Experiments on Building Ubiquitous Robotic Space for Mobile Robot Using Wireless Sensor Networks

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Abstract

Ubiquitous robot is a network robot which can communicate with any devices at any time in the surrounding physical space to obtain more diverse view points of the environment. We call ubiquitous computing environment, which the network devices provide the environmental information to the robot in, ubiquitous robotic space (URS). In this paper, a sensor network platform is proposed to build the ubiquitous robotic space and provide lots of types of environment information such as indoor environment condition, fire detection, and intrusion detection. Differently from the existing sensor network applications that assume the static sensor nodes and the base station, the proposed sensor network platform is designed to support seamless environmental monitoring on the mobile robot system. We then applied our sensor network platform toe the real robot system and evaluated the functionalities of the proposed system.

1. Introduction

Ubiquitous computing paradigm, provides users with various services they need, anytime, anywhere through any network devices deployed in the environment, affects a paradigm shift in robotics. Ubiquitous robot, which is the third generation robot, recognizes the diverse environmental information through the ubiquitous computing environment, learns the optimal response for the given situation through the network, and provides seamless and context-aware to the users. In this point of view, it can be said that the ubiquitous computing environment is an important requirement for the research of ubiquitous robot system, and Korea launched the URC (Ubiquitous Robotic Companion) project to realize the ubiquitous robot by utilizing its well-developed IT infrastructure [1]. The URC software framework is largely composed of URC robot, URC server, and URC services in a distributed manner. The URC robot can download various service and software from the URS server and control many home devices around it. It can also collect various kinds of environmental information such as location, vision, sound, etc., obtain the inferred knowledge from URS server. We call this ubiquitous computing environment, where the robot monitors the status of the environment by collecting information from sensors, interpreting them, and providing intelligent services, URS (Ubiquitous Robotic Space) [2].

In this paper, we build the ubiquitous robotic space by employing a sensor network platform. A wireless sensor network is used to monitor the indoor environment for HVAC control, guard the house against intruders, and control the environment by the actuator nodes. Moreover, since the mobile robot has role of the base station in the proposed system differently from the existing sensor network systems, our proposed sensor network platform is designed to provide seamless communication link to the mobile robot.

This paper is organized as follows. Section 2 investigates up-to-date researches about the use of sensor network and RFID technology for the ubiquitous robot, and Section 3 describes the ubiquitous robotic space proposed in this paper. Section 4 shows the sensor network platform including hardware, network stack and application for URS. The robot system in the experiment, the testbed system, and the demonstration will be addressed in Section 5, and we conclude in Section 6.

2. Related Works

Ubiquitous robot has been connecting with RFID and sensor network technology in order to complement

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a robot's limited perception ability. RFID technology has been utilized for supplying detailed information of the object to the robot and localizing the robot's position. The TAG project of AIST [3] used an IC tag which is attached to an object. By reading tags, the robot can recognize the manufacturer's network address and the knowledge information required for a robot to handle the object. Based on this acquired information, conventional vision system can achieve more accurate object location and the robot performs manipulation through the robot's arm more efficiently. The GUIDE project [4] applied RFID technology to robot navigation. The position information of the RFID tag is mapped to tag ID to achieve a high resolution localization system.

Sensor network technology has been used for intelligent space [5] and high accurate localization and navigation for robot [6, 7]. In [5], sensor network constructs the space that humans and robots coexist closely and interact naturally. The distributed intelligent network devices (DIND), which is equipped with a CCD camera and used as a sensor node, monitors location and behavior of both human and robot in ISpace where the DIND is installed throughout whole of the space. The information which is gathered from DIND in ISpace can help to perceive the indoor environment and read human intention. In [6, 7], the mobile robot estimates its own location using the position information from the sensor nodes and plans next path to navigate. For this kind of sensor network application, the mobile robot receives only the control messages around it instead of receiving from all the nodes in the network. Therefore, the sensor network platform doesn't need to consider the robot's mobility.

Even if there have been several researches to combine sensor network technology with the robot, sensor network has not been utilized for enhancing the robot's perception ability through monitoring diverse environmental information around the physical space. So, the way to report to the mobile robot from the multi-hop sensor nodes has also not been much studied. Even in the other sensor network applications in a real field, the network protocol for the mobile sink node like a robot haven't been applied to the real field yet. Most of sensor network applications assume that the base station is fixed; but, such assumption cannot be accepted to support the mobile robot.

3. Ubiquitous Robotic Space

The wireless sensor network platform proposed in this paper provides diverse environmental monitoring and control to construct the ubiquitous robotic space, while covering the large space such as homes, offices, and factories with the multi-hop ad hoc network topology.

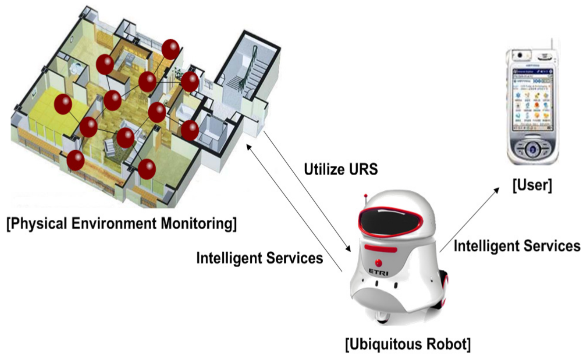

Figure 1 Building Ubiquitous Robotic Space

Figure 1 shows the architecture of proposed ubiquitous robotic space. The main functions of sensor network platform are to provide indoor environmental condition monitoring, fire detection, and intrusion detection. This sensing information is forwarded to the mobile robot in order that the robot provides intelligent services such as automatic HVAC control, fire alarm service, and home security guard services. For instance, when the robot receives intrusion detection events from the sensor network, it sends a SMS message to the user and records the video of the incident location to give detailed situation information to the user.

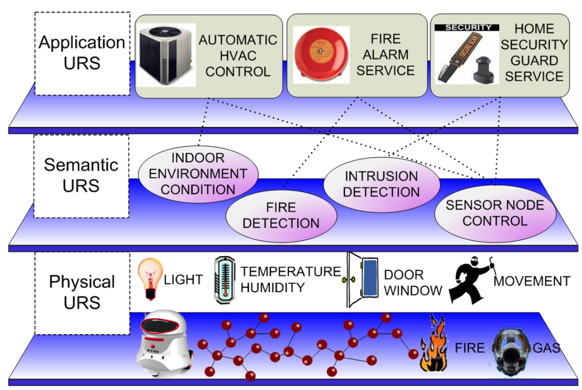

Figure 2 URS structure

According to the paper that introduced URS concepts [2], the URS in this proposed system can be divided into physical URS, semantic URS and application URS like Figure 2. Physical URS includes physical environment to be perceived such as light, temperature, humidity, doors and windows, fire, gas as well as robot, robot control function, sensor node and data communication protocol of sensor networks.

Semantic URS can be defined as the URS providing semantic information; for example, the functions provided by sensor network such as indoor environment condition, fire detection, intrusion detection and sensor node control can be a part of Semantic URS. Application URS provides the domain specific functionalities that the robot ultimately provides based on semantic URS, such as automatic HVAC control, fire alarm service, and home security guard services.

4. Sensor Network Platform

The sensor network platform to build ubiquitous robotic space has the following features, and the detail specification and the proposed algorithm for this sensor network platform will be addressed in this section.

- Robot is equipped with the communication module for the communication with sensor network and they communicate through the serial interface.
- Sensor nodes are equipped with the various kinds of sensors. The environment monitoring information such as temperature, humidity, and light is forward periodically to the robot, and urgent information such as fire detection and intrusion detection is transmitted to the robot immediately.
- The network protocol supports the mobility of the robot. In order words, the mobile robot should always keep its network connectivity despite the movement.
- Sensor nodes have an ability to find the routing path from themselves to the mobile robot and send the packet at any time when they have messages to notify the robot.
- The robot have to be able to transmit the control message to the specific sensor nodes to control the environment through the actuators.

4.1. Hardware Platform

We developed new sensor node hardware for URS. It is small in size (3.5cm x 5.5cm), and uses CC2430 from TI for low power consumption. The CC2430 has an 8051 microcontroller core with 2.4GHz RF transceiver so it consumes extremely low power compared to separate chips. The sensor node also has various sensors for providing environment information to a robot; temperature, humidity, brightness, density of CO, change of IR, status of a door and existence of a flame.

The sensor node hardware is separated to three parts; processor board, sensor board and programming board, which are represented at Figure 3. The processor board has CC2430, 2.4GHz PCB antenna, SMA antenna connector, temperature/humidity sensor, lightness sensor, and door sensor. The sensor board consists of PIR sensor, comparator, CO sensor, flame sensor, and it can be stacked on the processor board. The PIR sensor can detect movement of the object which radiates IR, for example humans and animals. The programming board has a USB programming interface and RS232 interface for communication between the robot and a node. The processor board can also be stacked on the programming board. A sensor node operates on two AA-size batteries. However, we can put an external power connector because sensor board consumes a lot of battery power. The node which has sensor board will operate using external power.

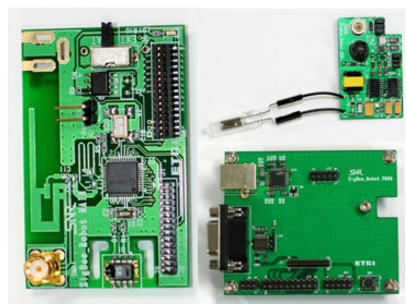

Figure 3 Processor, Sensor, and Programming Board

4.2. Software Platform

Software platform is largely divided into network protocol and URS application. The ZigBee network stack is applied for the network protocol because it is a good candidate for sensor network protocol stack that consumes low power and supports reliable data communication [8]. However, the ZigBee network stack is modified in this system, to make all the other sensor nodes forward to the mobile robot. URS application is developed to support monitoring information to the ubiquitous robot and sensor node management functions for controlling physical space by commands from the ubiquitous robot.

4.2.1. Network Stack. We applied TI Z-Stack as the ZigBee network stack on our sensor network platform. It is fully compatible with ZigBee Specification version 1.0, and has a ZCP (ZigBee Compliant Platform) certification from ZigBee Alliance. In our sensor network platform, users do not need to construct the network topology manually because the

ZigBee stack provides self-configuration features. The sensor node that is turned on first forms a network with a designated PAN Id in a specific channel. The other sensor nodes, that discover the existing PAN, verify PAN Id to check whether it is a URS sensor network or not. If it has the correct PAN Id, then they will join the network automatically. The communication module for the robot is the sensor node that is attached to the robot and transmits all the received sensing information to the robot through the RS-232 interface. As this communication module is used in our platform, we can reduce the installation cost of the other external networks interfaces such as WLAN, HSDPA, and CDMA for the communication between sensor network and the ubiquitous robot.

After the network formation procedure is finished, the sensor nodes transmit their sensing data to the robot using tree routing in ZigBee network. There are the tree routing and the table-driven routing in ZigBee networks, and table-driven routing requires route discovery procedure to find the optimal path from each sensor node to the destination. In the proposed system, the table-driven routing may have significant overhead if all the sensor nodes perform route discovery procedure whenever the mobile robot, that is a destination, changes its network address due to the network rejoin. Therefore, we selected the tree routing algorithm that transmits the data using tree topology without any routing table as shown in Figure 4. The detailed algorithm that sensor nodes are notified the network address of the communication module will be addressed at the URS application section later.

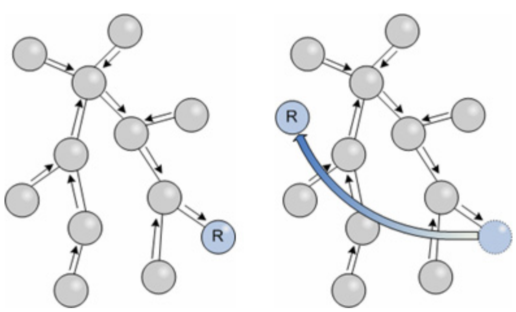

Figure 4 Routing algorithm and mobility problem of URS

In this system, the robot continuously moves and collects all sensing information from sensor nodes to provide intelligent service using the ubiquitous robotic space. If the robot moves out of the transmission range of its parent node, it cannot communicate with the sensor network as shown in Figure 4. Therefore, the algorithm to support robot mobility should be solved in order to provide seamless ubiquitous robotic space to the mobile robot.

In order to support mobility of the robot, the network protocol allows the communication module of the robot to rejoin the network and inform its network address whenever it is assigned a new network address. For example, if the communication module cannot receive the data from sensor node when the robot goes out of transmission range of its parent node, it will recover its communication link to the sensor network by a rejoining procedure in the proposed algorithm. The Figure 5 shows the detail procedure to support the robot's mobility and the following steps describes from the link failure detection to update the new network address of robot.

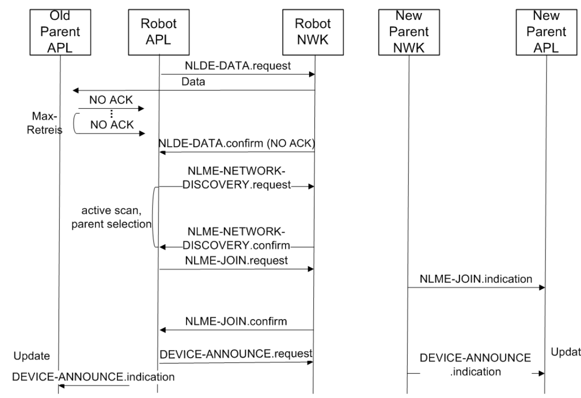

Figure 5 The algorithm to support Mobility

- Link Failure Detection Phase: The communication module periodically sends 'hello' message to detect link failure with its parent node. If acknowledgement is missed more than *MaxRetries* times, the network layer of the communication module notifies its upper layer that the link with the parent node is broken by putting NO_ACK parameter to the NLDE-DATA.confirm primitive.

- Network Discovery Phase: The application layer tries to discover potential parent nodes around the communication module by calling NLME-NETWORK -DISCOVERY.request. During discovery phase defined in ZigBee standard, it can find the potential parent node list and their PAN Id, tree level, LQI (Link Quality Indication), and so on. Then, the application layer chooses the potential parent node that has the smallest tree level and enough LQI value among nodes which have PAN Id for URS. The reason the communication module selects the node which has the smallest tree level is to reduce the routing cost from the sensor node, that is, the routing hops will be reduced because the routing follows a hierarchical tree.

- **Rejoin Phase**: After choosing parent node, it requests to rejoin the network by calling NLME-JOIN.request primitive. The network layer will transmit ASSOCIATION_REQUEST command by putting its 64bit extended address. The parent node decides that the child node requesting association can be permitted or not, by evaluating whether *PermitJoing* field is true or false and whether current number of child nodes exceeds the maximum number of child or not. If it can accept joining of child node, the parent node will assign 16bit new network address and send an ASSOCIATION_RESPONSE command back with the newly assigned network address.
- **Announcement Phase**: After the communication module successfully joins the new parent node, it broadcasts its new 16bit network address and IEEE 64bit extended address using DEVICE_ANNOUNCE command. The IEEE 64bit extended address is used as the identification of the communication module; so, sensor nodes update its destination network address and related fields in the neighbor table. Since the newly assigned network address of the communication module is notified to all the sensor nodes, the sensing information can be seamlessly routed to the robot without break.

4.2.2. URS Application. URS application is designed to provide ubiquitous robotic space to the robot such as indoor environment condition monitoring, fire detection, and intrusion detection. Within this URS, the robot can control the physical space using actuators attached to the sensor nodes as well as monitoring the environment.

- **Environment Monitoring Function**: Sensor nodes installed in the physical space report their sensing information to the robot device. As we described in the previous section, they construct the network by themselves. However, they don't know the network address of the communication module. The communication module at the robot periodically announces its network address and endpoint used at the ZigBee application layer. On receiving announce message from the communication module, sensor nodes can check the identification of the robot by the endpoint and set it as a destination address. Then, sensor nodes transmit its sensing data to the address of communication module with the standardized serial data format, and the communication module passes this message to the robot through the RS-232 interface.
- **Sensor Node Management Function**: In order for the robot to provide intelligent service by controlling and managing the sensor node, device discovery function and device control functions are supplied by the URS application.

The device discovery function is necessary to know the network topology. For example, if a specific sensor node doesn't report any data for some time, the robot can't know whether the sensor node has run out of battery, or it has no data to report during that period. In this case, the robot can find the reason by discovering the status of the sensor nodes. For the device discovery, the robot broadcasts device discovery packets to the network and all the sensor nodes will reply with their identification such as their application, network, and MAC addresses and their sensing information as a response.

The device management function is used to control the physical environment through the actuator nodes. The actuator attached to the sensor node provides RS-232 interface, and it is designed to do the specific action according to the command type. The command packet from the robot has an identification field to indicate the specific node and the command to deliver to that node. Using device management function, the robot can open the window or turn on the air conditioner if the temperature is very high, and close all the doors and windows if housebreaker intrudes inside.

5. Experimental Result

The robot used in the experiments is the house robot developed by ETRI, Korea. The robot called ROMI has many useful functions to provide ubiquitous services, such as a cleaning module, navigation, surveillance, and remote control. ROMI uses StarLITE navigation system [9] to navigate physical space. StarLITE is the ceiling vision based localization system. The image sensor which is mounted on top of the ROMI estimates its location by detecting the pixel position of infrared beacons attached on the ceiling of a space. The ROMI can transmit video with its wireless LAN connection, and can relay information to the external user's PC or phone.

At the beginning of the URS application, sensor nodes and the robot form the network, and the communication module of the robot announces its new network address to all the sensor nodes by broadcasting. This announcement is periodically sent to the sensor nodes, and sensor nodes report the environmental information to the robot based on the time receiving announcement packet. As the result of the experiment, it took about 180 msec to announce its network address with five sensor nodes, and 630 msec for the robot to rejoin the network. The broadcasting time depends on the number of nodes, where as the rejoin duration is independent from the number of nodes.

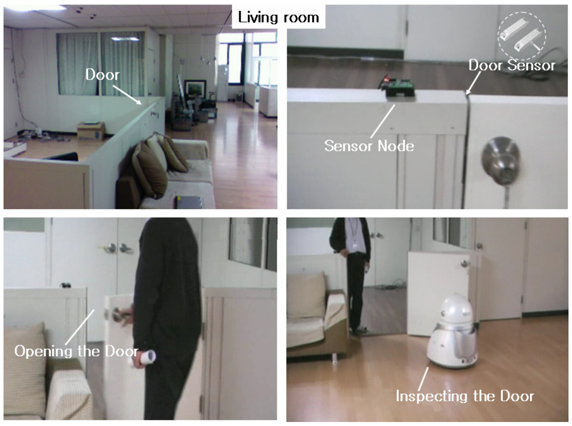

Figure 6 Snapshots of the experiments

In the demonstration, a home security service based on the sensor network platform is tested. Ten sensor nodes were installed in the house and the robot ROMI looks after the house. The ROMI finds the all identification information such as application address, network address, and MAC address through the device discovery function of the sensor network platform. This identification information is matched with the location information for the StarLITE, so, the robot can navigate to the spot that events are occurred. As you can see in the Figure 6, one sensor node that can detect the status of the door is installed near the door. The door sensor connected to that sensor node interrupts it if the door is opened without any permission, and such event will be notified to the robot immediately with the application address of sensor node. Then, the robot makes a judgment through its inference engine, and sends the SMS message to the user to notify intrusion into the house. The robot records the video image when it reaches that spot, and transmits it to the user's cellular phone to show the detailed situation inside the house.

6. Conclusion

In this paper, the sensor network platform is proposed as the technology to build the ubiquitous robotic space for the robot and test bed including the robot system is implemented and evaluated. The sensor network platform is equipped with various kinds of sensors for HVAC control, home security and fire detection services, a ZigBee based multi-hop ad hoc network stack, and application software to provide monitoring and management functions for the sensor network. The network protocol is also newly designed to support a mobile sink node. In order to allow the mobile robot to collect all environment information, the network protocol adds features such as detecting link failure, rejoining the network, and announcing the new network address. Based on the mobility supported network stack, the robot can communicate with the sensor network directly without other network interface such as WLAN and CDMA. Moreover, the ubiquitous robotic space built by sensor network platform provides not only monitoring of the physical space but also controlling it through actuators and sensor management functions.

7. References

[1] S. Lee, "Ubiquitous Robotic Companion", Documents Object Management Group, April, 2005.

[2] M. Jang, J. Sohn, Y. Cho, "A Semantic Framework of Smart Environment Comprehension for the Ubiquitous Robotic Space," 2006 International Symposium on Flexible Automation, Japan, July 10-12, 2006.

[3] Nak Young Chong, H. Hongu, K. Ohba, S. Hirai, K. Tanie, "A distributed knowledge network for real world robot applications," IEEE/RSJ International Conference Intelligent Robots and Systems, pp. 187-192, 2004.

[4] D. Hahnel, W. Burgard, D. Fox, K. Fishkin, M. Philipose, "Mapping and localization with RFID technology," IEEE International Conference Robotics and Automation, pp. 1015-1020, 2004

[5] K. Morioka, J. Lee, H. Hashimoto, "Human-Following Mobile Robot in a Distributed Intelligent Sensor Network," IEEE Transaction on Industrial Electronics, Vol. 51, No. 1, Feb 2004

[6] Y. Kim, H. Kim, S. Lee, and K. Lee, "Ubiquitous Home Security Robot based on Sensor Network," International Conference on Intelligent Agent Technology, 2006.

[7] K. Kotay, R. Peterson, D. Rus, "Experiments with Robots and Sensor Networks for Mapping and Navigation", International Conference on Field and Service Robotics, Port Douglas, Australia, 2005.

[8] T. Kim, D. Kim, N. Park, S. Yoo, T. S. Lopez, "Shortcut Tree Routing in ZigBee Networks," International Symposium on Wireless Pervasive Computing, 2007.

[9] H. Chae, J. Lee, W. Yu, and N. Doh, "StarLITE: a new artificial landmark for the navigation of mobile robot," JK-NRS2005, Kyoto, Japan, 2005.