A Testbed for Localization and Tracking in Wireless Sensor Networks

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Abstract—This paper discusses the significance of the use of wireless sensor networks and the wireless node localization for applications in factory automation and facilities management. We present a testbed that has been developed for implementing and testing wireless localization algorithms within harsh and dynamic automation environments.

Keywords—wireless sensor networks, localization, factory automation, facilities management, testbed.

I. INTRODUCTION

As a consequence of recent developments in wireless communication and MEMS IC technologies, the use of wireless sensor networks (WSN) is becoming increasingly widespread for a variety of monitoring and control applications, e.g., indoor navigation, environmental monitoring, people and objects tracking, logistics, industrial diagnostics, quality control, and manufacturing automation [1].

Apart from the need to build cheap, simple to program, simple to network and potentially long-lasting sensor nodes, a crucial and primary ingredient for developing actual applications is the sensing facility with which a sensor node can be endowed. A wireless sensor network is typically formed by deploying many sensor nodes to sense the physical characteristics of the world. The WSN can be developed at a relatively low-cost and can be deployed in a variety of different settings.

On the basis of nodes that have sensing and actuation capabilities, many different application scenarios can be constructed. The major application scenarios include; disaster relief applications [2]; environment; home/building automation [3]; remote/preventive maintenance; medicine and health care [4] and so forth.

Wireless technologies differ from wired networks in a number of ways. Besides the significant flexibility and cost savings that they provide, the differences pose significant challenges for the design of WSN architectures, protocols and especially the localization techniques for industrial and automation applications.

The employment of wireless technologies in industrial and factory automation environments is very attractive for many reasons. The wireless way of communicating makes plant setup and modification easier, cheaper and more flexible since in many factory and automation applications the communication needs are traditionally served by wired field bus systems and other industrial communication systems.

Wireless sensor networks allow information to be collected with more monitoring points, providing awareness for the environmental conditions that affect overall uptime, safety, or compliance in industrial environments and enabling agile and flexible monitoring and control systems.

In most of these applications, the sensor node's position is an essential input to a location-aware sensor network [5]. In many cases, such as in tracking an object within a manufacturing plant, the automatic detection of the sensors' location, namely localization, is the core technology. In other words, the location itself is often the primary data that needs to be sensed.

Design and implementation of WSN localization systems into factory automation and facilities management systems can enable adaptive and flexible automation and enable better process adaptability and quality control [6]. The wireless network connects critical processes or assets with the systems or experts that can interpret the data or take immediate actions. As a result, operational teams with more visibility into their processes can prevent shutdowns and increase efficiencies while reducing the total cost of data acquisition [7].

However, several challenges exist for applying the WSN localization techniques in harsh and dynamic automation environments which cause uncertainties in the radio communications amongst the wireless nodes.

In this paper, we discuss the challenges and requirements of developing efficient WSN localization algorithms for factory automation systems. For this reason, we introduce a prototype WSN testbed, which has been developed for performance evaluation of WSN localization systems in harsh and dynamic automation environments.

The remainder of the paper is organized as follows: Section 2 briefly describes the background of node localization in WSN; Section 3 discusses the challenges of WSN localization in factory automation; Section 4 introduces the experimental localization testbed with preliminary experimental results; and finally, Section 5 provides concluding remarks.

II. NODE LOCALIZATION IN WIRELESS SENSOR NETWORKS

Node localization can be defined as determining the location of a sensor node within the network with respect to an

origin. The WSN localization techniques usually consist of the algorithms that estimate the locations of sensors with initially unknown location information by using knowledge of the absolute positions of a few sensors and inter-sensor measurements, such as distance and bearing measurements. Sensors with known location information are called beacons or anchors. The anchors define the local coordinate system to which all other sensors are referred. The coordinates of the sensors with unknown location information, also called blind or non-anchor nodes, will be estimated by various sensor network localization techniques.

The localization in WSN is a significant, key enabling technology, attracting considerable research interest. With the constrained resources of network sensors, as well as their high failure rate, many challenges exist in the automatic determination of the sensor's location. Various application requirements, such as; scalability, energy efficiency, cost, accuracy, responsiveness and privacy, influence the research and development of sensor localization systems [8]. Moreover, the small amount of code space available in WSN nodes make the implementation of both the data service logic and the localization algorithm on a single node problematic, which forces the researchers to reduce the complexity of the localization techniques.

The effectiveness of the existing localization systems vary, depending on the parameters, such as: the physical phenomena used for location determination, the form factor of the sensing apparatus, power requirements, infrastructure versus portable elements, and resolution in time and space, etc. [9]. In most of the applications requiring long operation time, energy efficiency is an important consideration, due to the fact that the sensor nodes are dependant on limited run-time power, usually provided by on-board batteries. Due to distributed computation, numerous sensors that are close to the phenomenon can make the architecture of a system both simpler and more energy efficient.

It is very common to classify the existing wireless localization techniques according to the method of measurements; such as range-based' or 'range-free'. Moreover, in general, almost all the sensor network localization algorithms share three main phases: i) distance estimation, ii) position computation and iii) localization algorithm.

The distance estimation phase involves measurement techniques to estimate the relative distance between the nodes.

The measurement is basically performed by communication between two wireless nodes and about their connectivity/proximity and their geometric relationship. The distance estimation process highly influences the accuracy and precision of localization.

Various techniques have been developed for measuring the distance or angle between nodes in a network. The common methods are: the Angle of Arrival (AoA) [10], which detects the direction of the received signal in order to obtain range information; Time of Arrival (ToA) and Time Difference of Arrival (TDoA) [11], which use pulses of ultrasonic signals to determine the distance between two nodes.

The most popular method in distance estimation for wireless systems is the Received Signal Strength Indicator (RSSI) technique, which is based on the physical fact of wireless communication that theoretically, the signal strength is inversely proportional to the squared distance between the transmitter and receiver.

RSSI is the simplest and cheapest method amongst the distance estimation techniques, since it does not require additional, costly hardware for measurements. A known theoretical or empirical radio propagation model is used to convert the radio signal strength into distance. However, in practice, the RSSI is highly variable and unstable under the influence environment noises, obstacles, interference and the types of antenna, which makes it hard to model mathematically [12]. Various challenges exist in RSSI-based distance estimation.

The distance estimation process is not limited to the range measurements but is based on connectivity information between the nodes. The range-free methods do not need absolute range information for distance estimation but they generally use the number of hops between a node pair as a distance metric. The accuracy of range-free methods is less than the range-based ones but they satisfy the requirements for many applications. Because of the hardware limitations of WSN devices, solutions in range-free localization are being pursued as a simple and cost-effective alternative to more expensive range-based approaches. The most obvious disadvantage of this scheme is the fact that it performs poorly for irregular topologies [9].

According to the ways of their implementation, the current WSN localization algorithms can be classified into several categories, such as: according to node connectivity and topology (i.e. single-hop or multi-hop localization); dependency of the range measurements (i.e. range-based vs. range-free); and, distributed or centralized position computation- with or without an infrastructure (anchor-based or anchor-free). A detailed review of various localization algorithms can be found in [5], [9] and [13].

The second phase of localization is position computation which consists of algorithms to calculate the coordinates of the unknown node with respect to the known anchor nodes or other neighboring nodes. Several geometrical methods can also be used for calculating the coordinates of the blind node based on range/connectivity information. The well-known techniques are multi-lateration, triangulation and bounding-box.

The third phase is the localization algorithm, which in general, determines how the information, concerning distances and positions, is manipulated in order to allow most or all of the nodes of a WSN to estimate their positions. Optionally, the localization may involve algorithms to reduce the errors and refine the node positions, including iterative computational methods, clustering algorithms and mathematical optimization techniques.

III. WSN LOCALIZATION IN FACTORY AUTOMATION

A WSN interacts with a factory automation environment in the form of spatially distributed measurements, diagnosis and

possible actuations. A WSN typically consists of a homogeneous set of nodes with the same application. The majority of current applications provides only monitoring capabilities and hence contain only sensors. Machine control sensors, actuators and controllers are often on a separate network [14].

Wireless communication makes factory setup and modification easier, cheaper and more flexible. It provides a natural approach towards communication with mobile equipment where wires are in constant danger of breaking. It enables new applications where wireless transmission is the only option, e.g., measurements and control of rotating or highly mobile devices, and provides a novel approach to existing applications, such as the localization and tracking of goods.

The measure of success for an industrial grade WSN is not how any individual network device performs, but how the system as a whole ensures a reliable flow of critical data. Reliability is an absolute requirement for any monitoring technology, because if the data is not reliable, the economic benefits of its low installation costs are rendered irrelevant.

Specifically, for a wireless technology to be reliable in industrial applications, it must: (1) function in harsh industrial environments with unpredictable Electromagnetic Interference (EMI), RF fading, and multipath interference; (2) coexist in the field with other wireless devices or noise emitters such as machine equipment, communications devices, instant connect phones, pagers, cell phones, remote controls, and other wireless frequency emitters common in the industrial environment [7].

The accuracy and precision of a location sensing system is often used to determine whether the chosen system is applicable for certain applications [15]. The accuracy of the measurements plays a very important role in range-based WSN localization and it depends often on the implementation measurement techniques, device calibration noise and environmental conditions. Non-calibrated ranging readings are always greater than the true distance and are highly erroneous due to delays in transmitting and receiving. On the other hand, the cost and limitations of the hardware on sensing nodes prevent the use of some of the localization schemes in real-world tracking applications. In addition, accuracy, calibration, fault tolerance, scalability and energy efficiency are major issues that must be addressed in the area of automatic location determination of a sensor's location. Hence, there is already extensive research potential for optimizing the cost and energy consumption, while improving the accuracy, scalability and fault tolerance of the WSN localization techniques.

In the context of the implementation of WSN into factory automation systems for tracking or location-aware monitoring purposes, the challenge is to find out the most suitable localization algorithm for this application domain.

In the domain of the localization for WSN, for simplicity, the position computation problems are mostly formulated and solved in two dimensional planes. Several techniques that were developed address the 2-D solutions of location determination and only a few researchers provide detailed analysis and the benefits of the 3-D aspects of these solutions [16][17]. In addition, most of the software applications and tools, developed so far for WSN visualization, include 2-D presentation of the spaces.

V. PROTOTYPE IMPLEMENTATION: WSN TESTBED

The objective of the WSN Testbed is to recreate and test a wide variety of three dimensional, real-time wireless sensor node localization techniques to scale for various applications of factory automation.

Within the scope of the proposed project in this paper, the WSN testbed has been implemented in a former manufacturing lab, including machinery and manufacturing automation equipment, which can be considered as a small scale model of a factory. The harsh automation environment in the lab is aimed to yield a model of the possible factory implementation of WSN systems. This is expected to allow the flexibility to develop and to test certain sensor network services and applications prior to deployment. For this reason, the testbed should be designed with intended real world deployment; applications developed in the context of the testbed can be easily moved to the actual deployment environment.

The WSN testbed forms a flexible environment for testing various wireless localization algorithms prior to their deployment. The primary functions of the WSN Testbed are:

- Performing scalable experiments to determine the empirical radio signal strength characteristics for the indoor environments

- Developing, testing and benchmarking different wireless sensor localization algorithms, supporting low-power devices at the indoor factory environment

- Developing and testing wireless cooperative processing algorithms to optimize wireless communication performance, energy usage and reduce errors of path loss

- Visualization and validation of real-time sensor information with the location of sensor nodes in 3-D space using interactive computer graphics

- Developing distributed real-time workspace in order to support collaborative decision making based on the data provided by the wireless sensor network

A. System Hardware

For the development of the WSN testbed, a generic wireless sensor node platform, called a 'mote' has been used (see Figure 1). A mote without a power supply is typically several millimeters in length and width. External flash memory is also common to many nodes. Sensors and signal conditioning circuitry are external components, and thus maintain hardware generality. Several generations of mote platforms exist, ranging in size, power consumption, functionality and radio technology. In our study we have chosen several platforms having different microprocessor, radio and antenna configurations. We have been implementing our testbed using the TelosB platform [21].
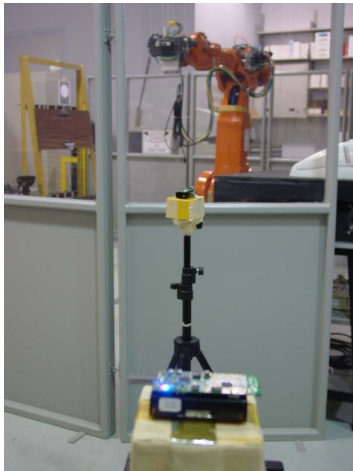
Figure 1.   Wireless Hardware used in the WSN Testbed

command functions between these modules. The wireless communication between nodes is managed with a carrier sense medium access data layer. Packets are encapsulated using an active message scheme [24].

As mentioned earlier, node localization is a complex problem that may need to be solved by either one-hop or multi-hop techniques. Several different architectures need to be studied in the proposed testbed. Initially, we have established the basic architecture using a base station, routers and several sending motes, and hopping packages to send signal/information to the centralized computer. A base station node physically connects to the computer and acts as a gateway. It runs a specialized program that interfaces the wireless sensor network to a serial port on the host computer. Typically, the base station is the same general hardware platform as the wireless sensor nodes. Router nodes bridge communication between the base station and sensor nodes that are beyond sufficiently reliable direct radio communication range.

B.   Software System Structure

The structure of the software system employed for the overall testbed consists of two layers; 1) Bottom-Level Wireless Operating System Layer, 2) Top-Level Data Management and User Interface Layer. The structure of the overall system is shown in Figure 2.

2)   Top-Level Interfacing and Data Management Layer

In the WSN testbed, the WSN localization algorithms are supported with a high-level information management and VR-based 3-D visualization system at the Top Level Interfacing Layer, running at the PC side.
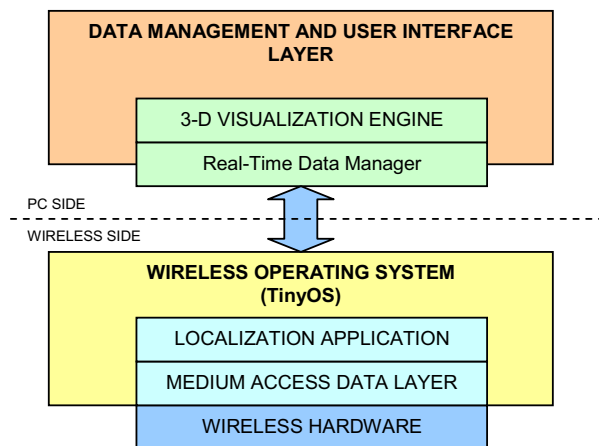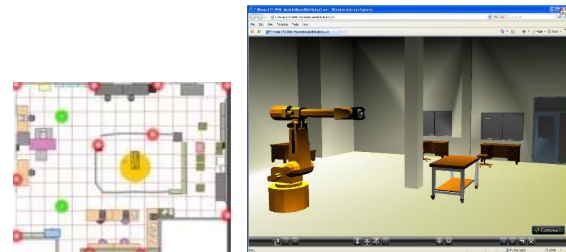

Figure 2.   Software System Structure

Figure 3.   2-D and 3-D Visualization Interfaces of the WSN Testbed

The 3-D Visualization Engine and Real-Time Data Manager are two main components of this layer, which work together to provide a user-accessible interface for managing the overall wireless sensor network (See Figure 3).

The Real-Time Data Manager provides a software abstraction layer to communicate with the wireless platforms. At the current stage, this layer has been designed and developed in Java language to operate as a generic bridge between the wireless operating system and higher level applications. The Data Manager uses the serial port communication with a wireless mote and helps to log, display and manipulate the wireless data for testing and experimenting purposes.

The 3-D Visualization Engine is the most significant element in the top layer. It interprets the location information using 3-D Virtual Reality (VR) models of the environment. This feature helps in real-time monitoring, control and deployment of the wireless sensor nodes, hence supporting the real world applications of WSN for the manufacturing industry. The 3-D real-time representation of the WSN data improves the

1)   Bottom-Level Wireless Operating System Layer

The Bottom level Wireless Operating System runs in the wireless platform and mainly operates the functions of the wireless embedded systems such as; i.e. microprocessor, radio, memory and other peripherals. This layer has been developed in TinyOS operating system, which is an event-based non-blocking event scheduler for embedded systems, specifically developed for WSN [21].

The TinyOS consists of a library of software modules coded in the NesC programming language [23]. The wireless applications are fundamentally operated by signaling events, handling events, calling command functions and performing

usability of spatial information and most significantly, the visualization of reality compares to a simple and flat 2-D representation. Of all of the drawbacks of 2-D graphics, the most vital is the lack of capability to offer users a life-like representation of real environments [18]. VR is a good example of such a visualization technology since it provides a three dimensional realistic environment to provide a sense of reality and the impression of 'being there'. VR has been widely referred and used in industrial applications [19], [20].

The 3-D Visualization Engine has been implemented in VRML Language and performs real-time data exchange with the Data Manager throughout the Java Script routines.

Within the scope of the testbed project, we intend to implement the 3-D Visualization interface over the internet in order to provide remote access to the information provided by the wireless sensor network. However, at the moment, it is only implemented locally.

IV. EXPERIMENTS

We have designed several initial experiments in the WSN Testbed to characterize the radio signal propagation model in order to correlate the RSSI and range (distance) empirically. When sensors are employed for indoor localization, the experiments attempt to measure the sources of error and path loss characteristics. In addition, we have carried out some of the signal strength experiments outdoors in order to determine the basic characteristics of wave propagation in free space with minimal reflection conditions.

For the experiments, we have used TelosB motes in various combinations. Basically, we have developed three types of motes: Sender mote, Receiver mote and the Base Station mote. The Sender mote periodically sends radio packets containing information pertaining to its own identification and location. The Receiver mote receives packets and measures the radio signal strength (RSS) of each received packet. Figure 4 shows the layout of the Sender and Receiver motes on tripods while testing.

The Receiver mote forwards all the information about the Sender's ID and RSSI in a packet to the Base Station mote in order to collect and log data using a PC or Laptop computer from a distant location.
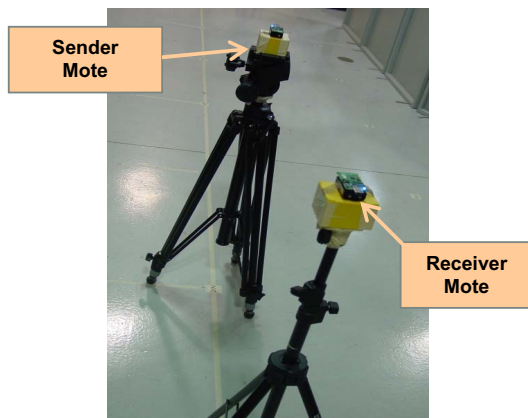

Figure 4. RSSI Measurement with Sender and Receiver motes

A. Preliminary Results

We have carried our some our experiments about the path loss by varying relative distances between the Sender and Receiver motes. The average of the RSSI values collected at the Receiver mote has been plotted versus various relative distances.

As a result of the experiments performed indoors, we have found that multiple RSSI values may exist at the same distance values, which makes it very difficult to measure the distance using RSSI indoors. The influence of the multipath reflection greatly disturbs the RSSI-distance curve due to the change in the phase of the multi-path radio signal [25].

However, as we test the same system outdoors, where it is assumed to have minimal reflection, the empirical RSSI-distance curve in free space (i.e. outdoors) is more stable and predictable at different distance values. Figure 5 shows a case of outdoor experiments, where the Sender mote is located on the ground level and the Receiver is located at 1 meter above ground level. Figure 6 pictures another case outdoors, where both sensors are located at 1 meter above ground level. The reflected radio signal path through the ground causes a shift in the signal phase.
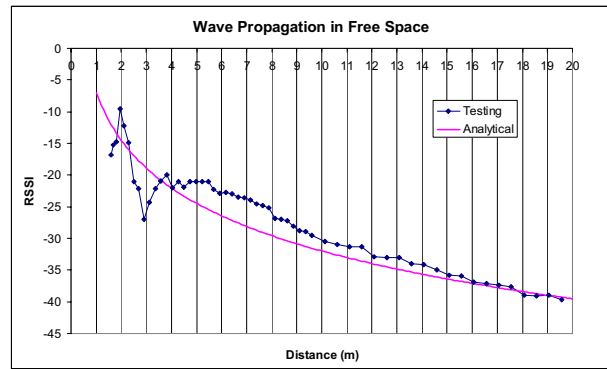

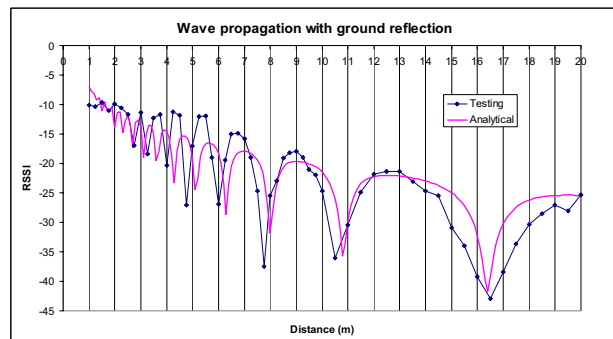Figure 5. The wireless wave propagation in free space (measured outdoors).

Figure 6. The effect of ground reflection to the RSSI-distance correlation model for TelosB platform (measured outdoors).

V. Conclusions

Wireless sensor network localization has attracted significant research interest. This interest is likely to continue to grow with the increase in the various, challenging applications of wireless sensor networks, such as manufacturing, logistics and factory automation. Despite significant research developments in the area, there are still many unsolved problems in indoor wireless sensor network localization, for harsh manufacturing environments.

RSSI might be an easy and less expensive way of predicting location in WSN, but it is often very problematic due to the path loss and multi-path reflection occurring in indoor environments, especially in low-power radio devices operating at high frequencies. This situation is more crucial when considering the harsh environments of manufacturing plants.

This paper has introduced an experimental WSN localization testbed for a factory automation environment. Several challenges and requirements in this area have been discussed.

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