

Sensor Network based Localization and Navigation of Mobile Robot

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Abstract: This paper presents a simple sensor network consists of a group of sensors, RF components, and microprocessors, to perform a distributed sensing and information transmission using wireless links. In the proposed sensor network, though each sensor node has a limited capability and a simple signal-processing engine, a group of sensor nodes can perform a various tasks through coordinated information sharing and wireless communication in a large working area. Using the capability of self-localization and tracking, we show the sensor network can be applied to localization and navigation of mobile robot in which the robot has to be coordinated effectively to perform given task in real time.

Keywords: Sensor network application, mobile robot control, ultrasonic GPS, Smart sensor

1. INTRODUCTION

Recent advances in robotics have increased the usage of mobile robots. However, there are still problems in environment perception, due to dynamic change of workspace and lack of information [15]. It is not easy to recognize the unstructured dynamic environment including persons and objects using small amount of sampling data from limited number of sensors embedded to robot. Accommodating a sensor network within workspace of mobile robot will help the robot with environment perception and self-localization by providing active beacons for absolute references of robot motion. A sensor network has been developed to gather global information effectively from interested area and can be used for mobile robot navigation.

Advances in electronics and wireless communication have enabled integration of sensor network by adding ubiquitous computing and processing units to the traditional sensor systems. The sensor network is short-range wireless network consisting of densely deployed large number of sensor nodes with different specs and functions. Each sensor node contains various sensors, low power processor, wireless transceiver, and limited amount of battery. The sensor node periodically samples environment data and sends processed data when there comes a request from other node. Since sensor network is highly redundant network in a small area and processors are highly distributed in each node, many samples of data can be obtained from every single phenomenon resulting in high fault tolerance [1-8]. Moreover, each sensor node can be used as smart beacon to recognize the workspace of mobile robot providing more useful information for localization and navigation of mobile robot than the traditional passive beacon. Interesting point here is since a mobile robot can be treated as a mobile node in the sensor network, the same routing and localization method could be used as the ordinary sensor network with only stationary sensor nodes.

In this paper, a set of ultrasonic GPS sensor modules [16-17] creates a simple sensor network. After calibration and self-localization of each deployed sensor node, the mobile robot can measure distance to more than three nearest nodes. Using the triangular method provides the global positioning of mobile robot and the dead reckoning error of mobile robot can be compensated. The process is easily propagated through the entire network and multiple robots can be coordinated within

the same workspace with collision free.

In our sensor network, a simple routing protocol is used for data flow and grouping between sensor nodes, where each sensor node is informed its absolute position when installed. Each sensor node covers 1m² area of plane located at 1m height and the total 6 sensors are installed to cover 1.5x0.6m² of workspace, implying high redundancy by intersecting the effective coverage area of sensors in the network. At every point stop of robot, the localization process is done if needed along the path tracked by the robot for given task. In between the global localization, the encoder sensors of motor provide a local change of position data by dead reckoning within the mobile robot. The experiment results demonstrate the effectiveness of sensor network based approach to mobile robot navigation with high scalability and fully decentralized sensor data processing.

2. SENSOR NETWORK

When perceiving and controlling a given environment, a lot of information has to be gathered using the features, which are extracted from sensed physical quantities of environment. For example, the air-conditioning system of building, the management process of manufacturing and product flow, and the surveillance unit of environment use many environmental sensors and actuators for proper operation. Since these sensors and actuators are generally in wired and fixed configuration, planning, equipping, and maintaining the systems demand high procedural complexity and cost, which in turn implies difficulties in constructing ubiquitous computing environment for ambient information collection, processing, and transmission of, e.g., daily necessities in intelligent home and office.



Fig.1 Building sensor network.

The difficulties can be overcome by introducing the wireless sensor network that consists of a group of sensor nodes and hence are completely different from the LAN and existing wireless communication network [1-8]. One of the

most significant differences is that while a few powerful computers construct the existing client-server framework for communication network, the sensor network is comprised of a group of sensor nodes with low processing power and provide a short range wireless Ad-hoc network. While sensor network is composed of a large number of sensor nodes that are densely deployed inside and periphery of interested area, it can gather highly accurate data for single phenomenon and cover large area with great fault tolerance.

There are a lot of current sensor network projects and many researchers are currently engaged. e.g. Cots Dust, Smart Dust[19] in Berkeley Univ., WINS[21] in UCLA, SensoNet in Georgia Univ.[22], EYES [23] , Pico Radio, Aware home[20], and PEN.

2.1 Sensor node

Sensor node is basic unit of sensor network; consist of low-power processor, sensor, memory, low-power RF and battery. Including different sensors to detect temperature, humidity, intensity, acceleration, terrestrial magnetism, infrared from human, sensor node can be used for various applications. Each sensor node constructs wireless network by communicating with adjacent sensor node. Usually they collect and analyze sensor inputs periodically, while performing appropriate tasks when requests from other nodes arrived. While sensor node can communicate using various wireless communication media such as RF, IR, LASER and ultrasonic [19], in general low power ISM band FM transceiver or Bluetooth module are used. Low power RF module reaches within order of 10m, can reduce energy consumption and communicate simultaneously by constructing adjacent node group. To guarantee network availability, many nodes should be survived, so each node must be designed in low power consumption and high efficiency since they operate in battery powered.

2.2 Link and Routing in sensor network

Connections of each node in the sensor network need to be robust for network survivability; link layer and routing algorithm is one of the most essential issues. Ad Hoc Demand Distance Vector (AODV) and Temporally Ordered Routing Algorithm (TORA) are not suitable because of the low mobility of the system. So, it is preferable to go with a table-based system for sensor networks. Each sensor updates a table periodically, and always keeps the routing path available to reduce transition overhead, network traffic, and packet losses. [2-3] In addition, since thousands of nodes in the small area, network should be carefully managed, and using global ID such as MAC address is not recommended. Each node needs to be accessed via attribute-based naming instead of explicit addressing, i.e. direct diffusion [9].

2.3 Sensor node Localization

Self-Localization of each node is important in sensor network. However confirmation of all node position (generally order of from tens to millions), which are randomly scattered in the interest area, manually is impossible. Moreover, including GPS module in every node is inefficient from a cost and energy consumption point of view.

So, we construct a network with placing several reference nodes that can measure their absolute position, mixed into large quantity of ordinary nodes. Using these reference nodes, self-localization of normal nodes can be served. After measuring distances or angles to reference, using positioning algorithm like triangular method or ABC (Assumption Based Coordinates) can calculate absolute position of each node. Distances between each node can be measured by signal arrive time difference or by strength of received signal (TOA, TDOA, RSSI), while angles between nodes can be measured by vector pressure sensor or acoustic sensor array (DOA, AOA).

Related topics are Active Badge[10], Active Bat[11], Cricket[14], RADAR[13], VOR/VORTAC, and Cellular Networks.

2.4 Robotics Applications

Deliberation is traditional planer-based control algorithm but unresponsive and slow to adapt to dynamic environment. Reactive system that has tightly coupled perception and action is responsive but lack of generality and ability to store representation for serving complicated tasks. Modern, behavior-based control generalizes reactive control by introducing the notion of behavior as an encapsulated, time-extended sequence of actions. Perception and response are still coupled as in reactive systems, with the added benefits of representation and adaptation without any centralized control. In robot control, as seen in before, sensing and action is tightly coupled, and accurate environment recognition should be provided for correct robot responds. Improving a single sensor performance is limited and costs high. Moreover, using few samples from limited number of sensors embedded in robot, to estimate the environment is not enough. Combination of mobile robot and sensor network enables the sensor fusion, and many samples obtained from every single phenomenon, can increase the measurement accuracy

3. SYSTEM CONFIGURATION

In this chapter, we propose following system to control a mobile robot using sensor network.

Install ultrasonic GPS nodes to the ceiling of robot working space and build a network with existing sensor nodes. Each GPS nodes should have enough intersection of ultrasonic

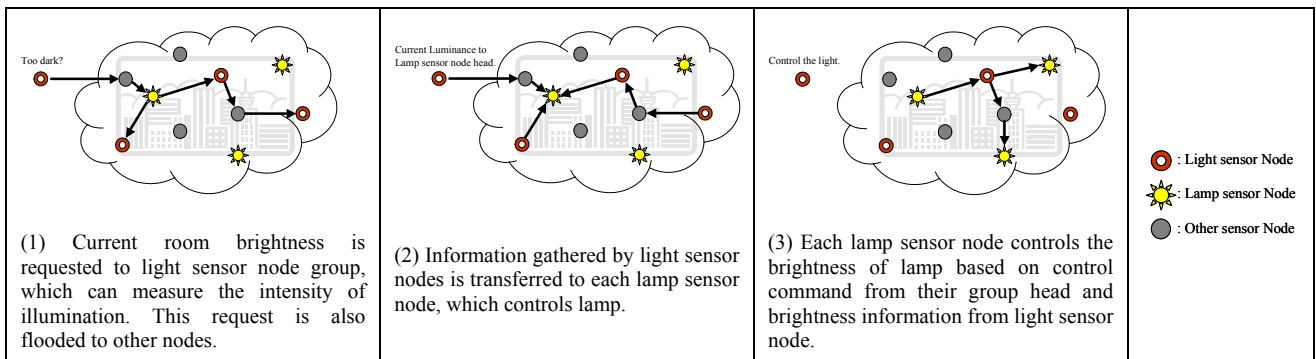


Fig.2 Environment control using sensor network.

signal arrival range to the next node. From this system, the mobile robot can measure its absolute position using nearby GPS nodes, and also can gather environmental information and status through the network.

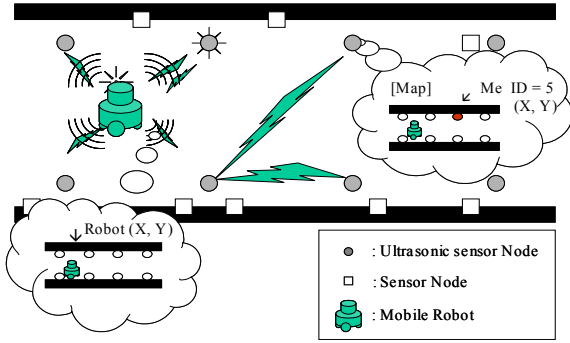


Fig.3 System overview.

Since our system is fully decartelized, every operation is done in distributed way without any central processor. Even in the multi-robot system, other robots can find this robot by informing its location to the network. These are the main difference between this system and existing location system such as Active Bat [11] and Cricket [14]. In this chapter, we describe each component in detail.

3.1 Sensor node component - Hardware

Sensor node is made up of five components, as shown in Fig.4: a sensing unit, a processing unit, a transceiver unit, power unit, and actuator unit.

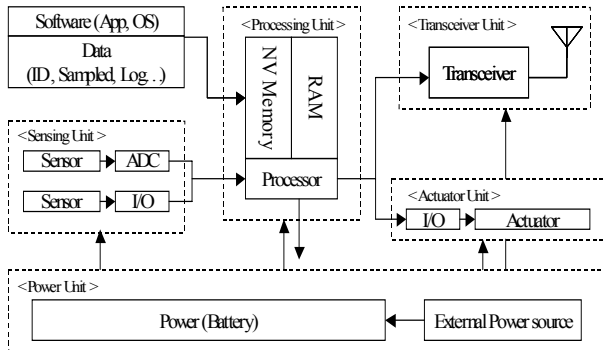


Fig.4 Hardware block diagram.

The sensing unit consists of sensor and ADC, converts the analog signals produced by the sensor to digital data and then fed into the processing unit. NV memory in processing unit contains OS for node management, and binary image of node assigned tasks. Furthermore, this space can be used to store processed data and operation log, so, when the node or network failure occurs, node can restore job after the error recovered. A transceiver unit connects the node to the network. Various kinds of media can be used, while for indoor application, short range RF is recommended. A power unit cuts off the power supply to unused unit and charge internal battery while external power source is available. An actuator unit is an optional component such as beep, or LED for node's output operation. To increase stability, and reduce the power consumption and size, system needs to be designed in single chip. [19]

3.2 Sensor node component - Software

Compact and smart OS (i.e. tinyOS in Berkeley Univ.) is embedded in the sensor node. This OS offers common node functions: protocol stack, link management, routing path control, and power management, and carry out the assigned sensing tasks.

Task scheduler manages every task running on the node. Some special tasks, which require real-time response, should be performed in extra priority. Power management is one of the most important processes in sensor node. Based on CPU time of each process, collected by power monitor, power manager turns off the node power and reschedule the node processes. For effective data exchange, every tasks shares buffer memory.

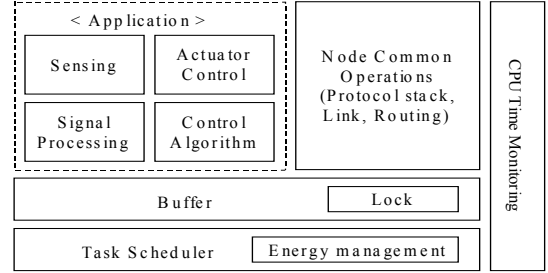


Fig.5 Software block diagram.

Data transfer rate, which is a major factor in network traffic and node lifetime, is determined by amount of data and protocol used. Protocol stack should be optimized, while traditional OSI 7-layer architecture has many layers and needs extra bytes for encapsulation, is not recommended to sensor network. Stack needs to be simplified without damaging compatibility. In the network, each node should transmit only the required and partially processed data. Especially, careful consideration is required to select data to transfer, since energy needed to transfer 1Byte is same to executing several ten thousand of CPU instruction. Also, the size of packet and transfer rate need to be decreased, since collision exponentially increases as the number of node increases.

3.3 Localization using Ultrasonic GPS

Absolute position of mobile robot can be calculated using the triangular method from the distances to three nearby references. [16-17]

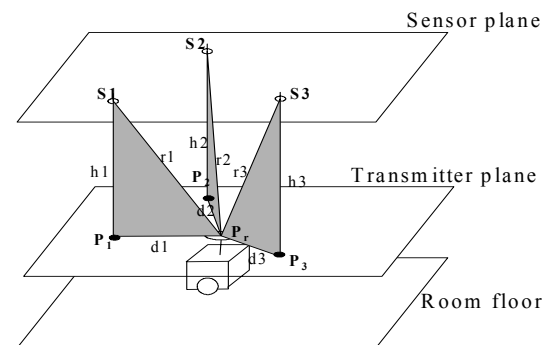
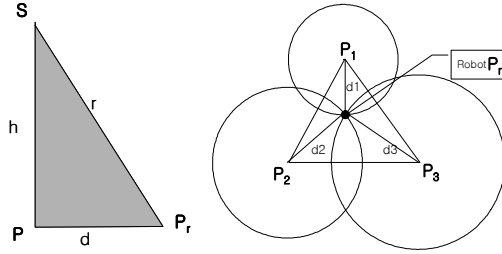


Fig.6 Ultrasonic GPS system.

Fig.6 ultrasonic GPS system, location (x_a, y_a, h_a) of each reference point S_a in the working area is measured while deploying, and notified to robot. Robot finds out more than 3 nearest references, and measures the distance

(r_1, r_2, r_3) using RF and ultrasonic trigger arrival difference. Robot location $P_r = (x_r, y_r)$ can be calculated by Eq. (1)~(4). Error in distance can be reduced using filtering algorithm such as Kalman filter or moving average after several sampling.



$$d^2 = r^2 - h^2 \quad (1)$$

$$d_1^2 = (x_1 - x_r)^2 + (y_1 - y_r)^2 \quad (2)$$

$$d_2^2 = (x_2 - x_r)^2 + (y_2 - y_r)^2 \quad (3)$$

$$d_3^2 = (x_3 - x_r)^2 + (y_3 - y_r)^2 \quad (4)$$

Fig.7 Triangular method.

Using this method, we can calculate the location of robot, but we cannot find where the robot is heading for. To get directional information, sensor for directional measurement: a digital magnetic compass [18], an array of ultrasonic sensor [11-12, 14] is needed. With array of ultrasonic sensor, we can get directional information from differences of signal arrival to two detached receiver. However in small robot, sufficient distance between receivers cannot be obtained, so error will become larger. To solve this problem, accurate measurement detecting the phase difference and correction of signal should be used. Meanwhile, digital magnetic compass can get absolute angle relative to earth, measuring terrestrial magnetism. Since this device is quite sensitive, to use in the mobile robot, we need to cut off the magnetic force of motor using magnetic field shielding materials.

3.4 Robot localization using sensor network

Robot localization in the sensor network is performed in the following order (Fig. 8). While, the moment of localization is important for both robot and network, the effective mechanism should be defined. In our system, ultrasonic transmitter is attached to robot, while receiver is in GPS

sensor node, so we can get several data simultaneously from nodes using one trigger signal. Such system can greatly enhance precision in measurement by repetitive measurement (1). However this is not always an efficient method when number of robot and devices to be localized increases. In such a case, broadcasting method by transmitter-included beacon used in Cricket system [14] is better solution.

Also it is possible to trace robot by periodically send its position to sensor network. However, if many robots are in the same area, and network renewal or robot localization period are too short, network will be hung up. So, we need to define default renewal period (long term renewal), and then, update their renewal period proportional to moving distance or velocity. This enables efficient management of system and avoids collision of robots and packets. Moreover localization during the movement is possible by remembering its initial position at the sending trigger signal, and corrects the measured result.

4. IMPLEMENTATION AND EXPERIMENT

In this experiment, we focused on the localization and the navigation in the Lab environment.

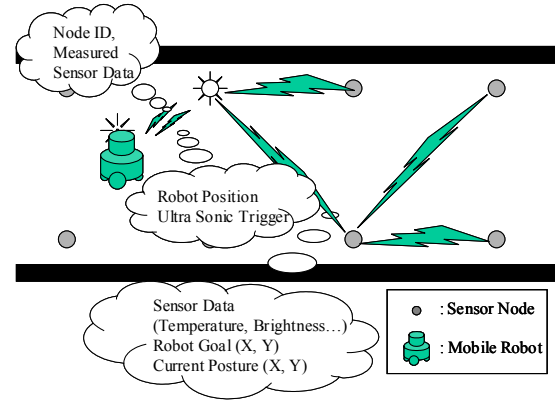


Fig.9 Data flows in experiment system.

Total 6 of ultrasonic sensor nodes were installed in the workspace, one mobile node (mobile robot), and one host PC were used to build up the system. Each node was assigned a unique ID, and absolute location of node notified to robot, which was measured during the installation. Assume that, every node on the network was survived, and there was no malicious interference to network. Broadcasting, ID based

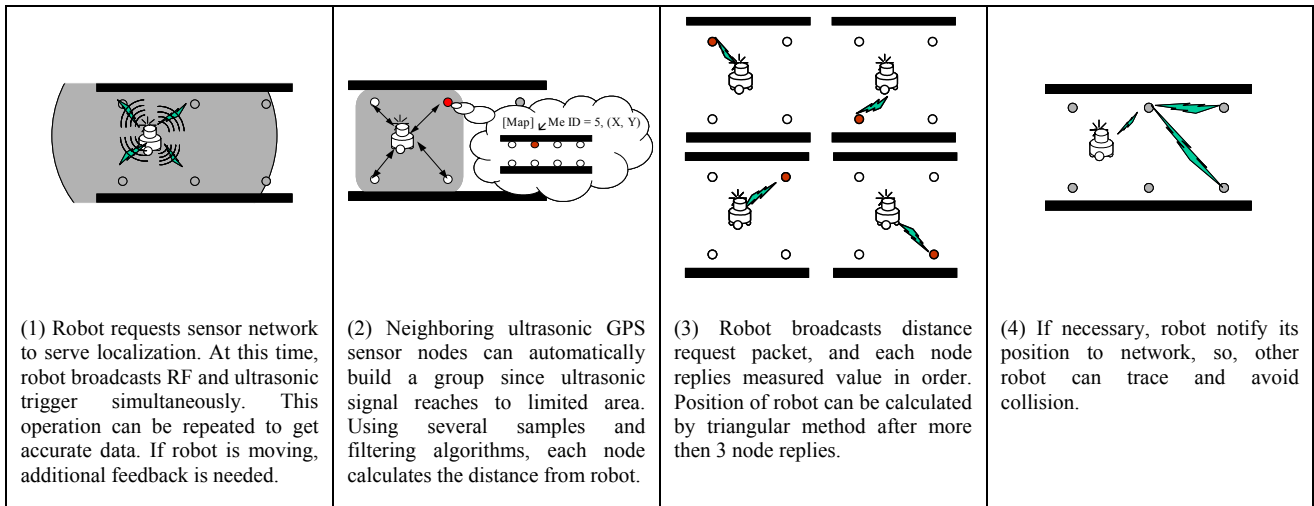
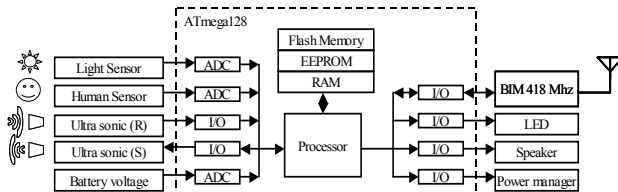
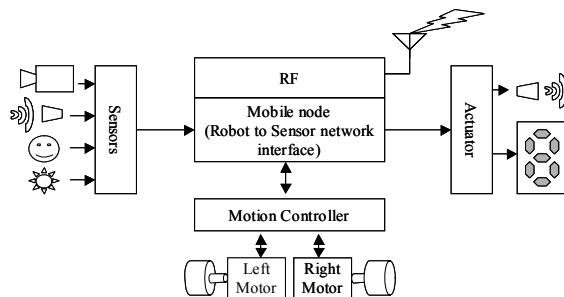


Fig.8 Robot localization in sensor network.

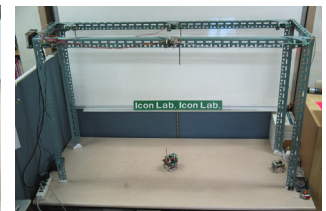
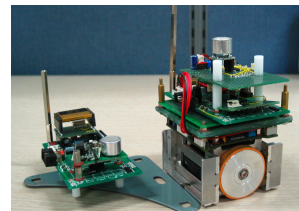
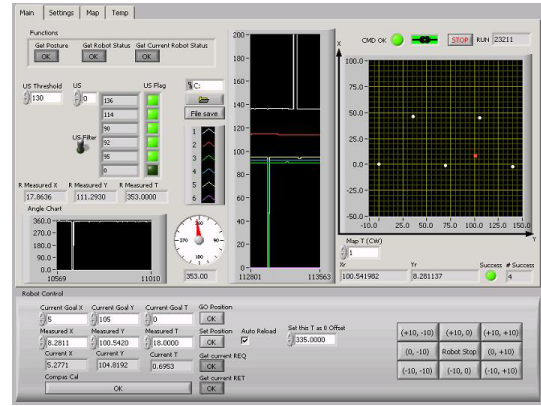
ATMega128 microcontroller from ATMEL was used for sensor node to compact the system, and reduce the external peripherals. 400ST/R160 ultrasonic sensor, which has good receiving sensitivity and transmitting sound pressure, was attached, and BIM 433Mhz FM transceiver from Radiometrix with RF carrier detection for collision avoidance was used for wireless communication. Finally, additional sensors were embedded to each sensor nodes to monitor the environment: light, temperature, and human detection.



8cm * 8cm * 14cm size of mobile robot consists of 2 components: mobile node for network interface, and behavior based motion controller. Mobile node is the same system as used in the ordinary node, executes received command, and passes desired goal to motion controller. Furthermore, carry out the localization to compensate robot posture, by measured direction angle from digital magnetic compass, and calculated triangular position using measured distance to nearby ultrasonic nodes. Motion controller executes dead reckoning and feedback control used Intel 80C296 CPU, and carry out the behaviors according to command from upper controller, such as 'move to desired goal'.



RF Dummy	Start	Target ID	Source ID	Command	Len	Arg	Sum	End	RF Dummy
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Table.1 Location of nodes.

ID	(X, Y)
1	(0 , 0)
2	(0 , 46)
3	(75 , 0)
4	(75 , 46)
5	(150 , 0)
6	(150 , 46)

Table.2 Goals.

Seq	(X, Y)
1	(105, 10)
2	(105, 30)
3	(70, 30)
4	(35, 30)
5	(35, 10)
6	(70, 10)

respectively. In our experiment, error boundary of position and angle was set to $\pm 3\text{cm}$ and $\pm 2^\circ$ respectively, and convergence to each goal was possible. In Fig.16 (b) after 1 loop, robot could return to initial point within position error boundary. Results are precise enough to localize an ordinary mobile robot in the room. Measurement error was occurred by signal strength change and signal arrival direction, which is a function of robot position. This problem could be solved using phase correction, however sensor to detect phase must be tightly coupled, synchronization using RF trigger cannot be applied, and receiver should have multiple sensors.

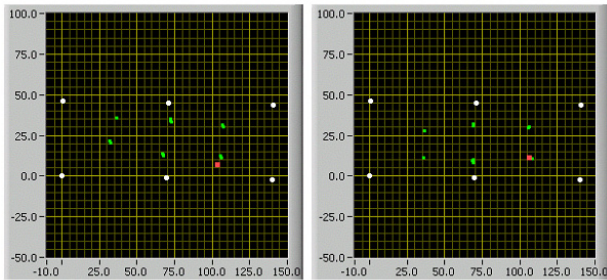


Fig.16 (a)

Fig.16 (b)

Also we got sufficient precision in trace of slowly moving robot (Fig.17), by successive localization.

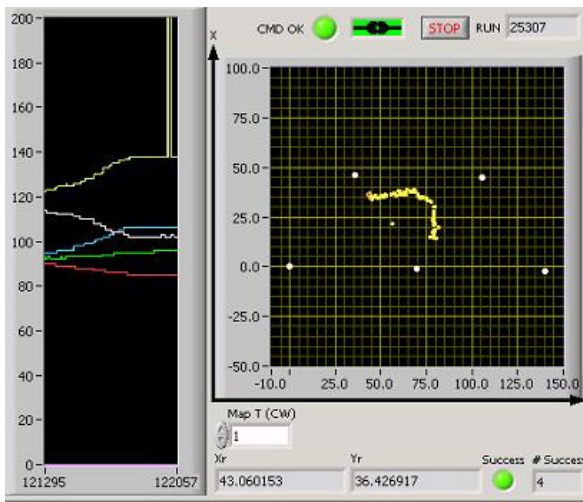


Fig.17 Measured distance by ultrasonic and trajectory of traced moving robot (with 5 nodes).

5. CONCLUSION AND FUTURE WORKS

We propose a simple sensor network for real-time localization and navigation of mobile robot. Combined usage of sensor network with the local sensors within mobile robot enables the sensor data to be fused for acquisition of information from dynamically changing environment. With the sensor network used, while the position errors of mobile robot are limited in few cm orders, the exact localization in the room is possible. Moreover, since the whole processes executed in decentralized, it is superior to extend with great fault tolerance.

Developing efficient mechanism to serve a complicated job in densely deployed nodes, such as multi-robot localization environment, and self-localization, calibration of each sensor node should be studied for the future research.

REFERENCES

- [1] D. Estrin, D. Culler, K. Pister, and G. Sukhatme, "Connecting the Physical World with Pervasive Networks", *IEEE Pervasive Computing*, pp. 59-69, January-March 2002
- [2] Praveen Rentala, Ravi Musunuri, Shashidhar Gandham, Udit Saxena "Survey on Sensor Networks"
- [3] Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., and Cayirci, E., "A Survey on Sensor Networks", *IEEE Communications Magazine*, August 2002.
- [4] Chien-Chung Shen, Chavalit Srisathapornphat, and Chaiporn Jaikaeo. "Sensor information networking architecture and applications", *IEEE Personal Communications*, 8(4):52-59, August 2001.
- [5] Roy Want and Trevor Pering. Intel Research Santa Clara, Gaetano Borriello, Keith I.Farkas "Disappearing Hardware" *IEEE Pervasive Computing*, pp.36-47, IRS-TR-02-001, Jan. 1, 2002
- [6] G. J. Pottie and W. J. Kaiser. "Wireless integrated network sensors", *CACM*, 43(5):51-58, may 2000.
- [7] Gaetano Borriello. "Key Challenges in Communication for Ubiquitous Computing" *Intel research Seattle*
- [8] James WeatherAll. Cambridge University, Alan Jones. "Ubiquitous Network and Their Applications" *AT&T Laboratories Cambridge Limited*
- [9] John Heidemann, Fabio Silva, Chalermek Intanagonwivat, Ramesh Govindan, Deborah Estrin and Deepak Ganesan, "Building Efficient Wireless Sensor Networks with Low-Level Naming", *In proceedings of the 17th ACM SOSP '01*.
- [10] R. Want, A. Hopper, V. Falcao, and J. Gibbons, "The active badge location system," *ACM Transactions on Information Systems*, vol. 10, no. 1, Jan. 1992.
- [11] A. Ward, A. Jones, and A. Hopper, "A new location technique for the active office," *IEEE Personal Communications*, vol. 4, no. 5, Oct. 1997, pp. 42-47
- [12] L. Girod, "Development and characterization of an acoustic rangefinder," *Tech. Rep. 00-728, CS Department, University of Southern California*, Apr. 2000.
- [13] P. Bahl and V. N. Padmanabhan, "Radar: An in-building rf-based user location and tracking system," *In Proceedings of the IEEE Infocom 2000, Tel-Aviv, Israel*, vol. 2, Mar. 2000, pp. 775-784.
- [14] N. Priyantha, A. Miu, H. Balakrishnan, and S. Teller. "The Cricket Compass for Context-Aware Mobile Applications". *In Proc. of the 7th Annual ACM/IEEE MOBICOM 2000*.
- [15] J. Borenstein, H. R. Everett, and L. Feng, Contributing authors: S. W. Lee and R. H. Byrne, "Where am I? Sensors and Methods for Mobile Robot Positioning"
- [16] Zhao Feng-Ji; Guo Hai-Jiao; Abe, K, "A mobile robot localization using ultrasonic sensors in indoor environment", *Proceedings, 6th IEEE International Workshop on*, 1997 Page(s): 52 -57
- [17] Ghidary, S.S.; Tani, T.; Takamori, T.; Hattori, M., "A new home robot positioning system (HRPS) using IR switched multi ultrasonic sensors", *Conference Proceedings. 1999 IEEE International Conference on*, Volume: 4, 1999, Page(s): 737 -741 vol.4
- [18] "Vector 2X and 2XG Electronic Compass Modules", Complete App. Notes
- [19] <http://robotics.eecs.berkeley.edu/~pister/SmartDust/>
- [20] <http://www.awarehome.gatech.edu/>
- [21] <http://www.janet.ucla.edu/WINS/>
- [22] <http://www.ece.gatech.edu/research/labs/bwn/>
- [23] <http://eyes.eu.org/>