Robot Assisted Emergency Search and Rescue System With a Wireless Sensor Network

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Abstract

The unprecedented number and scales of natural and human-induced disasters in the past decade has urged the emergency search and rescue community around the world to seek for newer, more effective equipment to enhance their efficiency. Search and rescue technology to-date still rely on old technologies such as search dogs, camera mounted probes, and technology that has been in service for decades. Intelligent robots equipped with advanced sensors are attracting more and more attentions from researchers and rescuers.

This paper presents the design and application of a distributed wireless sensor network prototyping system for tracking mobile search and rescue robots. The robotic system can navigate autonomously into rubbles and to search for living human body heat using its thermal array sensor. The wireless sensor network helps to track the location of the robot by analyzing signal strength. Design and development of the network and the physical robot prototype are described in this paper.

Keywords: *Wireless Sensor Networks Artificial Immune Systems, Humanitarian Search and Rescue, Distributed Systems***.**

1. Introduction

Humanitarian search and rescue operations can be found in most large-scale emergency operations. Tele-operated robotic search and rescue systems consist of tethered mobile robots that can navigate deep into rubbles to search for victims and to transfer critical on-site data for rescuers to evaluate at a safe spot outside of the disaster affected area has gained the interest of many emergency response institutions. Distributed wireless sensor network applied in many different fields including, medical [10], civil [9], and environment research [12], has demonstrated its value in conveying data over large area with high level of power efficiency, which is particular suitable for tracking the location of search and rescue robots in large search field.

This research demonstrates the use of distributed wireless sensor network to track search and rescue robot in an open field. The goal of the research is to develop a physical prototype to demonstrate feasibility of the proposed application that can help to acquire realistic data to use as simulation parameters in future search and rescue research.

This paper begins with an introduction to humanitarian search and rescue and robotics search and rescue systems. Then the paper moves on to describe the basic specifications of the wireless sensor network system. An introduction to AIS and the implementation of GSCF into the mobile robot tracking prototyping system is also included in the second half of the paper. Conclusions and future works are discussed at the end of the paper.

2. Humanitarian Search and Rescue

Natural and human-induced disasters in the past decade has claimed millions of lives and demolished astronomical sum of assets around the world. Natural disasters such as the Hurricane Marilyn in 1995 [2], the Oklahoma Tornado in 1999 [8], the Indian Ocean Earthquake [13] and Hurricane Katrina in 2005 [3], and the Pakistan Earthquake in 2005 [1], all claimed deadly and costly tolls to the affected communities. Human-induced disasters such as the civil war between Uganda government and the LRA (Lords Resistance Army) that dragged on for nearly two decades since 1987, the long-running Somali civil war since 1986, and the never-ending Palestinian conflict in Hebron and the Gaza Strip caused much more causalities than nature has ever claimed. Searching and removing landmines during and after the war can reduce civilian casualty and sooth local tension. De-mining and defusing landmines after the settlement of a war is a humanitarian responsibility that war parties should bear. However, until today, yet-cleared minefields still scatter in countries like Vietnam and Cambodia, claiming lives of ill-fated civilians.

Collapsed buildings are common field environment for humanitarian search and rescue operations. Earthquakes, typhoons, tornados, weaponry destructions, and catastrophic explosions can all generate damaged buildings in large scales. The use of heavy machinery is prohibited because they would destabilize the structure, risking the lives of rescuers and victims buried in the rubble. Only by hand should the pulverized concrete, glass, furniture and other debris be removed (see Figure 1).

Figure 1. Pakistan earthquake 2005, locals attempting to search for survivors in a collapsed girl's college. The structure was in unstable condition; excavation and lifting machineries were prohibited from the site. (Pictures taken on site by author during mission)

Rescue specialists use trained search dogs, cameras and listening devices to search for victims from above ground. Though search dogs are effective in finding human underground, they are unable to provide a general description of the physical environment the victim locates. Camera mounted probes can provide search specialists a visual image beyond voids that dogs can navigate through, however their effective range is no more than 4-6 meters along a straight line below ground surface.

3. Robot Assisted Search and Rescue Systems

Robots designed for search and rescue had been discussed in scientific literature since the early 1980's [6]; however, no actual systems had been developed or fielded until 2001. With the advancement in sensor miniaturizations and exponential increment in the speed and capability of microcontrollers, rescue robots small enough to thread through rubbles are rolling out of experimental laboratories into the catastrophic areas. The first real research on search and rescue robot began in the aftermath of the Oklahoma City bombing in 1995 [7]. Robots were not used at the bombing response, but suggestions as to how robots might have been applied were taken. In 2001, the first documented use of urban search and rescue robots took place during the 9/11 World Trade Center (WTC) disaster. Mobile robots of different sizes and capacities were deployed. These robots range from tethered to wireless operated, and from the size of a lunch box to the size of a lawnmower [11]. Their primary functions are to search for victims and to identify potential hazards for rescuers.

4. Wireless Mobile Robot Tracking System

The low-cost autonomous robotic search and rescue system (Figure 2) presented in [4] was designed to cooperate in large quantity to search for survivors in rubbles. These robots were equipped with wireless communication module to facilitate data and video/audio transfer. These wireless robots, with no tethers, can navigate freely in obstructed environment but are difficult to track their locations once they wander out of the operators' sights. The Zigbee communication module equipped in each of these mobile robots offers an opportunity to track down their locations. The following paragraphs will describe how a Zigbee based sensor network interacts with the onboard Zigbee communication module on each robot to estimate their locations.

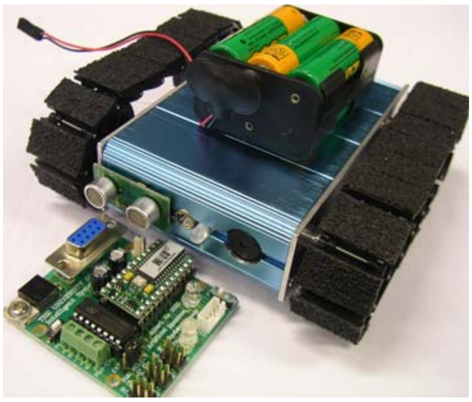

Figure 2. The physical prototype of the newly developed robot. The battery pack on top of the robot serves as a scale to show the robots' dimension.

ZigBee (http://www.zigbee.org/en/index.asp) is a wireless technology developed to address the need for a standards-based wireless networking systems for low data-rates, and low-power consumption applications. ZigBee supports many network topologies, including Mesh. Mesh Networking can extend the range of the network through routing, while self-healing increases the reliability of the network by re-routing a message in case of a node failure. These unique features are highly desirable for search and rescue robots operating in unstructured environment. The ZigBee-based sensor network hardware employed in this research is based on the Chipcon 2431 (http://www.ti.com/lit/gpn/cc2431) development kit (Figure 3).

Figure 3. Zigbee moduleds used in this project. On the left is a stand alone Zigbee module, to the right is a module installed on the development board.

The sensor network built with the 12 Zigbee modules in the development kit has 9 modules programmed as reference nodes, and 2 modules programmed as blind nodes. The 9 reference nodes were distributed around the laboratory roughly resemble a square grid as show in Figure 4. The two blind nodes were installed on each of the two mobile robots. The last Zigbee module (or the first) of the 12 was gallantly sacrificed in short-circuit during programming.

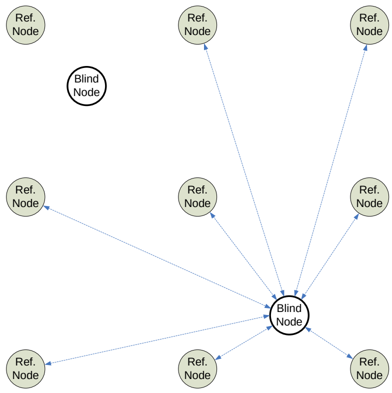

Figure 4. Zigbee modules in grid. Reference nodes are represented by blank circles, where blind nodes are represented by crossed circles.

Reference nodes are static nodes placed at known position and can tell other nodes where they are on request. Reference nodes do not need the hardware for location detection and do not perform any calculations. Blind nodes, on the other hand, are programmed to collect signals from all reference nodes responding to their request; then read out the respective RSSI values, feed the values into the location engine, and afterwards read out the calculated position and send to the control console. Since all location calculations are performed at each blind node, the algorithm is genuinely decentralized. This property reduces the amount of data transferred in the network, since only the calculated position is transferred, not the data used to perform the calculation. The system is therefore highly scalable.

The ZigBee modules used are embedded with 8051 8-bit single-cycle processor, 128 KB in-system programmable flash, and 8 KB RAM, which adds up to roughly 8 times the performance of a standard 8051. This processing power allows the blind nodes to use up to 16 reference nodes to estimate its current position. In theory, signals from 3 reference nodes is the least to make a sensible estimation, the more reference node signals received, the more accurate the estimation is.

Algorithm used to estimate locations of the blind nodes within the sensor network is straightforward. To estimate its current location, the blind node on the mobile robot broadcast a specific signal to the surrounding. All reference nodes within range response to the signal by sending a packet containing the reference nodes' relative coordinate. The algorithm uses Received Signal Strength Indicator (RSSI) values to estimate distance from each reference node. Since RSSI value decreases as distance increases, the blind node would chose the 8 nearest reference nodes by comparing RSSI values between all reference nodes in range. Based on the strength of these returned signals and the origin of each signal included in the packet, position of the blind node can be estimated.

5. Distributed Wireless Sensor Network

The distributed wireless robot tracking system presenting in this paper is based on the GSCF [5] developed for controlling decentralized systems. For the wireless robot tracking system in this research, the primary objective is to continuously track the location of each robot by evaluating a collective set of feedbacks from multiple sources. These feedbacks include coordinates from the Zigbee Communication Module, motor encoders, and electronic compass. The only system constraint to be incorporated into the system is accuracy of the estimated robot locations.

The low-cost Zigbee based sensor network used in this research is suitable for tracking robots in large area and to relate information over long distance in an energy efficient manner. However, position estimations obtained from RF based systems are venerable to interferences; therefore additional referencing sensors are often desirable in more accurate applications. The solution for this particular application is to take advantage of the readily available motor encoders and electronic compasses installed in the robots to generate more reliable position estimations, though these sensors all exhibits inherited reliability issues in their own way. Table 1 lists their advantages and disadvantages.

Table 1. Advantages and disadvantages of the three feedbacks used in the system.

Sensor types	**Advantages**	**Disadvantages**
Received Signal Strength Indicator (RSSI)	Covers large area Low Power Consumption	Susceptible to interferences
Electronic Compasses	High accuracy	Slow response time
Motor Encoders	High precision	Cannot detect slippage

Based on the strength and weaknesses of each type of sensors listed above, RSSI is a more reliable source to quickly estimate the robots position without accumulative error. Motor encoders are not reliable for long distance tracking as slippage error would accumulate, however it is good for short distance position tracking. Electronic compasses can be used to confirm the direction in which the robot is moving towards, which in turn can verify the accuracy of the coordinates produced using RSSI estimation. In general, the blind node on the mobile robot would sample surrounding reference nodes 10 times per estimation. Each set of 10 RSSI returned per reference node are converted to distances. The highest and lowest readings of each set of RSSI are removed, and then standard deviation of the remaining readings in the data set is produced to evaluate the reliability of the estimated distance. The estimated distance is more reliable if the standard deviation is low, otherwise the reliability is low.

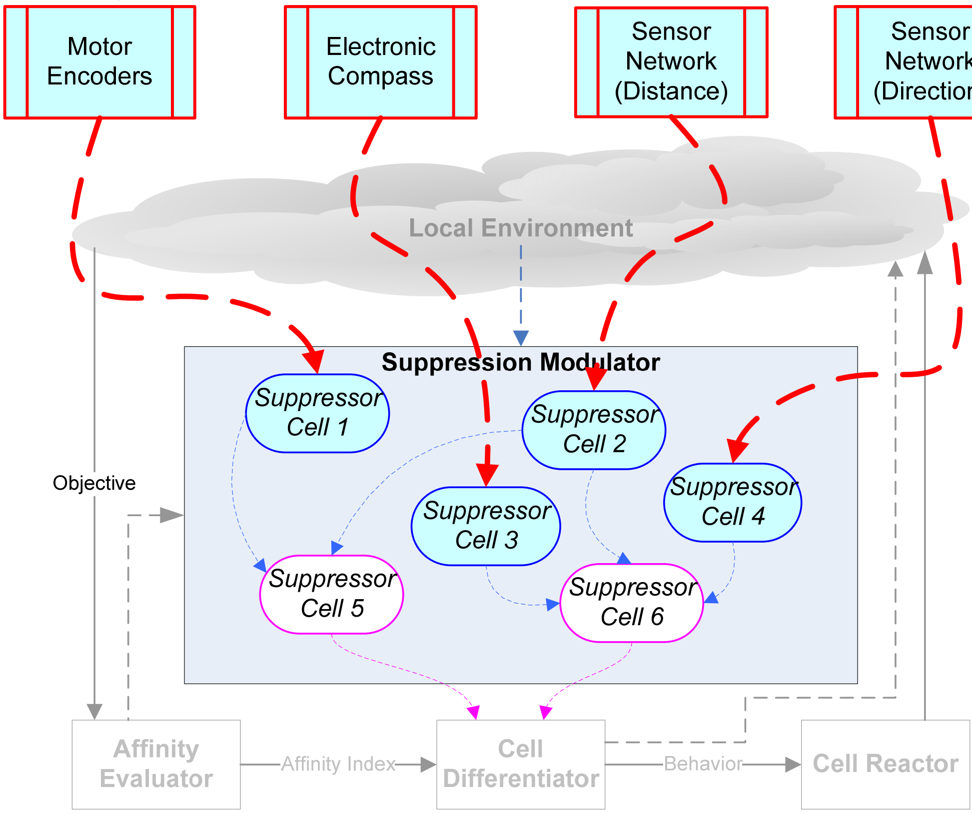

Figure 5. The General Suppression Control Framework. Dashed lines represent humoral signal transmissions, where solid lines represent cellular signals. The suppression modulator can host any number of suppressor cells.

The distributed wireless robot tracking system under discussion has two additional sensor sources that influence the robots' behaviors. The encoder tells the displacement of the robot by counting rotations made by the motor. The electronic compasses read the robots direction at any instant with reference to the earth's magnetic field. Suppressor cells that have high sensitivity to the changes of these sensors readings are situated in the Suppression Modulator (Figure 5). Though there are only three types of sensor sources, there are six types of suppressor cells in the system. Table 2 lists their functions.

Table 2. Summary of suppressor cells in the Suppression Modulator.

	Suppressor Cell Duties	Output to Cell Differentiator
SC_1	Output estimated travel distance since last sampling based on	Output to SC_5

	feedback from motor encoders	
SC_2	Output estimated travel distance since last sampling based on feedback from RSSI readings	Output to SC_5 Output to SC_6
SC_3	Output estimated current traveling direction based on feedback from electronic compass	Output to SC_6
SC_4	Output estimated travel direction based on feedback from RSSI readings	Output to SC_6
SC_5	Output a suppression index that indicates the compliance of readings from SC_1 and SC_2 Suppression index lowest when the two readings agree.	Suppression Signal 1-10
SC_6	Output a suppression index that indicates the compliance of readings from SC_2 and SC_3 in respect to condition of SC_2 Suppression index lowest when the two readings agree.	Suppression Signal 1-10

The function of summation cell SC5 is designed to compare the estimated travel distance from encoder and from the sensor network. For example, a mobile robot driving against an obstacle would report high counts on the encoder but the estimated position reporting from the sensor network would probably remain unchanged. This discrepancy between estimations from two sensors would reflect in the suppression index produced by SC5, the higher the discrepancy level, the higher the suppression index (see illustration in Figure 6).

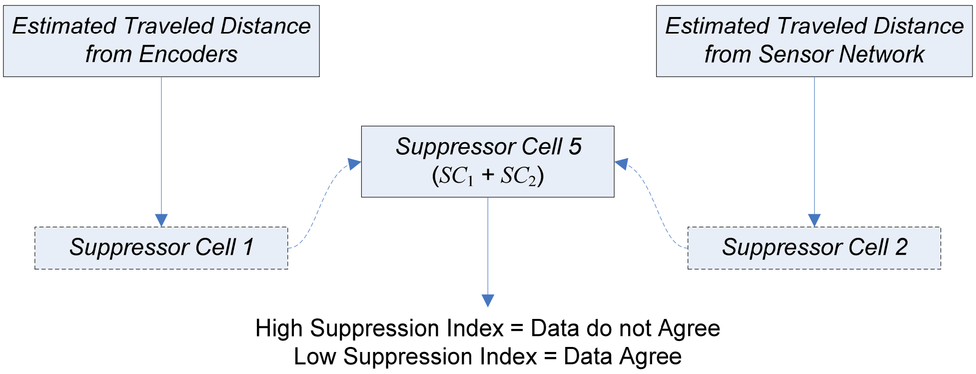

Figure 6. The function of SC1, SC2, and SC5 illustrated as an independent system. In short, SC5 fuses data for Cell Differentiator to evaluate.

Function of summation cell, SC6, is similar to that of SC5, except it considers an additional constraint. SC6 determines whether the readings obtained from sensor network is reliable by comparing the estimated direction from sensor network against the reading from electronic compass. SC6 takes in the initial and final estimated locations from sensor network to trigonometrically estimate the direction the robot is moving, then compare this estimation against the electronic compass reading from SC3 to produce a suppression index that reflects the discrepancy, the higher the discrepancy level, the higher the suppression index. Suppression index from SC5 and SC6 are crucial for Cell Differentiator to adapt a behavior that best fit the situation.

Cell Differentiator is responsible for integrating complex information from different sources into simple instructions and converts intricate problems into quantitative outputs. The decision flow of the Cell Differentiator can be summarized in a flow chart as shown in Figure 7.

The suppression indices from the suppressor cells have priority over all others, it is being evaluated first to see whether the estimations based on encoders, sensor network, and compasses comply with each other. If the suppression index is low, meaning the estimation from sensor network agree with additional sources (encoder and compass); the suppressor modulator will not react strongly. If the Affinity Index is low, meaning the RSSI data is sable, the system will behave in tolerant mode. Otherwise, the suppression index is high or the affinity index is high, the system will switch into aggressive mode.

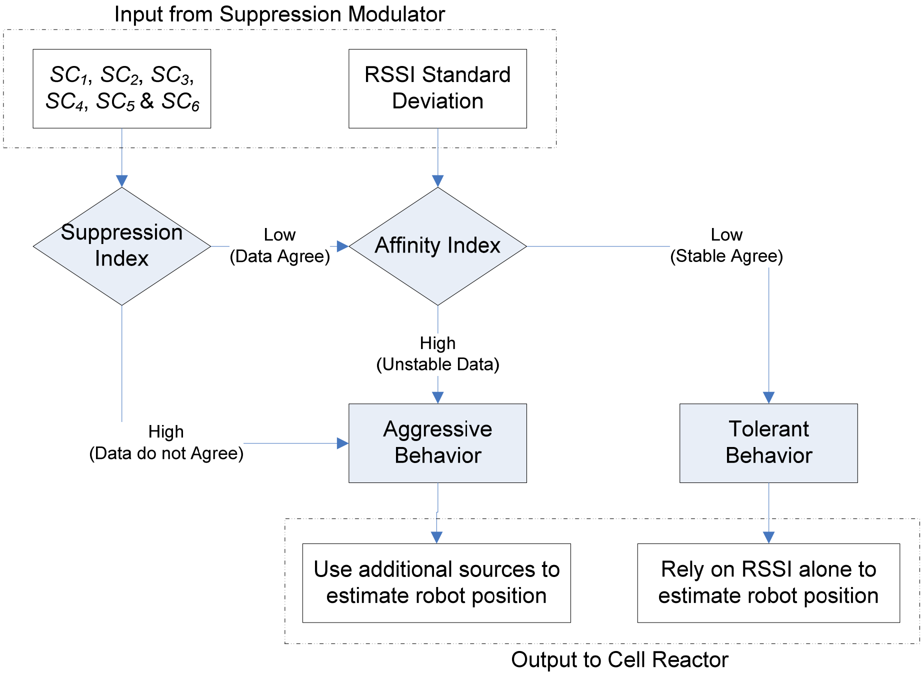

Figure 7. Decision scheme in the Cell Differentiator of each modular fireguard.

Since the Cell Differentiator in GSCF is only responsible for producing high-level behavioral instructions such as “sound the alarm”, “stand fast”, “search for heat”, etc. There has to be a component to interpret these high level instructions into low-level instructions for the mechanical controllers. This component is called Cell Reactor. Since mechanical control schemes varies greatly between different operation platforms, GSCF delegates this work to Cell Reactor, so the high level design of other components can remain platform independent.

6. Conclusions

The AIS-based distributed tracking system developed for the mobile search and rescue robots are being tested indoor in a laboratory between tables, chairs and miscellaneous obstacles. Within the environment there are uncontrolled RF interferences of different sorts, including Wi-Fi routers, mobile phones, activated The suppression indices from the suppressor cells have priority over all others, it is being evaluated first to see whether the estimation based on encoders, sensor network, and compasses comply with each other. If the suppression index is low, meaning the estimation from sensor network agree with additional sources (encoder and compass) the suppressor modulator will not react strongly. If the Affinity Index is low, meaning the RSSI data is sable, the system will behave in tolerant mode. Otherwise, the suppression index is high or the affinity index is high, the system will switch to aggressive mode.

RFID systems, Bluetooth devices (keyboard and mouse), and EMF from various mechanical devices. Despite the abundant sources of interferences, the test environment is far from practical for what this system is designed for. Long term work is to develop methods to evaluate accuracy of sensor network estimated position against actual position in obstructed environment, i.e. in rubble. This work would provide a base to compare and evaluate results of different control and tracking algorithms. In addition, technologies and methods that can help to setup the system quickly for emergency application is another important area to make the system truly applicable.

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