for surveillance tasks at a disaster site. The robot system consists of a large-scale outdoor robot to serve as a carrier of small robots and a fleet of small robots to be deployed at a specific spot such as an inside of a building complex. A combination of a laser range scanner and an omni-directional camera is used to acquire high resolution 3D geometry data and rendering images. Those data and images are displayed using *Mixed Reality* (MR) technology at a remote site to provide an overall picture for operation managers with high fidelity. This paper presents our initial experiments using a robot test bed with an emphasis on remote operation over rough terrain and for acquisition of high resolution 3D geometry data and telepresence using MR technology.

Key words: Disaster Mitigation, Surveillance Robots, Wireless and Satellite-Based IP Communication, Ad-hoc Networking, Telepresence and Teleoperation, Omni-directional Camera, Laser Range Scanner, Mixed Reality

1 Introduction

Development of robotic systems for search and rescue operations receives increasing attention and national priority after the Hanshin-Awaji earthquake in 1995, Japan [1] and the World Trade Center incident in 2001, U. S. A. [2] In case of such natural or man-made disasters, it is necessary to grasp a whole picture of the extent and degree of the damages and victims as quick as possible. But when the extent and degree becomes grater it becomes more and more difficult to do immediate surveillance and rescue operations, because the access of the human teams becomes difficult and the communication networks go disorder due to physical damages on the ground facilities and the rush of access from a general public. To the robotics community, the development of remotely operated robots for immediate surveillance and possible rescue operations is strongly expected to mitigate the disaster by saving the lives of victims and avoiding a secondary disaster on the human rescue teams.

Since 2003, a group of present authors have been working on a newly initiated project of networked robotic system for disaster mitigation, under the support from the Japanese Ministry of Internal Affairs and Communications (MIC). The project aims at the development of a robotic system for surveillance of a remote disaster site. However the focus is not limited to the development of a single robot, but covers more *Information Technology* oriented subjects and integration of those robotics and information technologies. Three key issues of our project are summarized as follows:

1. Development of a network configuration and congestion control technologies to secure the emergency communication by making maximum use of Internet and wireless ad-hoc networks in case of wide-area disasters.
2. Development of a robotic system that can be deployed in the disaster site and teleoperatively or autonomously do surveillance tasks by cooperating among multiple robotic agents.
3. Development of a *Mixed Reality* technology to effectively display the high resolution 3D geometry data and images of the disaster site, acquired by the robotic agents, to the operation managers at a remote site with high fidelity.

Finally, the project looks at a possibility to demonstrate the integrated technology by using a satellite-based IP communication link that will be provided by ETS-VIII, a Japanese Engineering Test Satellite for advanced telecommunication technologies. Currently, satellite-based communication has a disadvantage of lower transmission bandwidth, however it has a grater advantage that the satellites are not damaged by the disasters on the ground.

This paper presents our initial experiments using a robot test bed with an emphasis on remote operation over rough terrain for acquisition of high resolution 3D geometry data and telepresence using MR technology.

2 System Concept and Mission Scenario

We develop a robot system consists of a large-scale outdoor robot (hereafter termed as a “parent robot”) to serve as a carrier of a fleet of small robots

Fig. 1. Artist's impression of the parent robot

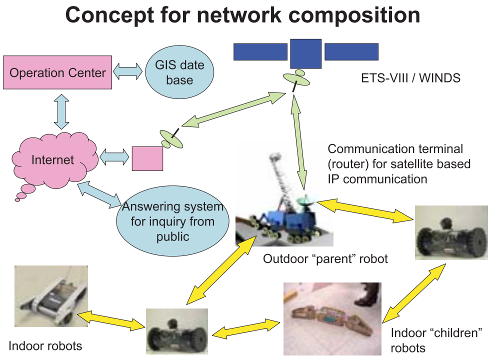


Fig. 2. A concept of the networking for the proposed robotic surveillance system

(hereafter termed as "children robots") to be deployed at a specific spot such as an inside of a building complex. Fig. 1 depicts an artist's impression of the parent robot. The parent robot should provide rough terrain mobility to approach a collapsed building, then using a ladder lift up children robots and deploy them on the higher floors of the building. After the deployment of the children robots, the parent robot could serve as a router for the wireless network of children robots and a bridge to the satellite-based communication link. Some of the children will go deep inside of the complex where the wireless signals from the parent cannot reach. In such a case a communication link should be established by relaying through a chain of children robots. Fig. 2 depicts our concept of IP based operation network that connects multiple surveillance robots at the depth of a disaster site and an operation center that could be located far from the site, via local area wireless transmission, satellite-based wireless transmission, and the Internet in the undamaged area.

The mission of the robot system is to acquire 3D geometry data and photo images of the site. For this purpose a combination of a laser range scanner and an omni-directional camera will be mounted on each robot. The geometry data and images are displayed using *Mixed Reality* technology at the operation center to provide an overall picture of the disaster site for operation managers with high fidelity. Also, other sensors for detecting victims such as infrared and CO_2 sensors should be mounted on the robots.

3 Mobile Robot Test Bed

For the initial development and tests of the technologies, a four-wheel mobile test bed was designed and developed as depicted in Fig. 3. The test bed weighs about 30 kg including an on-board computer, electronics and batteries. Each wheel has an independent motor drive (with Maxson 22W DC motors)

Fig. 3. A four-wheel mobile test bed for initial experiments

and a steering control. On each side the front and rear wheels are connected by a mechanical link that looks like a leg, and the left and right links are differentially connected at the central main body. This differential suspension system is called "rocker" suspension [3] and shows highly adaptive capability in traveling over rough terrain.

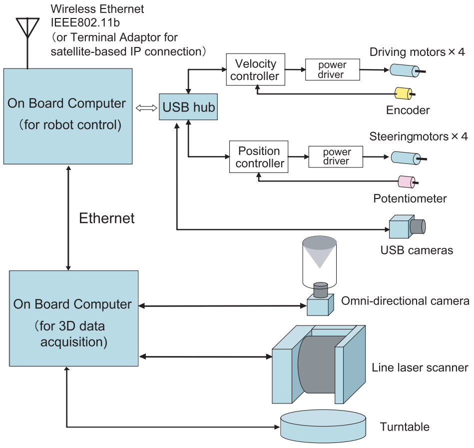


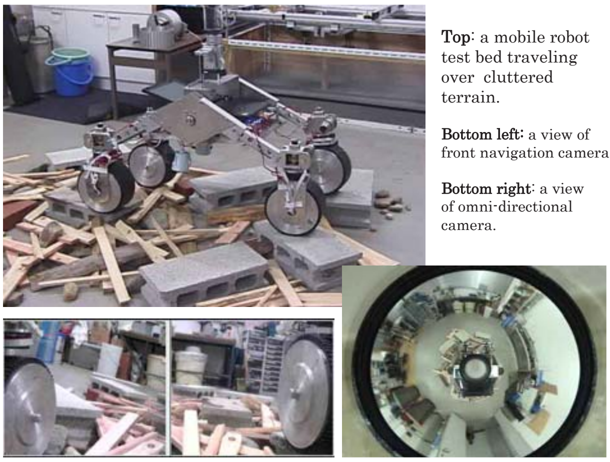
Fig. 4. Block diagram of the on-board control system

Fig. 4 depicts a block diagram of the on-board control system. As for the motor controllers and power drivers, we used common and commercially available products as much as possible. Particularly, for the interface with an on-board computer which is a standard laptop PC, we use USB. Through the USB hub, we can add more motors and sensors onto the system easily.

Wireless ethernet connection (IEEE802.11b), the modem of which is built in the on-board laptop computer, is used for remote operation of the robot. The traveling velocity and steering angle commands are given by a remote operator using a joystick and transmitted to the robot, then the local feedback control is performed by USB interfaced motor controllers (iMCs01, iXs Research Corp, with Hitachi H8 micro processor at 20MHz clock) on the robot to follow the given commands. The views of navigation cameras (with VGA quality, Motion JPG format at 6fps) are transmitted back to the operator for hazard detection.

For the acquisition of geometry information and picture images, a combined sensor system with a line laser scanner and an omni-directional camera is mounted on the central body of the robot. The line laser scanner turns stepwise by the turntable controller. The details of the telepresence technology are elaborated in the following section.

For the hazard detection during the rover locomotion, a stream of visual images around the front wheels is strongly necessary. But the quality of the images is not necessarily so high. On the other hand, for the construction of a map around the environment, the resolution of 3D measurements should be as higher as possible. However, we do not need to transmit a high-quality video stream, but three dimensional mesh data and still images taken at selective locations. This strategy eases the requirement for the transmission bandwidth. Eventually, in our test bed experiments, the overall bandwidth of the wireless connection between the robot and an operator console is just within 11Mbps, including the video stream from the navigation (hazard) cameras.



Top: a mobile robot test bed traveling over cluttered terrain.

Bottom left: a view of front navigation cameras.

Bottom right: a view of omni-directional camera.

Fig. 5. A snapshot of the experiments of teleoperation

The experiments of teleoperation were carried out successfully with the above apparatus. Fig. 5 depicts a snapshot of the indoor experiment traveling over a cluttered floor.

Note that the robot test bed used in the experiments here does not represent the parent robot or children robots in terms of the size, mechanical design, or specific mobility performance. The parent robot in our mission scenario should be much bigger and tougher for outdoor operation, and the children robot can be much smaller for the investigation in a narrow space. But in terms of wireless teleoperation and data acquisition, core technologies are common in any mobile robots with different scales or designs.

4 Telepresence Using Mixed Reality Technologies

4.1 High Resolution 3D Geometry Acquisition of a Remote Environment

As a preparation of reproducing a remote environment using Mixed Reality technologies, our high resolution 3D geometry acquisition system of a real scene is described in this subsection. Instead of using a pair of stereo cameras which has a disadvantage of inaccurate depth measurement for distant targets, an acquisition method using a laser range scanner is employed with a co-axis omni-directional camera on a turntable. Although a number of laser scanning systems have already been commercialized, our method is advantageous over them in terms of drastic cost reduction and measurement flexibility.

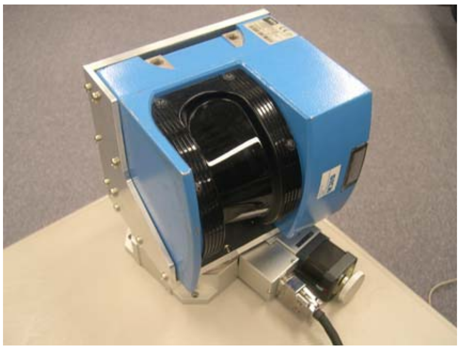


Fig. 6. A line laser scanner (SICK, LMS291) mounted on a turntable

At a measurement site, the depth information of the real scene is measured by a line laser range scanner (SICK, LMS291) on a turntable (Chuo Precision Industrial, QT-CM2 and ARS-136-HP) and sent to an operation center together with omni-directional images. At the operation center, a 3D polygon model (mesh model) is reconstructed from the depth information (point cloud) and images (texture data) received, and projected on an immersive display (Matsushita Electric Works, CyberDome, approx. 140 degrees of horizontal viewing angle). The line laser range scanner measures depth information along a line. The 3D reconstruction is realized by rotating the measurement line and by integrating a series of depth information. Fig. 6 shows the line

Fig. 7. A scene of a remote site

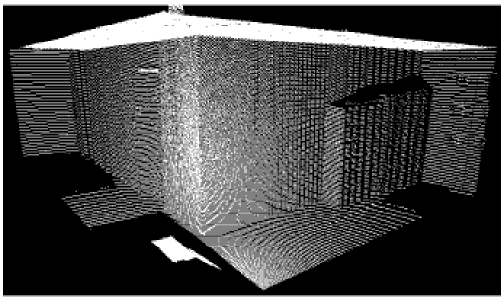


Fig. 8. A reconstructed 3D polygon model of the remote site

laser range scanner on the turntable. Fig. 7 and Fig. 8 show examples of a measurement site and a reconstructed 3D polygon model, respectively. In this case, 901 lines were measured in about two minutes by rotating the turntable with an interval of 0.1 degree, each having 361 measurement points scanned by the line laser range scanner with an interval of 0.5 degree.

In order to acquire the texture information of a real scene, if a symmetric omni-directional camera is used, a single shot is enough to obtain the image around 360 degrees. But if using a non-omni camera or an asymmetric omni-directional camera whose images has the highest resolution in the directions of 0 and 180 degrees [4], it is effective to rotate the camera on the same turntable of the laser scanner.

4.2 Telepresence Technique Combining Model-based and Image-based Approaches

The requirement for the surveillance of a disaster site is twofold. One is image based surveillance in which visual features such as smoke and fire or some characteristic colors are important. However, this kind of surveillance does not provide fine 3D geometry information. The other is the acquisition of relatively high resolution of 3D geometry data of the environment. This kind of information is particularly useful for the localization and navigation of the robot. In case exploring an unknown environment, map building of the environment is a priority task. The former can be termed “image-based” approach and the latter “model-based.” A comparison of these two approaches is summarized in Table 1.

In this research, we develop a telepresence technique that satisfies the requirements of both image-based and model-based approaches. Based on the assumption that the environment does not change so quickly, we construct the geometry model and make telepresence with color (texture) information obtained from visual images. Our technique is advantageous over both model-based and image-based telepresence approaches.

Table 1. A comparison of telepresence techniques

	image-based	model-based		proposed method
type of data	images	fine 3D geometry	coarse 3D geometry	images and 3D geometry
photorealisticy	high	high	low	high
real-time construction	possible	difficult	possible	possible
movement of viewpoint	difficut	possible	possible	possible

In the proposed technique, the color (texture) information of a patched area obtained from a still-camera image is allocated onto the corresponding 3D polygon model. Since the calculation of a huge amount of intersecting points by a CPU is too time-consuming to perform in real-time, a multi-pass rendering algorithm has been newly developed. The algorithm achieves a two-step projection for texture mapping by high-speed GPUs [5]. Fig. 9 depicts a texture-mapped version of the wire-framed model that was shown as Fig. 8.

Fig. 9. A texture-mapped representation of the 3D geometry model

By using this technique, a telepresence system has been realized, in which the latest image is updated in real-time while fine texture is gradually mapped on the entire model according to the camera movement in the environment. In the telepresence display, a human operator can interactively choose an arbitrary viewpoint of data representation. An indoor high-precision 3D tracker (3rdTech, HiBall-3100) was employed for sensing the position and orientation of human operator's head, so that the display can synchronize with the operator's view point and line of sight.

Fig. 10 depicts a snap shot of the developed MR-based teleplesence system. The scenes around the disaster cite are displayed (right) from an arbitrary

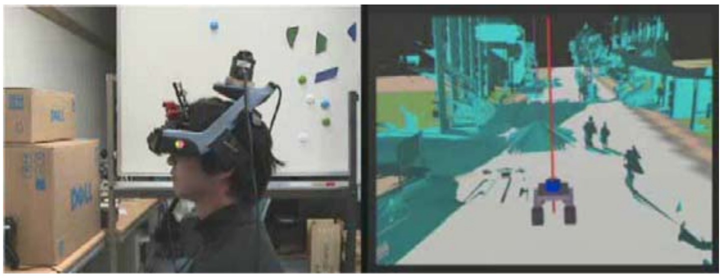


Fig. 10. A snap shot of the developed MR-based teleplesence display (right) that is interactive with the operator's head motion (left)

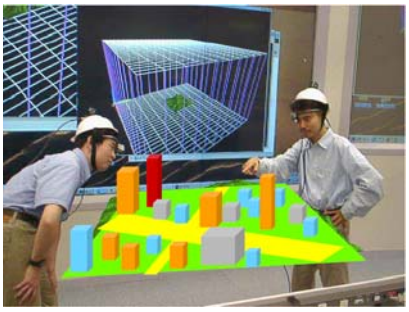


Fig. 11. A concept of an MR-based decision making room for operation managers

viewpoint with an arbitrary view angle according to the head motion of the operator (left). Fig. 11 depicts a concept of an MR-based decision making room where multiple operation managers can share the whole picture of the disaster cite with their individual view points through the individual head-mount displays.

For the incremental 3D geometry map construction along with the rover's motion, odometry information was used in the initial indoor experiments with the robot test bed, but odometry becomes unreliable when traveling over rough terrain. Alternative methods for the estimation of camera positions and orientations in practical situations need to be developed. SLAM (Simultaneous Localization and Mapping) technologies, around which there are an increasing number of papers and tutorials recently [6], are strong candidate for this purpose. We are currently looking into the practical implementation aspect of the SLAM algorithms in terms of less computational complexity and robustness in a real world.

5 Remote Navigation of the Robot

By integrating the developed technologies of teleoperation and telepresence, a "Stop and Go" type navigation is possible for practical surveillance tasks.

1. Before starting, the 3D geometry data should be obtained around the robot. A couple of minutes later, texture-mapped mixed-reality (MR) images of the environment will be displayed to a remote robot operator. Then the operator decides where to go.
2. During the robot motion, geometry measurement is not necessary, but the images of the navigation (hazard) camera should be transmitted at maximum available bit rate (but VGA quality at 6fps is enough). The images from the omni-directional camera are also useful, but the transmission frequency does not need as high as the navigation camera.
3. The MR display should show the model-based images with the moving viewpoint according to the robot movement. Simultaneously the real-time images obtained by the navigation camera should be superimposed for the operator to recognize immediate hazard.
4. The robot can continuously travel until the boundary of the model constructed by the recent previous measurement. The effective range of the 3D geometry acquisition is about 10 m in our test bed. Then, stop and obtain the 3D range data after every 5-10 m of locomotion for the incremental map building of the environment.
   Go back to step 1 and repeat the navigation.

6 Conclusions

In this paper, a newly initiated project of networked robotic system for disaster mitigation is introduced. The key concepts of the project are (1) utilization of the Internet and ad-hoc wireless networks for emergency communication, (2) coordination of multiple robots for outdoor and indoor surveillance tasks, and (3) the mixed reality representation of the disaster environment to the operation managers by combining the image-based and model-based techniques. Finally, the project looks at a possibility to demonstrate the integrated technology by using a satellite-based IP communication link, which has an advantage that the satellites are not damaged by the disasters on the ground. In this paper, the focus was made on the development of key technologies for the topics (2) and (3).

A robot test bed was developed as a general and common research platform that has a standard laptop PC with wireless ethernet communication interface as an on-boad controller. Operation of the robot is relatively simple. Just give the traveling velocity and steering angle commands by a joystick. For immediate hazard detection, navigation cameras are mounted on the robot gazing around the wheels. The camera images are transmitted within the bandwidth of 11 Mbps. In addition, the robot carries a laser range scanner and an omni-directional camera mounted on a turntable, in order to acquire high resolution 3D geometry data and rendering images of the environment around the robot. Those data and images are displayed using *Mixed Real-*

ity technology at a remote site to provide an overall picture for operation managers with high fidelity.

A key technology for telepresence display was developed in combining the advantages of image-based “reality” and model-based “substance.” In the proposed technique, the color texture information of the camera images is allocated onto the corresponding 3D polygon model in real-time. This technique allows us interactive display of the scenes from arbitrary viewpoints. A feasible operation scheme for the teleoperation of a remote robot with the assistance of the MR based telepresence was developed and tested by our mobile robot test bed.

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