Robot Assisted Wireless Sensor Network for Monitoring and Detection of Explosives in Indoor Environment

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Abstract— In recent years, remote environment monitoring has been significantly improved with wireless sensor networking technology. This paper presents the real time streaming of an indoor environment using a wireless sensor network and a set of self-navigating robots. Mobile robots with mounted sensors will autonomously navigate through an indoor area with unknown obstacles. The robots will be able to avoid obstacles and move around the region. The robots sense the environmental parameters of the region, and send that data to the remote monitoring terminals using an underlying wireless sensor network. This design is applicable to networks where some of the sensors may not have sufficient range to sense data more accurately and closer monitoring is required. Effective path planning for the mobile robot is achieved by combining a map of the area, the sensor readings and the radio strength of the sensor network. Email alerts can be sent to officials if the sensed data goes above a predefined threshold level, thus successfully detecting the presence of explosives in a given area. This system streams the data in real-time to the Internet making it possible for authorized personnel to view the status of the environment online.

Keywords-wireless sensor network; mobile robotics; real-time monitoring

I. INTRODUCTION

In today's world, systematic monitoring of the environment is necessary to detect environmental issues such as presence of explosive contents in public places. Wireless sensor networks [1] are one of the most suitable technologies for the continuous remote monitoring of such environments. Sensor nodes deployed in the wireless sensor network can monitor the area of interest and can send useful information to the remote users. Some sensors in the network may not have sufficient range to sense the data more accurately and close monitoring is required. In such situations we can embed those sensors in the robot and use it for close monitoring.

Recently, robots are becoming increasingly popular because they can reduce the workload of human beings. For the effective functioning of a robot, navigation is a very important factor. Navigation is the process of determining a proper path between initial and a target location [2]. This paper proposes the design of a hybrid wireless sensor network for environmental monitoring in an indoor area. The wireless sensor network includes a set of static sensors and mobile robots. The main functions of these static sensors are environmental sensing, data forwarding and guiding the mobile robots to find their path. Mobile robots will find obstacle free pathways in the environment, sense environmental parameters and communicate to the wireless sensor network. A central controller in the wireless sensor network will analyze the incoming data and give indications to the officials based on the analysis. Robots use a map, sensor information and the signals from the wireless sensor network to plan an effective path. To minimize possible errors in the system, the proposed algorithm uses more than one technique for navigation. As the robots are operating in an indoor area, a partial map of environment is known to the robot. To handle changing obstacles, it uses sensor readings. For the localization of mobile robots the system also uses the help of wireless sensor network. Using the radio strength of the signals from wireless sensor network, robots can localize in large areas. The environmental monitoring sensors, in the robot, will sense data and send it to the wireless sensor network, where the data will be real time streamed. The robots in the system will be able to communicate with each other and thus avoiding deadlocks in the area.

The paper is organized as follows: Section II describes a brief review of related work. Section III presents the system model. The algorithms used in the system are described in section IV. Section V deals with the implementation of the system followed by the conclusion.

II. Related Works

Wireless sensor networks are very useful for the continuous remote monitoring of an environment. The assistance of robots (for mobility of the sensors) within a wireless sensor network increases the accuracy of the data to be sensed and will reduce the noise. Several algorithms are available to navigate the robot to the target location. Each technique has its own advantages and disadvantages. In [3] authors developed a robot navigation and localization algorithm based the floor plan map. The robot recognizes the floor map and finds path to destination by using the landmarks in the floor plan. The algorithm is fast and can perform map recognition, landmark extraction and landmark recognition within few minutes. The authors of [4] propose a new scheme for map building for mobile robots using a 2D laser rangefinder. They used line segments as the basic element for the purpose of localization and to build the map. Line segments provide accurate and fast localization. Virtual line segments are drawn, for points that do not describe a line segment on the range data. These points are further explored via the movement of the robot and this technique provides an efficient mobile robot exploration scheme.

Maxim A and et.al [5] describe an algorithm for robot navigation using a sensor network. This method does not use a map; instead the sensor nodes in the network provide path information. The navigation decision is based on the nearest node and computed using small low-power radios. Maxim et al. developed an algorithm based on the processing of radio signal strength data so that the robot could successfully decide which node neighborhood it belonged to. In [6] authors propose a simple but efficient collaborative path planning algorithm and a communication protocol for the sensor multirobot systems where the energy consumption is reduced and the time taken, by the robot, to reach the destination is shortened. Also the algorithm can enable the sensor robots to complete the tasks even if some robots fail due to accidents. The authors of [7] present an algorithm, for path planning to a target, for mobile robot in unknown environment. ‘The path finding strategy’ is designed in a grid map form, of an unknown environment, with static unknown obstacles. It will plan an optimal or feasible path for itself, avoiding obstructions in its way, and minimizing a cost such as time, energy, and distance.

III. System Model

The proposed system is a multi robot platform, within a wireless sensor network, to monitor the presence of explosives in an indoor area. Figure 1 shows the design of the system, which includes static wireless sensor nodes and mobile nodes. There is a central server, which will collect all the data, analyze it and take appropriate decisions. Static nodes also act as path guides to the mobile robots. The robot will be able to communicate with the wireless sensor network and to other robots in the network through a zigbee communication module. Embedding sensors into mobile robots allows for the sensors to perform closer monitoring of the environment at shorter ranges.

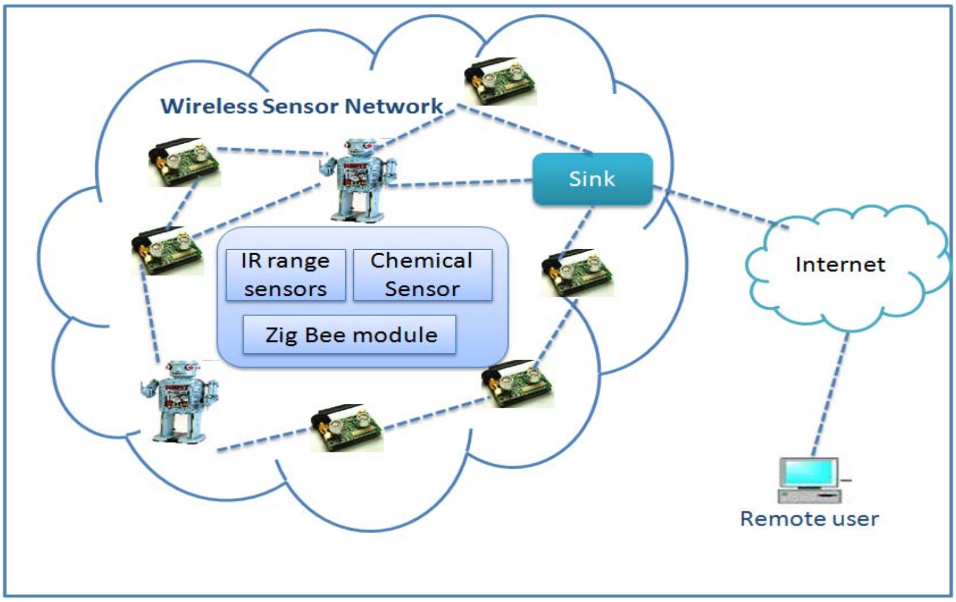

Figure 1. System model

IV. ALGORITHM DESIGN

In the proposed project, the major tasks involved are robot path planning, wireless sensor network setup, data analysis, data aggregation, packet routing and localization. For robotic path planning, we are using multiple parallel techniques. As the scenario is an indoor area, we know the map of the area and a partial knowledge of the obstacles present in that area. So one of the methods selected for path finding is a map searching method. To handle dynamic obstacles, we use readings from ultra sound sensors and update the map with current obstacle positions. For region localization, the system can make use of the signals from the wireless sensor nodes..

A. Navigation Algorithm

The mobile nodes in the network needs obstacle free path to move effectively in the given area. The mobile robot knows the permanent obstacles present in the area. So it refers the known map of the area for its path planning. Each robot is embedded with multiple number of obstacle finding range sensors. In each step of robotic move it will refer map and distance sensor readings. The central controller of the network will assign specific operating regions to each robot. This helps to balance the sensing load of the system. Mobile robots will randomly select target locations in its allotted region and compute a path based on known map. For path generation, the algorithm will search cells in the grid and assign a rank. Highest rank will be assigned to cells nearer to the target and lower ranks will be assigned to farther cells or cells which are closer to known obstacles. After rank assignment, robot will select move with highest rank and navigate through the area using greedy approach. During navigation, the robot will check the readings from obstacle sensor. If the obstacle sensor reading exceeds threshold, mobile robot will stop at that point and searches the map to find an alternate location. Also the robot uses radio signals from the wireless sensor nodes to confirm its operating region.

The robot can receive different types of messages from the wireless network. The important messages are reduce_sampling_rate, goto_given_location, neighbor_localize, time_sychronize and location_finder_beacons. If the robot is receiving a reduce_sampling_rate message from the central controller, it will change its state to advanced_sensing and reduce the sampling rate of sensing, change the sample space of data fusion and speed of ITS? dc motors. If itWHAT receives a goto_given_location message, it will stop exploring the current path tree and find a path to new target location and changes its state to path_finding. When the robot computes a path to the new target, it will select the local maxima in each step and reach the target. neighbor_localize is a query message sent by the neighboring robots to localize their position in case of errors. If a mobile robot receives this neighbor_localize message, it will send a reply message with its current location and nearby landmarks to the neighbor. Location_finder_beacons are sent by the static nodes in the wireless sensor network for region localization. By receiving location_finder_beacons, the mobile robot will calculate the signal strength and update the region code, in case there is a high signal strength. Time synchronization messages are used to update the clock with respect to central controller.

B. Wireless sensor network clustering

The proposed wireless sensor network contains both static and mobile nodes. The robots moving, inside the indoor area, act as mobile nodes. As the network topology of the system is dynamic, we cannot use a predefined path for packet routing. So, the ability to compute routes on demand is required. For effective communication of robot and the wireless sensor network, clustering is needed. The wireless sensor network contains a set of nodes called location finder nodes. These location finder nodes know their geographic location in the given area. The location of the node deployment is selected in such a way that they will cover the whole area with minimum overlaps. The main function of location finder nodes is to periodically broadcast their location information to help other nodes for localization. The following figure shows network topology.

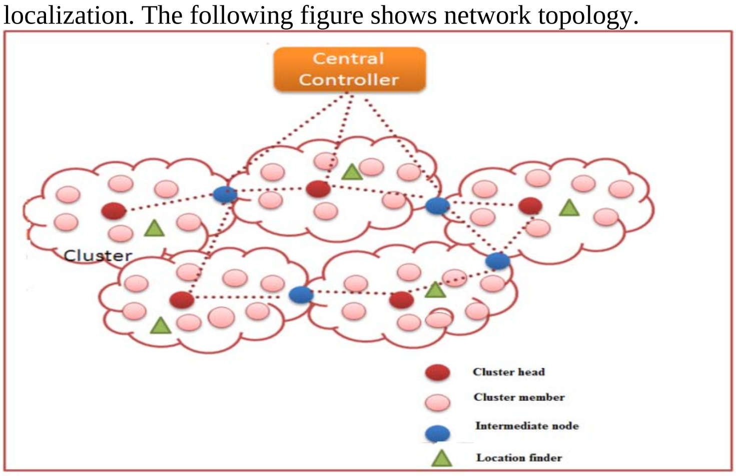

Figure 2. Network Topology

The wireless sensor network includes static nodes, location finder nodes and robots as mobile nodes.The mobile robot finds paths, avoids obstacles, senses data and communicates to the wireless sensor network. Initially, the location finder nodes will broadcast initial_message containing their location information to all other nodes. While receiving initial_message, nodes will respond with their ID. Location finder nodes will calculate an estimate of the distance to each node from the received signal strength. In the next step, each node will send an invitation message to all other nodes. After a specific time delay, nodes will send count_message to location_finder nodes, which indicates the number of invitations received. Location finder nodes will elect a cluster head with the maximum number of invitations and minimum distance estimate to the location_finder. The ID of elected cluster head is send to all other nodes. Nodes receiving cluster head ID will send a join message and the cluster head confirm the membership in the cluster.

Node Clustering Algorithm

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1. Location finder nodes broadcasts $initial_message$ $\{ID, location\}$
2. Nodes recieving $initial_message$ replies with their ID
3. Location finder estimates distance to all nodes from the reply message
4. Nodes send *invitation_message* $\{ID\}$ to each other
5. After timeout interval count the number of invitations
6. Send *count_message* $\{ID, count\}$ to location finder
7. Location finder elects node with maximum count and minimum distance estimate as cluster head
8. Location finder broadcasts *elect_message* $\{clusterheadID\}$
9. Nodes send *join_message* $\{ID\}$to cluster head
10. Cluster head responds by sending *confirm_message*
11. Intermediate nodes are elected based on number of invitations from cluster head

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C. Communication Algorithm

After the clustering phase, the nodes can communicate with each other. The static sensor nodes send the sensed data to the cluster head. The cluster head will aggregate the data and forward it to the central controller through link nodes and other cluster heads. But the robot cannot send the data to a particular cluster head as it is a mobile node. Here we are using an algorithm to dynamically select the cluster head. In this algorithm, the mobile node will check the signal strength of any location finder node and select the location finder node with highest signal strength. Then the mobile node queries the location finder node about the ID of the cluster head to which it has to communicate. Location finder node responds with the cluster head ID. If the distance estimate of the mobile node to location finder node is greater than maximum, then the locations finder node will send a warning message to change the cluster head. The mobile node searches for higher signal strength and then will switch to the next cluster head. The dynamic cluster head selection algorithm follows:

Dynamic Clusterhead Election Algorithm

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1. Select a location finder with maximum signal strength
2. Mobile node send a query *find_clusterhead* $\{MID\}$ to location finder
3. Location finder responds with the ID of attached cluster heads to mobile node
4. Mobile node retrieves the clusterhead ID and communicates to it
5. Check the signal strength of current location finder node
6. **if** $strength < threshold$ **then**
   Switch to next location finder with maximum signal strength
7. **end if**

D. Data fusion algorithm

In order to reduce the network overhead, the mobile robot is not sending all the sensed data. So we can achieve a significant improvement in communication cost. The data sensed by the mobile robot is represented by a random variable *X*. The collection of sensed values are represented using the sample space S={ S_1, S_2, …. S_n }. Size of the sample space is fixed to a value $n = 10$ for testing but it can be varied depending on the sensitivity of the system. To reduce the error factor in the aggregated value, we are using a prioritized average fusion technique. Let P_1, P_2, …. P_n represents the priorities of sensor readings S_1, S_2, …. S_n .Initially, p_i is set to 1 for all i, $1 \le i \le n$. Sample space S is analyzed to find the most occurring reading. Calculate the deviation vector d ={ d_1, d_2, …. d_n }from the most occurring value. Different threshold levels are set for the deviation vector. If the deviation is greater than the threshold level T_i , then the algorithm will update the priority vector by dividing it by a factor of S_i,/ T_i. Following is the data fusion algorithm.

Data Fusion Algorithm

1. Collect $S = \{S_1, S_2, ...S_n\}$
2. Initiallize $P = \{P_1, P_2, ..., P_n\}$
3. Set threshold levels $T = \{T_1, T_2, ..., T_m\}$
4. Find most occuring value maj
5. Calculate deviation vector $d = \{d_1, d_2, ..., d_n\}$
6. Depends on the deviation, find priority level $P_i = S_i/T_i$
7. Calculate aggregate as mean of S_i if P_i greater than threshold

E. Robot Localization

To localize the robot within the given area, we are using two orthogonal parallel approaches. One method based on the signal strength of the wireless sensor nodes and the other based on the sensor readings. We have multiple MicaZ nodes deployed in the scenario and they know their geometric location. From the signal strength of the nodes, the robot will calculate the distance to each node. Let P_{tx} and P_{rx} be the transmit and receive power of Micaz motes. Using the received signal strength indicator *r* we can calculate the received power P_{rx} as

$$P_{tx} = (10)^{\frac{r}{10}} + \log(P_{ref}) \qquad (2)$$

where Pref is the reference power. From the received power we can calculate the estimate of distance *d* from that node using the following equation

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{P_{tx}}{P_{rx}}} \qquad (3)$$

Let d1 and d2 be the calculated distance estimate from the known node locations (x1,y1), (x2,y2) to the unknown node. Calculate the distance between known nodes as d3. Then we can form a system of linear equations and can solve it using Guass elimination method to find the unknown coordinate (x,y).

An alternate parallel method used for robot localization uses the reading from gyro sensors. Here, the location of the robot is represented by the location vector *loc(x,y,θ)*. The origin (0,0) is fixed to one of the corners of the indoor area. Suppose the robot starts from location $loc_i(x_1, y1, \theta 1)$ which is mapped with the origin. The robotic platform is equipped with gyro sensors and an accelerometer which will give change in rotation angle of two wheels and the change in translation.δ_{trans}).

$$\delta_{trans} = \sqrt{(x1 - x2)^2 + (y1 - y2)^2} \qquad (4)$$

$$\delta_{r\,\theta\,w1} = atan2\left(\left((y2 - y1, x2 - x1)\right) - \theta 1\right) \qquad (5)$$

$$\delta_{r\,\theta\,w2} = \theta_1 - \theta_{2-}\delta_{r\,\theta\,w1} \qquad (6)$$

From these values we can compute current location $loc_j(x_2,y_2,\theta_2)$ with respect to $loc_i(x_1,y_1,\theta_1)$. Let δx,δy and δ*θ* be the changes in x coordinate, y coordinate and angle. We are using the following equation (7) to get the location vector of the current position with respect to origin.

$$loc_j(x_2, y_2, \theta_2) = \begin{pmatrix} x_1 \\ y_1 \\ \theta_1 \end{pmatrix} + \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \delta x \\ \delta y \\ \delta\theta \end{pmatrix} \quad (7)$$

For error reduction, we will compare the values obtained from the above two methods and selects a best estimate with respect to the region code.

F. *Time synchronization*

In a sensor network, there may be propagation delays of the packets due to some environmental factors. A time stamp is added to packets, while transmitting data, in order to avoid the processing of late packets. Each sensor node is associated with a clock, based on its oscillator frequency. Due to atmospheric conditions such as temperature and pressure, there may be slight difference in the oscillating frequency. This will result in a drift from the original clock. But the network protocol requires a common clock to avoid erroneous data. In the system, the clock in all the nodes of the network is synchronized with respect to the clock of central controller. The central controller uses a spanning tree algorithm to find connected components of network graph. It will send a synchronization message with the current clock time to the cluster heads. Cluster heads will propagate it to the cluster members.

G. *Real time streaming*

The end users of the system can view the sensed data through the remote monitoring terminals. The authorized users can login to the web server and can see the status of monitoring. Also they can view the graph of the sensed data in real time. If the presence of explosive material is confirmed by the central controller, then the system will provide an early warning to the concerned persons. For the indication of explosive material presence, it uses existing mobile network and the Internet. The system will automatically give e-mail alerts to the important security officials. Depending on the variations in the sensed data, the officials can take immediate actions. In the case of threat messages or calls, the administrator can configure the system to change the sampling period and threshold limits so that the system can provide improved results.

V. IMPLEMENTATION

The robotic platform selected for this project is Pololu 1060 with ATmega microcontroller. For implementation, we have selected AVR studio 4 and programmed using Embedded C. In the test area, we have placed a set of obstacles. The robot was able to reach target location by avoiding obstacles. The algorithm was tested for varying number of obstacles and varying number of robots. Also the robot communicated with wireless sensor network and other robots present in the test area. Communication between robots helped to avoid deadlocks in the system. We have compared the performance of each individual path planning technique with the proposed combined parallel navigation scheme. The result indicates that the localization errors are significantly reduced in the proposed navigation scheme.

To implement wireless sensor network, we used MicaZ motes and ZigBee technology. The sensor nodes and gateway in the system are using CC2420 RF transceiver. Each cluster member in the system can sense the data and communicate to higher level nodes. Also they can receive synchronization messages and other control messages from higher level nodes. The transmission and reception of the messages are through MicaZ mote embedded with ZigBee compatible RF transceiver .It uses a communication frequency between 2400MHz and 2483.5 MHz. TinyOS is the operating system used for the development. The components and interfaces of TinyOS are used to communicate messages in the network. Robots in the system are not sending all the sensed data to the central controller to reduce communication cost and network overhead. They are using a data fusion algorithm to aggregate the values collected in fixed time interval. We have compared the result obtained from the data fusion algorithm with reference to the static sensor reading. Reading obtained from static sensor of same type in that specific location is considered as optimal sensor reading. Figure 3 illustrates that the probability of error in data fusion is significantly reduced in the proposed algorithm.

Sink node of the network collects data forwarded by sensing nodes and analyses to make decisions. Threshold levels of different sensors are stored in the sink node. Administrator of the network can change the threshold levels in special situation. Using internet, authorized users can login to the system and can check the environmental parameters. Also they can view the real time plot of sensor data without visiting the site. The graph is updated in every 60 seconds. If the sensed value goes above the predefined threshold level, the system will give indications through the website. Figure 4 shows the real time plot of the sensed data.

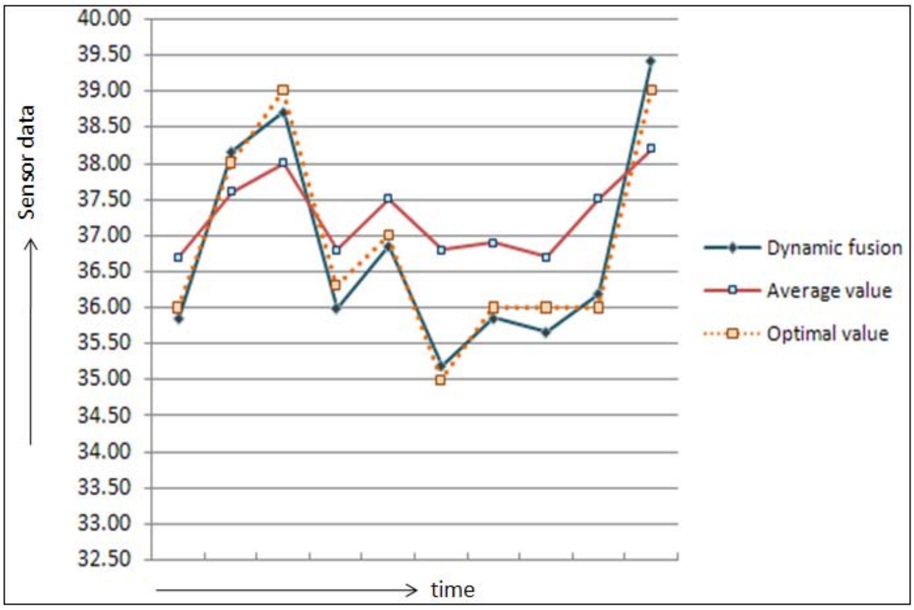

Figure 3. Performance comparison of data fusion algorithm

Figure 4. Real-time plot of sensor data

VI. CONCLUSION

The paper discussed the design of a hybrid wireless sensor network to monitor environmental parameters with in an indoor area. A set of mobile robots are operating inside the wireless network acts as mobile nodes. We have developed a navigation algorithm for the collision free movement of multiple robots with in the test area. The embedded sensors in the robot allow close monitoring of environmental parameters, provide minimal noise and accurate data to the wireless sensor network. This design can be applicable when dealing with sensors with low range capabilities and where it is of the utmost importance that the sensors give accurate readings (as in the case of detecting explosives).More than one type of method used for navigation allows the system to reduce errors in path planning. With the help of this multi robotic platform, the wireless sensor network allows autherized users to view the status of the environmentin the Internet and thus provides real-time streaming.

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