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Deployment of Wireless Sensor Network using Mobile Robots to Construct an Intelligent Environment in a Multi-Robot Sensor Network

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1. Introduction

A Wireless Sensor Network (WSN), consisting of a huge number of small devices called sensor nodes (each with wireless communication functionality, various sensors, a processor, and a power source), is a network system that can communicate and use sensing data gathered mutually by each spatially distributed sensor node. An ad-hoc network connecting each sensor node one by one can be constructed only by deploying an enormous number of sensor nodes, and such a network can be enhanced very easily compared with wired and fixed networks. WSNs can provide various services by collecting and processing the information acquired by the sensor node. WSN technology is expected to be applicable within many fields, such as in the cooperative monitoring of the condition of an environment with a large area, factory equipment, or buildings, as well as in disaster relief support.

Additionally, in the area of robotics research, there have been studies on such topics as environmental information structuring and intelligent environments that examine the creation of intelligence not just in robots, but also in ambient environments (e.g. Sato *et al.*, 1996). WSN technology is now the object of attention among researchers attempting to create such intelligent environments.

We thought that it would be possible to construct a mobile ad-hoc network with autonomous mobile sensor nodes, environmentally adaptative WSN deployment, and applications within various intelligent systems. Autonomous mobile robot can be used and act as high-performance mobile sensor node in WSN because robots equipped with various sensors and communication capabilities. If a robot can manipulate sensor nodes, that robot can change the range and topology of its WSN according to the communication conditions, sensing and adapting to the environmental situation. Through a fusion of WSNs and robotics, it may be possible to extend communication and sensing areas, replace failure nodes by robots, and reconstruct WSN by relocating its sensor nodes.

Moreover, WSNs provide advantages for robots by enabling them to gather and communicate wide-ranging environmental information to one another without relying on

existing network infrastructures. Robots grasp the environmental circumstances using various sensor data obtained from the WSN, and use these data in several different tasks. We expect such systems to be superior with respect to the respective costs of deployment, movement, communication, energy, etc. Additionally, we expect these systems to exhibit robustness superior to that of conventional WSNs composed of fixed sensor nodes or homogeneous mobile sensor nodes when sensing environments with remarkably adverse wireless communication conditions and wide ranges. Such systems, which we refer to as MRSNs (Multi-Robot Sensor Networks), are the current focus of our research efforts. This chapter introduces applications of MRSN that the authors are currently investigating. The rest of the chapter is organized as follows: Section 2 describes disaster area information gathering supported by the application of MRSN. Section 3 explains the autonomous construction and management of WSNs by autonomous mobile robots, and Section 4 details the design and development of MRSN systems for the support of disaster area information gathering. Concluding remarks are given in Section 5.

2. Support for disaster area information gathering by MRSN

Large-scale earthquakes occur in various regions of the world, and the disaster awareness of most populations has risen in recent years. Thus, in addition to disaster prevention, researchers have focused on "disaster mitigation," which reduces the damage after the occurrence of a disaster, as a measure to counteract difficulty of predicting certain types of incident. In disaster mitigation, it is necessary to understand the disaster situation as promptly as possible. For instance, analytical research conducted following the Great Hanshin-Awaji Earthquake (Kobe, Japan) of 1995 highlighted the importance of the prevention of secondary disasters such as fires occurring after the main incident to the effectiveness of the rescue operation. Therefore, it is crucial that information gathering and surveillance be promptly and continuously implemented in large disaster areas if the symptoms of such secondary disasters are to be detected sufficiently early. However, it is difficult to collect disaster area information over adequately large areas because the human resources, including fire-fighters and rescue team members, in these various locations are generally limited.

Study of the manual deployment of sensor nodes on building ceilings, streetlights, etc., for preemptive disaster area information gathering following a disaster (Kurabayashi *et al.*, 2001) is in rescue research projects (Tadokoro *et al.*, 2003) commissioned by the Ministry of Education, Culture, Sports, Science and Technology in Japan. Preemptively deployed fixed sensor nodes can collect information at any time continuously before a disaster occurs. However, their functionality following a disaster cannot necessarily be guaranteed. If people are relied upon to deploy sensor nodes, human resources are often insufficient, as previously stated. Moreover, human sufferings might be caused by secondary disaster during information gathering activity.

Based on the above mentioned information, we thought that we would be able to preserve the sensing functionality and the network through the prompt deployment of a WSN by using a MRSN autonomously and adaptively, and that we would be able to collect disaster area information adaptively. Such a system is potentially applicable as an information support system for information gathering and situation awareness in large disaster areas

and the reduction of suffering from secondary disasters through the deployment WSNs by MRSNs, the collection and processing of their sensor information, and the provision of information services based on the information thus collected.

The following describes some elemental technologies developed for MRNS-based environmental information gathering support systems in disaster areas.

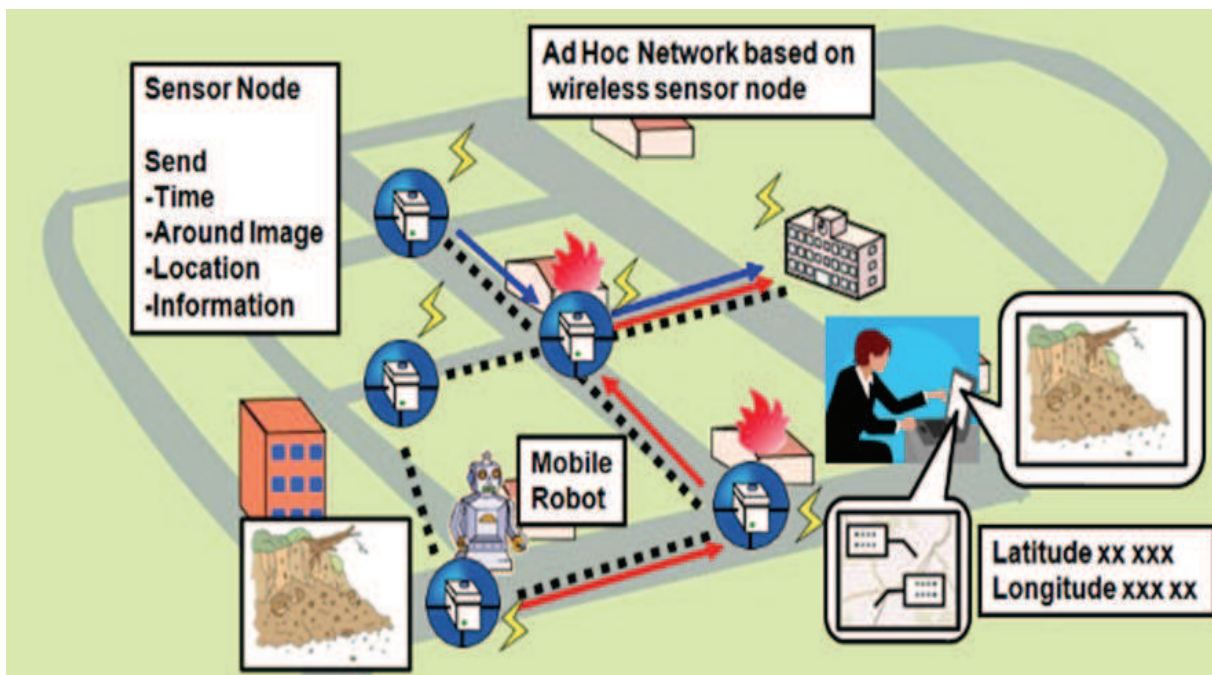


Fig.1. Conceptual sketch of MRSN-based environmental information gathering support system

3. Autonomous construction and management of WSNs by autonomous mobile robots based on electric field strength measurements

3.1 Autonomous construction and management of WSNs by mobile robots

The autonomous construction of WSNs has been previously discussed in conventional studies on sensor node deployment. The methods proposed in these studies consist mainly of randomly scattering many low-cost sensor nodes, constructing WSNs with mobile sensor nodes, etc. (McMickell *et al.*, 2003, Dantu *et al.*, 2005, Parker *et al.*, 2003). However, in the scattering deployment method, there is a possibility that the sensor nodes may not necessarily be deployed to the desired locations. Although it may be possible to evade such a problem by scattering a massive number of sensor nodes, the costs and increased communication traffic associated with the deployment of a large number of sensor nodes may prove problematic. In WSNs composed of mobile sensor nodes, the sensor nodes can be deployed to any position desired. However, sensor nodes with mobile capabilities are expensive. Moreover, the sensor nodes need not necessarily all move, depending on the environment. In general, system cost is a significant problem because a large number of sensor nodes are needed to gather information over a wide disaster area. Therefore, it is necessary to consider the costs of the sensor nodes and thereby reduce the energy costs for the entire system.

Other methods for sensor node deployment have been proposed; these were based on maximum communication or sensing range using mobile sensor nodes or mobile robots (Batalin *et al.*, 2002, Miyama *et al.*, 2003, Sugano *et al.*, 2006) and deployment by virtual interaction between sensor nodes based on physical models (Howard *et al.*, 2002, Pac *et al.*, 2006). However, these studies assumed that it would be difficult to guarantee communication between sensor nodes due to obstacles and interference waves that might block communication channels. Moreover, it is possible for that the communication between sensor nodes in WSNs to be interrupted due to decreases in sensor node battery levels or device breakage. Therefore, it is necessary to understand the status of WSNs, to ensure communication between sensor nodes, and to maintain their functionality as adaptive information communication network.

In our approach, the sensor node cost problem is solved by using low-cost sensor nodes that can perform the minimum functions necessary for environmental information gathering. Moreover, the energy cost problem is solved by enabling mobile robots to construct WSNs. In order to ensure communication between sensor nodes, the electric field strengths between nodes are monitored while the robot-deployed nodes are in transit to their designated locations. The robots confirm that the sensor nodes can communicate with one another, and deploy sensor nodes while guaranteeing communication channels between them. This proposed method is expected to enable construction of WSNs adaptable to changes in field strength caused by environmental interference.

After such a WSN is constructed, the circumstances under which it would be unable to continue functioning are estimated according to the battery level decrease that would result in the failure of a sensor node. Its robots can then specify the necessary details for a replacement sensor node by using positional information recorded when the original sensor node was deployed (odometric information, for instance). When a signal can be received from the sensor node, the accuracy of the detection of its location is improved using the field strength. Finally, the mobile robot moves to the location of the target sensor node, the alternative sensor node is deployed, and the function of the WSN is maintained.

3.2 Prototype system for verification of proposed method

A prototype platform that assumed the construction of a WSN in an indoor environment was developed and tested to verify the proposed method. The omni-directional mobile robot ZEN (Asama *et al.*, 1995) was used as the mobile robot platform (Fig. 2(b)). Mica2 MOTEs (Crossbow Technology, Inc.) were used as the sensor nodes (Fig. 2(d)). Each sensor node had a unique ID. Because the sensor nodes sent the transmission signals to on another that included the values of their own battery voltages, the condition of each of sensor node could be monitored over the WSN. A sensor node transportation and deployment device was developed for WSN construction. The device consisted of a sensor node tray into which sensor nodes were placed (Fig. 2(c)) and a sensor node manipulation mechanism able to carry and place the sensor node tray on the ground. This sensor node tray moved in a vertical direction due to the screw turned by Motor 2. Motor 1 moved the entire unit including screw and Motor 2 up and down vertically. The sensor node tray could be grounded by turning Motors 1 and 2. A single robot was able to transport and install 5 - 10 nodes at once using this device.

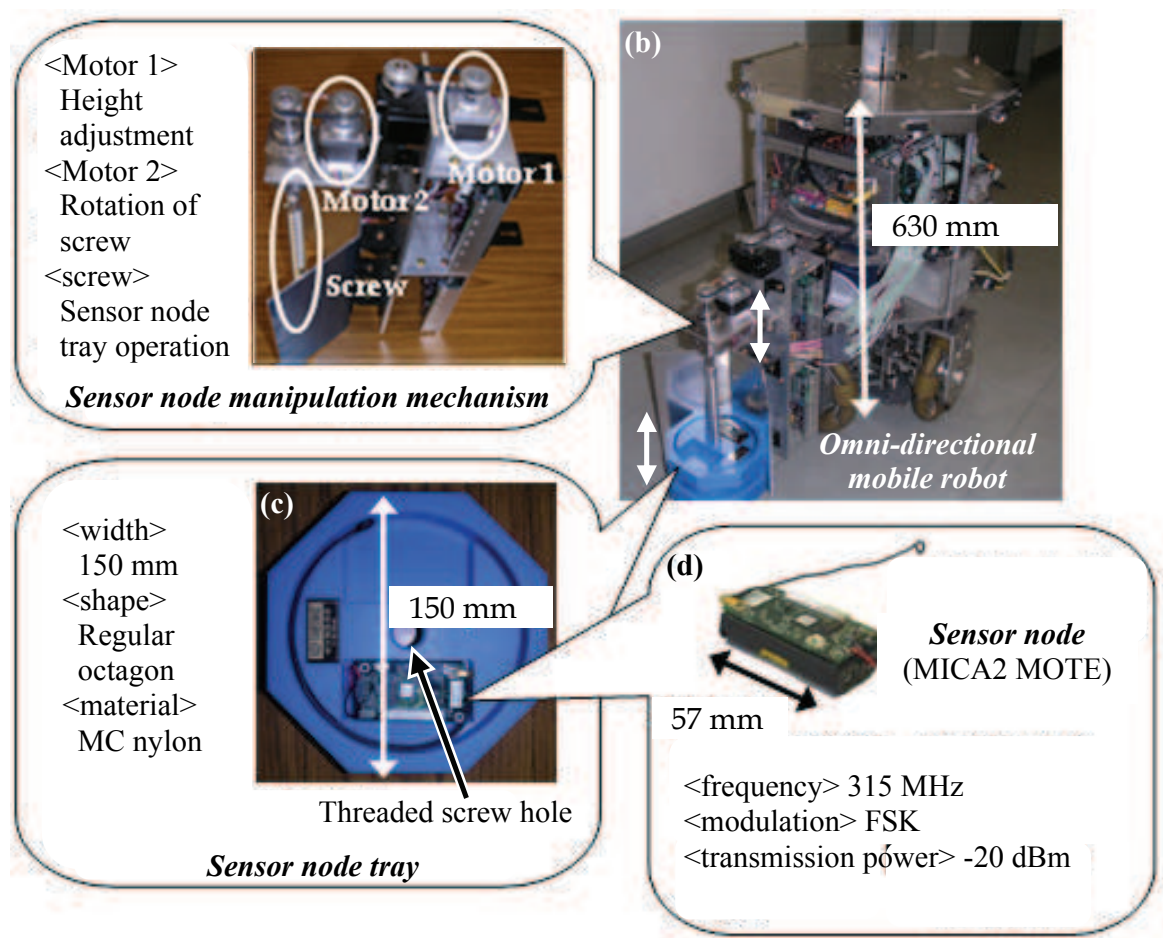


Fig. 2. Overview of prototype system

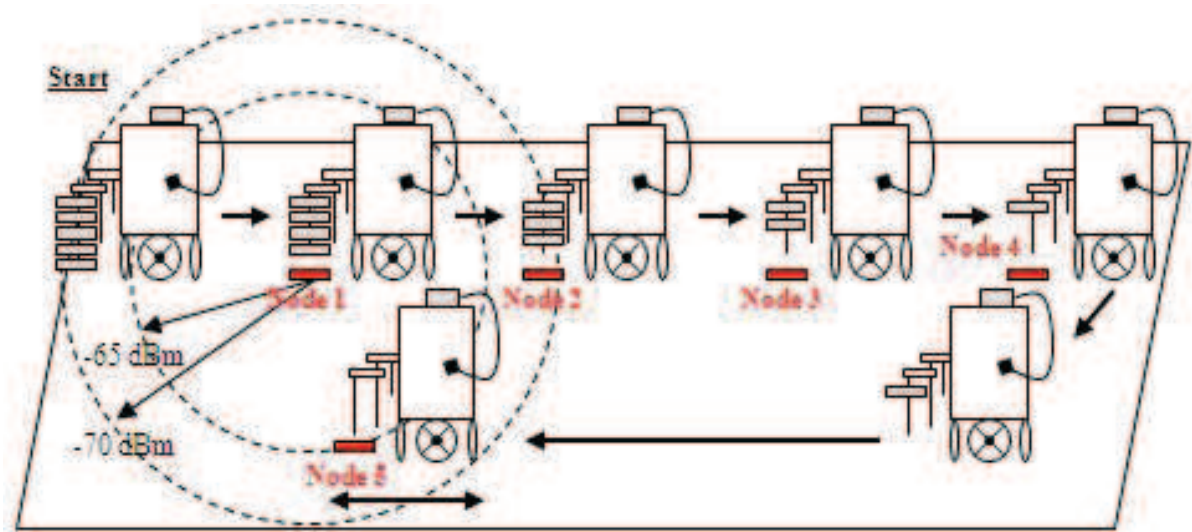


Fig. 3. Outline of the experiment based on the scenario

3.3 Experimental set-up and results

A preliminary experiment was conducted in order to confirm the characteristics of the electromagnetic waves propagated between sensor nodes in order to enable stable communication between these nodes.

The results confirmed that the an electric field strength threshold of -70 dBm would be needed to ensure stable communication between sensor nodes. This experiment measured the electric field strength of a robot moving after installing a sensor node. The robot installed sensor node one by one measuring the electric field strength threshold of -70[dBm]. The experiment was executed in an indoor passage (height: about 2.24 m, width: about 1.77 m, total length: about 40 m) of a ferroconcrete building.

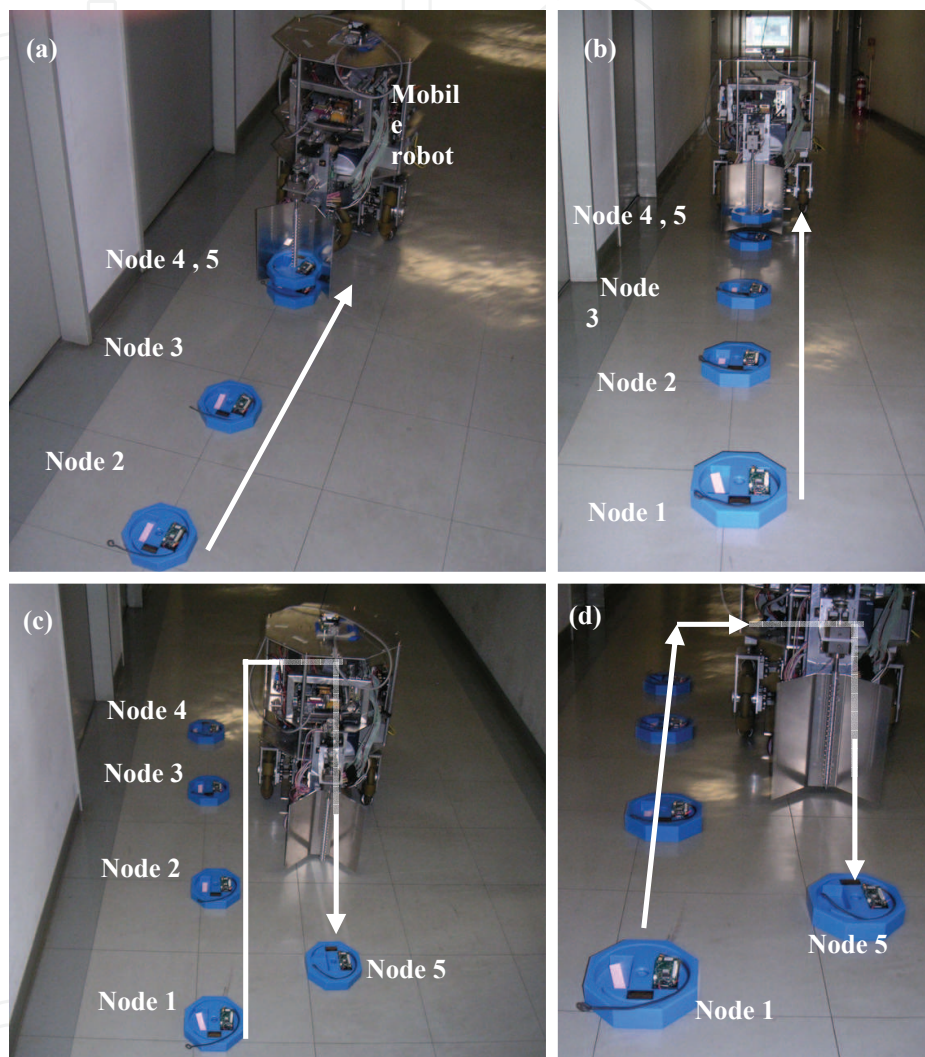


Fig. 4. Actual experiment on the autonomous construction and management of a WSN using a MOTE and omni-directional mobile robot

The scenario modeled in the experiment was as follows. The robot was given the task of installing sensor nodes. The robot initially placed a sensor node on the ground after receiving a command to carry out the autonomous construction of a WSN. The robot moved while simultaneously measuring the electric field strength between sensor nodes until it reached a preset value. The second sensor node was deployed at the point where this occurred. The robot constructed a WSN by repeating this operation, deploying sensor nodes one by one while measuring the field strength between sensor nodes. In this experiment, the battery levels of the sensor nodes were also assumed to be randomly decreasing. The robot was programmed to detect sensor nodes with low batteries, move to vicinities of such nodes, and deploy replacement sensor nodes near in order to maintain the WSN.

Figure 3 shows an outline of the experiment based on this scenario. Photographs of the actual experiment are shown in Fig. 4. In this experiment, the robot deployed five nodes. The robot constructed a WSN using Nodes 1 to 4 by measuring electric field strength and deploying the sensor nodes with respect to its values. A simulated low battery signal was then sent from Node 1. The robot registered the status of Node 1 via the WSN and moved to a nearby location. A replacement sensor node, Node 5, was then deployed within the communication range of Node 2. Figure 4(a-b) shows the construction of the WSN. Figure 4(c-d) shows that Node 5 was deployed near Node 1 after the simulated low battery signal was detected. Figure 5 shows the distances between the successive sensor nodes. In this experimental environment, there was a distance difference of up to 10 cm between deployed sensor nodes. This is because the location of each sensor node was decided according to fluctuations in the electric field strength due to the particular characteristics of the sensor node and the status of communication within the environment. Therefore, we confirmed that it was possible to construct a WSN that ensured communication channels between sensor nodes and to manage a WSN using proposed method to restore interrupted communication paths.

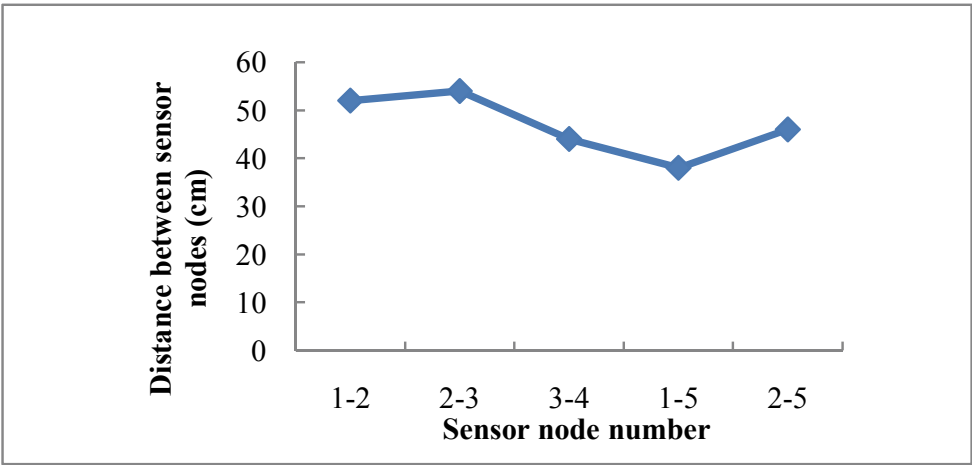


Fig. 5. Distance between deployed sensor nodes

4. Design and development of MRSN for disaster area information gathering support

4.1 Sensor node for disaster area information gathering support

In disaster areas, rubble is often scattered due to the collapse of houses and other facilities, and lifelines, infrastructure, etc., often rupture or break down. A new sensor node device with infrastructure non-dependence, easy deployment, and the ability to construct a WSN is needed to gather information under such circumstances, because most conventional sensor nodes are difficult to use in disaster areas. We discussed the required specifications of such a new sensor node, and thought that the following functions would be necessary:

1. Power supply equipment for independent maneuvering
2. Wireless communication
3. Ability to construction of an ad hoc network
4. Information processing

5. Ability to acquire image of the surrounding environment and thereby recognize the environmental circumstances
6. Localization for effective use of sensor data
7. Low-cost direction control without depending on deployment method

Though other devices that capture transmits images of it in the hazardous areas have been developed, such as the Search Ball (Inoue *et al.*, 2005) and the EYE BALL R1 (Remington Arms Company), a device with all of the above-mentioned functions as well as an ability to construct WSNs does not yet exist. Thus, we have designed and developed a prototype for a new sensor node satisfying these criteria.

4.2 Development of spherical sensor node equipped with passive pendulum mechanism

The sensor node that we developed consisted of a main controller with wireless communication capability, various sensing devices, and a passive control mechanism for maintaining constant sensor direction. Figure 6(a) shows the configuration of the sensor node. A small Linux computer, Rescue Communicator, produced by Mitsubishi Electric Information Technology Corporation was used as the main controller of the sensor node. Many various sensor devices could be connected together because the Rescue Communicator had many input and output sites. The sensor node was equipped with a compact flash memory card, wireless LAN card, omni-directional vision camera connected with a LAN cable and mounted with a fish-eye lens for capturing 2π sr images of its surroundings, a 3-degree acceleration sensor for measuring the postural sway of the camera and a GPS system for localization. The Rescue Communicator and all of the sensors could be driven by the sensor node's battery.

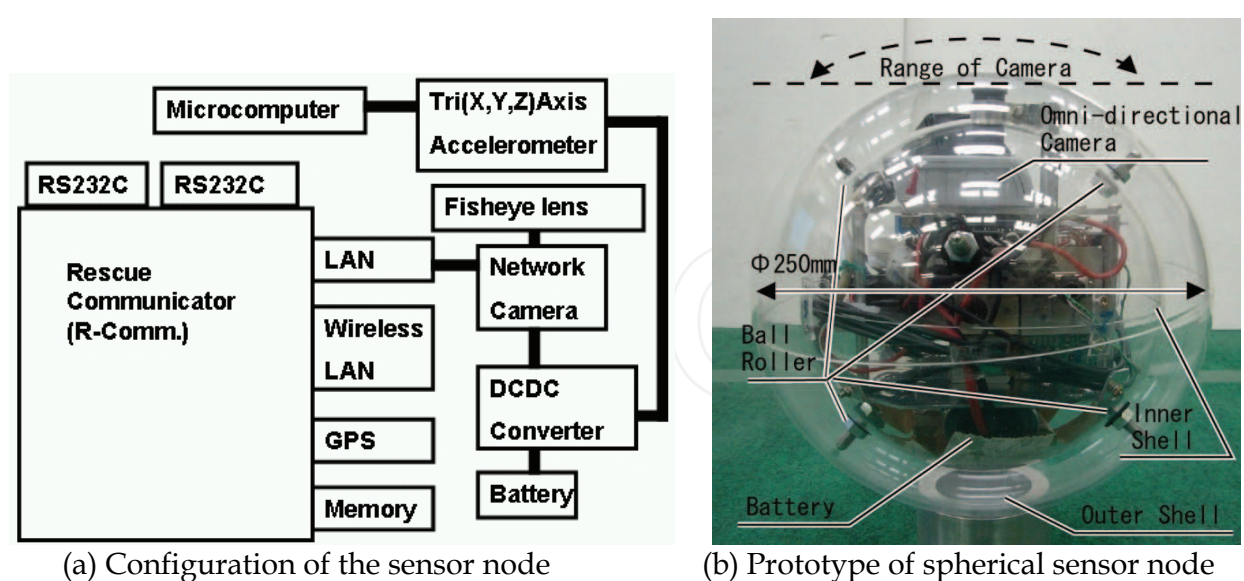


Fig. 6. Spherical sensor node equipped with a passive pendulum mechanism

Moreover, we designed the sensor node as shown in Fig. 6(b) to enable low-cost sensor postural control. The sensor node was designed so that the main body (inner shell) was surrounded by a spherical acrylic shell (outer shell) supported by the six ball rollers. The sensors (camera, etc.) were placed in the upper part of the inner shell, and heavy

components such as batteries were placed in the bottom. The inner shell rotated freely inside the outer shell by way of the ball rollers. Thus, the camera always remained upright within the outer shell because the heavy load was placed opposite the sensors, creating a passive pendulum mechanism and keeping the camera view in the upward direction. Therefore, it was possible to obtain omni-directional images from the same point regardless of the direction from which the device was deployed. AODV-uu was installed on the Rescue Communicator to enable construction of an ad-hoc network.

4.3 Functional verification of prototype sensor node model

An experiment was executed in order to confirm the information-gathering functions and ad-hoc networking capabilities of the developed sensor node. Figure 7(a) shows the experimental environment. In this experiment, an ad hoc network was constructed in an the outdoor containing a building, and the image data acquired by the sensor node was transmitted to the host PC in two hops. The sensor node transmitted image data of about 10 kbytes in the size of 320×240 pixels, along with information on the time the image was taken and latitude and longitude data recorded by the second.

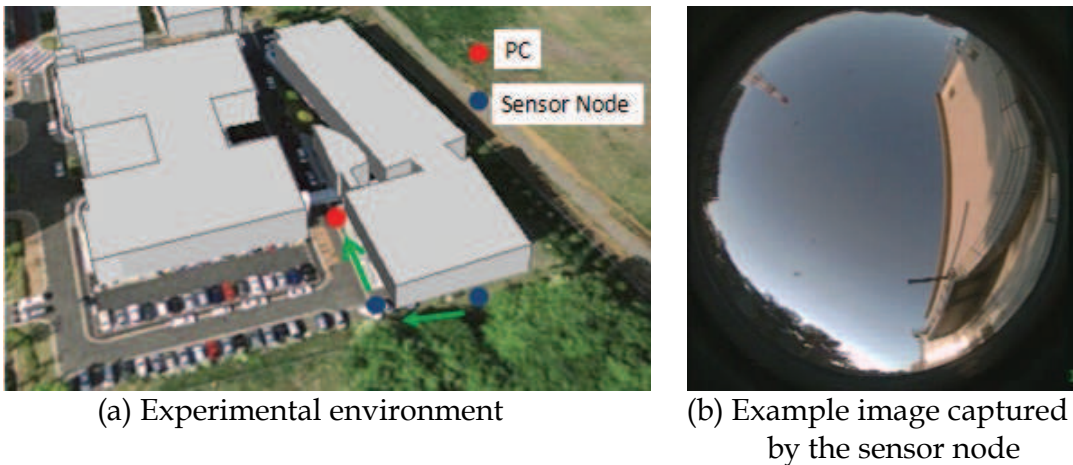


Fig. 7. Experimental set-up for functional verification of the sensor node

Table 1 shows the results of the data received on the host PC. Information on the sensor node, including time, latitude, longitude and transmitted image (Fig. 7(b)) was transmitted to the host PC. Figure 8 shows the time required to receive on the host PC the images sent by the sensor node. At points where the image capture time was notably longer, communication between the sensor nodes and host PC was interrupted. However, the host PC was able to receive images in an average of 2.3 seconds.

Total number of images received	427
Number of transmissions including time and location	81
Average time taken to receive an image (sec/ data)	2.3
Total time spent capturing image data (sec)	975

Table 1. Results: Time taken for host PC to receive data from sensor node

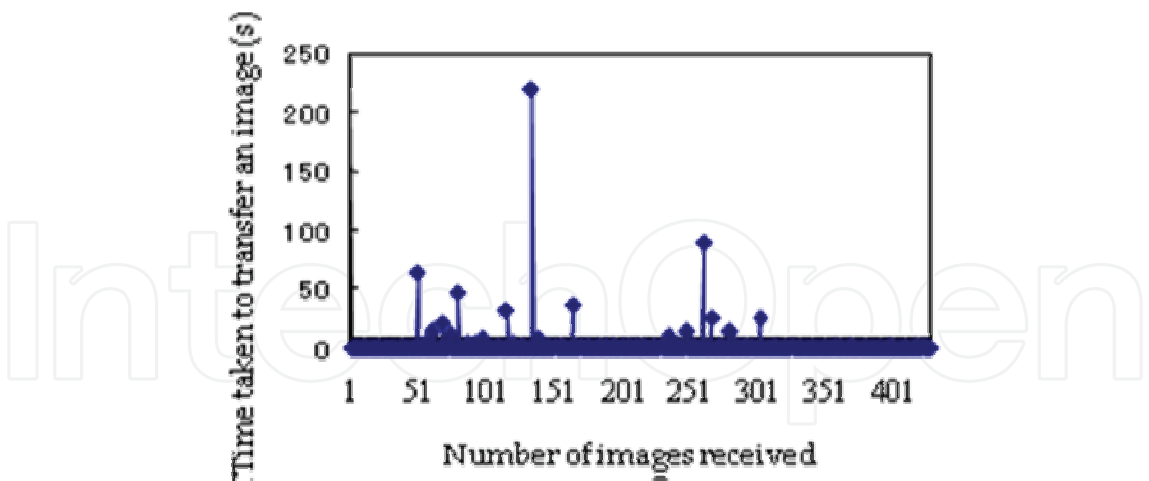


Fig. 8. Time taken to receive images on host PC

4.4 Design and development of transportation and deployment mechanism for spherical sensor node

A device was developed to enable mobile robots to carry and deploy the spherical sensor node. This device was designed to roll spherical sensor nodes onto the ground using sloped guide rails because the sensor node was spherical and could be deployed easily without regard to the direction of installation.

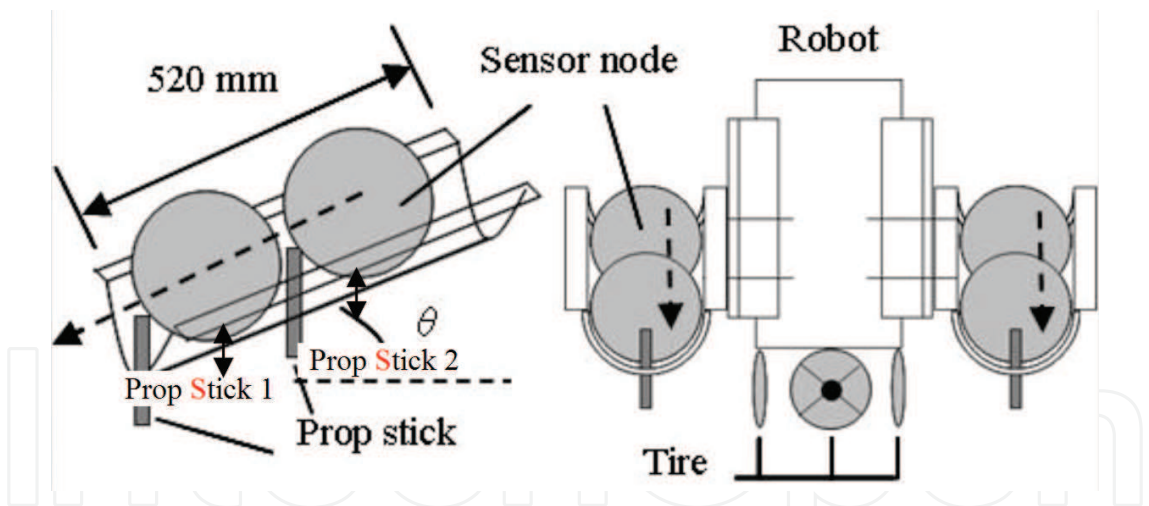


Fig. 9 Concept of the device for the transportation and deployment of spherical sensor nodes

Figure 9 shows an outline of the device. Two sloped guide rails were mounted on to the right and left sides of a robot. The robot was able to carry and deploy four spherical sensor nodes because each guide rail was able to hold two spherical sensor nodes at once in current system. The robot was able to deploy the sensor nodes by controlling prop sticks using the solenoid in this device. The first, lower sensor node rolled out by using its own weight to pull down Prop Stick 1 without moving Prop Stick 2, so that only one node was deployed into the environment. Next, the second, upper sensor node rolled down, by pulling down Prop Stick 2, to a position in front of Prop Stick 1 and was stopped the pushed-up Prop Stick 1. The second sensor node then rolled out by pulling down Prop Stick 1, and was deployed

into the environment. This transportation and deployment of the sensor node was made possible by taking advantage of the node’s shape and characteristics and did not require an actuator or active control over position and attitude.

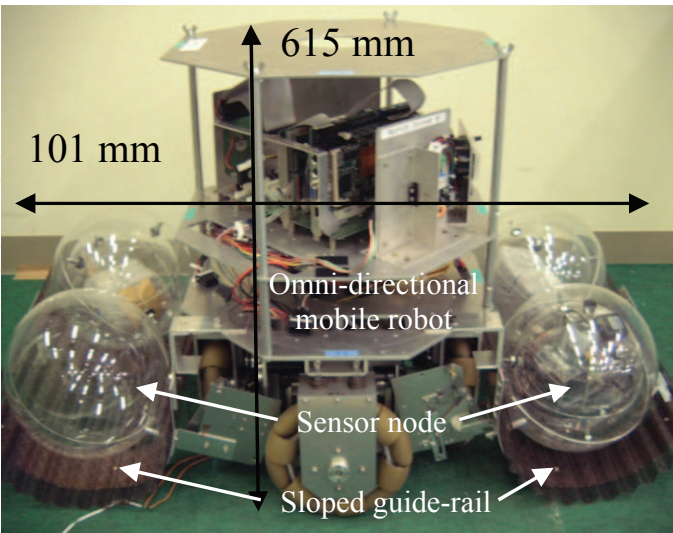


Fig. 10 Prototype of the transportation and deployment device

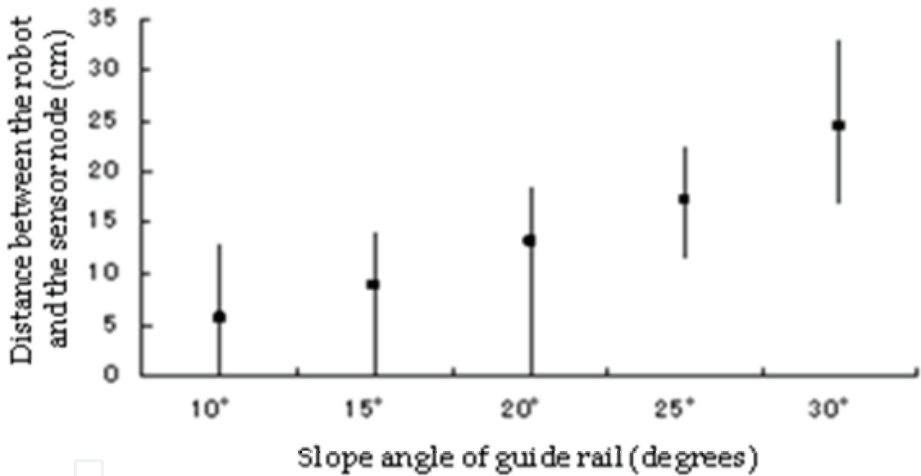


Fig. 12. Distance between the robot and the sensor node as a function of guide rail slope angle

Figure 10 shows an image of the transportation and deployment prototype device mounted onto the omni-directional mobile robot. The guide rail was made from a corrugated polycarbonate plate in order to provide strength and reduce the contact surface area between the rail and the sensor node. The slope angle was adjustable. This design enabled the sensor node to roll easily from the guide rail into the environment. Figure 12 shows the distance between the robot and the final positon of the sensor node after deployment as a function of the guide rail slope angle. It was possible to deploy a sensor node to within about 35 cm of a target position on a plain floor. Figure 13 shows the change in the visibility of a target image as a function of the error distance d from the target sensor node position. It was possible to recognize the surroundings of a target position when d was within 1.4 m.

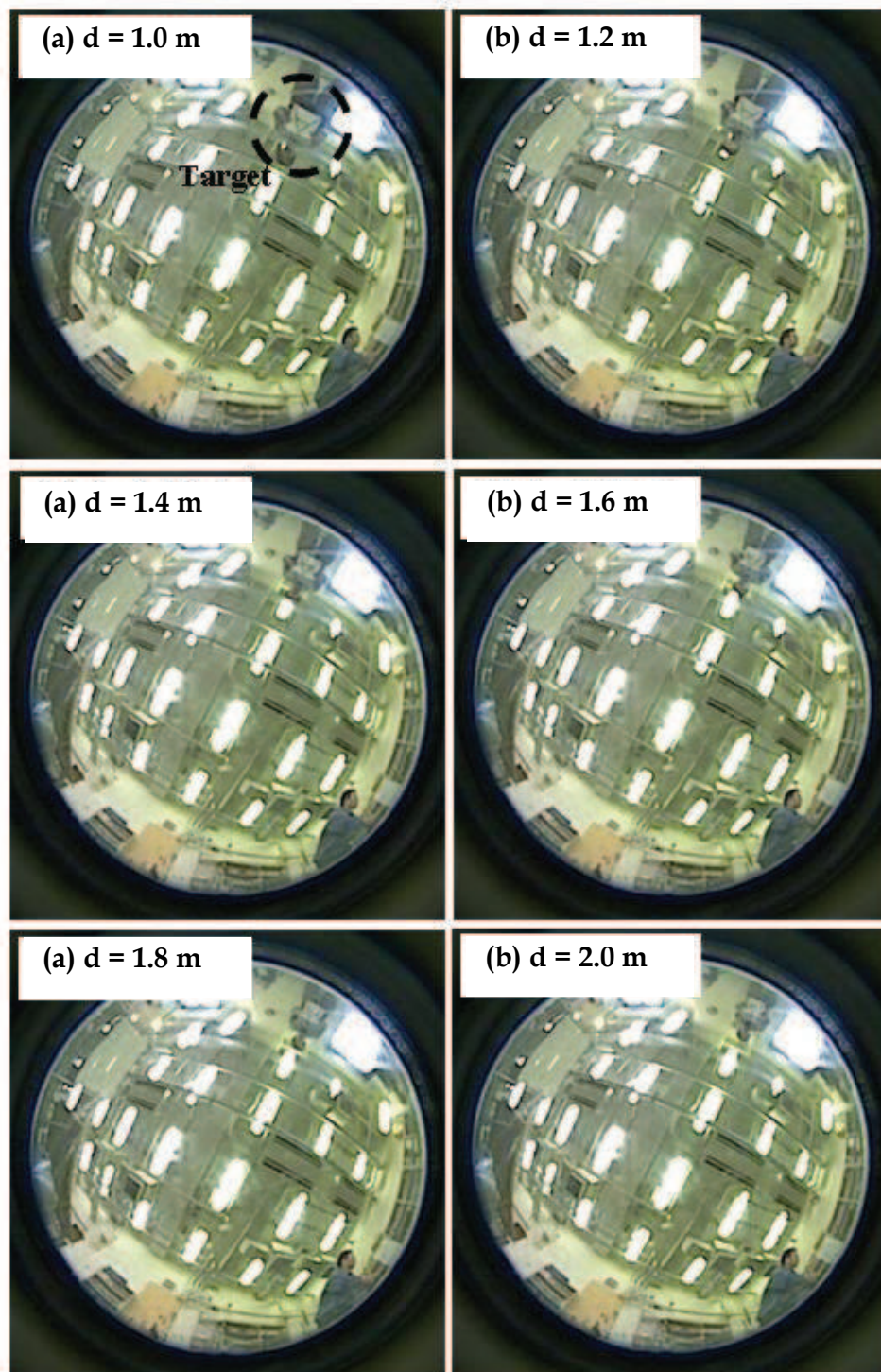


Fig. 13. Images captured at different sensor node deployment positions

5. Conclusion

This chapter has described the issues relevant to MRSNs consisting of WSNs and multiple robot systems. Additionally, we have introduced our work, which aims to develop support systems for information gathering in disaster areas via the application of MRSNs. Section 3

showed that a robot was able to construct and manage a WSN autonomously and adaptively by measuring electric field strength. Section 4 covered the design and development of a sensor node and its manipulation system for supporting disaster area information gathering. The system introduced here was a prototype; thus characteristics such as the robot's shape and the sensor node's environmental resistance must be further improved and developed to enable its practical application. Our future aims include the integration and upgrade of the component technology, as well as the improvement of the system so as to enable its use within realistic environments such as the outdoors and disaster areas. In addition, we will examine the communication protocol, information management, data transfer routing and the integration and processing of a large flow of information that would be appropriate for the proposed method.

MRSNs can construct WSNs adapted to their environments, and WSNs enable the robot mobile sensor nodes to gather and communicate a wide range of environmental information to one another without relying on an existing network infrastructure. We expect that MRSNs will be applicable within adaptive sensing, the adaptive construction of information networks and various intelligent robot systems.

6. Acknowledgments

The work presented here is a portion of the research project "Robot sensor network for rescue support in large-scale disasters," supported by the Research Institute for Science and Technology, Tokyo Denki University, Japan. We would like to thank Ryuji Sugizaki and Hideo Sato of the Graduate School of Engineering, Tokyo Denki University, for making part of the system and measuring data.

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Advances in Service Robotics

Edited by Ho Seok Ahn

ISBN 978-953-7619-02-2

Hard cover, 342 pages

Publisher InTech

Published online 01, July, 2008

Published in print edition July, 2008

This book consists of 18 chapters about current research results of service robots. Topics covered include various kinds of service robots, development environments, architectures of service robots, Human-Robot Interaction, networks of service robots and basic researches such as SLAM, sensor network, etc. This book has some examples of the research activities on Service Robotics going on around the globe, but many chapters in this book concern advanced research on this area and cover interesting topics. Therefore I hope that all who read this book will find lots of helpful information and be interested in Service Robotics. I am really appreciative of all authors who have invested a great deal of time to write such interesting and high quality chapters.

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