IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

Wireless Sensor Networks for Industrial Process Monitoring and Control with Security Architecture: A Survey for Research Issues

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Abstract

Recent advances in radio and embedded systems have enabled the proliferation of wireless sensor networks in industrial uses. Wireless sensor networks are tremendously being used in different environments to perform various monitoring tasks such as search, rescue, disaster relief, target tracking and a number of tasks in smart environments. In many such tasks, node localization is inherently one of the system parameters. Node localization is required to report the origin of events, assist group querying of sensors, routing and to answer questions on the network coverage. One of the fundamental challenges in wireless sensor network is node localization. This paper provides a survey on implementing wireless sensor network (WSN) technology on industrial process monitoring and control. First, the existing industrial applications are explored, following with a review of the advantages of adopting WSN technology for industrial control. Then, challenging factors influencing the design and acceptance of WSNs in the process control world are outlined, and the state-of-the-art research efforts and industrial solutions are provided corresponding to each factor. Further research issues for the realization and improvement of wireless sensor network technology on process industry are also mentioned. This paper also reviews different approaches of node localization discovery in wireless sensor networks. The overview of the schemes proposed by different scholars for the improvement of localization in wireless sensor networks is also presented.

Keywords: Process Monitoring and Control, Quality of Service, Reliability, Topology Control, Wireless Sensor Networks, Coordinate system stitching based distributed algorithms, Diffusion, Bounding Box, Gradient, Centralized Localization, Distributed Localization, Beacon-based distributed algorithms, Relaxation-based distributed algorithms, Wireless Sensor Networks.

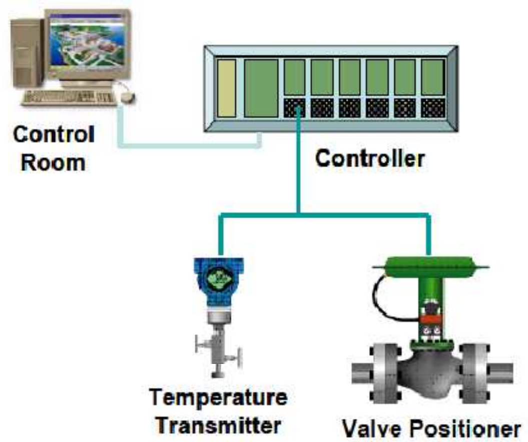
Introduction

The massive advances of micro electromechanical systems (MEMS), computing and communication technology have fomented the emergence of massively distributed, wireless sensor networks consisting of hundreds and thousands of nodes. Each node is able to sense the environment, perform simple computations and communicate with its other sensors or to the central unit. One way of deploying the sensor networks is to scatter the nodes throughout some region of interest. This makes the network topology random. Since there is no a priori communication protocol, the network is ad hoc. These networks are tremendously being implemented to perform a number of tasks, ranging from environmental and natural habitat monitoring to home networking, medical applications and smart battlefields. Sensor network can signal a machine malfunction to the control centre in a factory or it can warn about smoke on a remote forest hill indicating that a forest fire is about to start. On the other hand wireless sensor nodes can be designed to detect the ground vibrations generated by silent footsteps of a burglar and trigger an alarm. Wireless sensor network technology has demonstrated a great potential for industrial, commercial, and consumer applications. Specifically, in process monitoring and control, process data such as pressure, humidity, temperature, flow, level, viscosity, density and vibration intensity measurements can be collected through sensing units and transferred wirelessly to a control system for operation and management. Adopting WSNs for process monitoring and control provides great advantages over traditional wired system. As a ubiquitous technology, general issues regarding WSNs have been extensively researched in the academic arena. However, WSN technology is not considered mature enough to be widely implemented in process control applications. Even though wireless transmission of data has been utilized for over ten years in process control applications such as supervisory control and data acquisition (SCADA), industrial WSN products for process monitoring and control are not commercially available until recently due to its specific requirements and challenges. For these advantages precise knowledge of node localization in ad hoc sensor networks is an active field of research in wireless networking. Unfortunately, for a large number of sensor nodes, straightforward solution of adding GPS to all nodes in the network is not feasible because:

- In the presence of dense forests, mountains or other obstacles that block the line-of-sight from GPS satellites, GPS cannot be implemented.
- The power consumption of GPS will reduce the battery life of the sensor nodes and also reduce the effective lifetime of the entire network.
- In a network with large number of nodes, the production cost factor of GPS is an important issue.
- Sensor nodes are required to be small. But the size of GPS and its antenna increases the sensor node form factor.

For these reasons an alternate solution of GPS is required which is cost effective, rapidly deployable and can operate in diverse environments.

Industrial Applications



Process monitoring and control is a combination of architectures, mechanisms, and algorithms used in the industrial factory for monitoring and control the activities of a specific process to achieve the goal. Let us explain this by illustrating a simple wired application. For example, cooling down a reactor by adjusting the flow rate through the cooling jacket is a process that has the specific, desired outcome to reach: maintaining a constant predefined temperature over time. As shown in Fig. 1, all the devices are hardwired together. Here, the temperature is the controlled variable. At the same time, it is the input variable since it is measured by a temperature sensor and used in a special function to decide the adjustment of a valve to manipulate the flow rate through the cooling jacket. The desired temperature is the set point. The valve opening position (e.g. the setting of the valve allowing cooling material to flow through it) is called the manipulated variable since it is subject to control actions. In practice, the temperature value is transmitted to the controller; the controller implements the functions and calculations, transmits the output to control the valve and issues alarm if there are faulty conditions. In the meantime, all data information can be archived for future reference when a review of process trends could provide additional improvements. By utilizing WSN technology, sensing and action devices will communicate wirelessly with an access point (e. g., a gateway or router), which is connected to the control station wirelessly or through wired methods (e.g., Ethernet, Modbus).

Problem Definition

Consider the case when we have deployed a sensor network consist of N sensors at locations
S = {S1, S2,…….,SN}.
Let Sx i refer to the x-coordinate of the location of sensor i and let Sy i and Sz i refer to the y and z coordinates, respectively. Constraining Szi to be 0 suffices the 2D version of this problem. Determining these locations constitutes the localization problem. Some sensor nodes are aware of their own positions, these nodes are known as *anchors* or *beacons*. All the other nodes localize themselves with the help of location references received from the anchors. So, mathematically the localization problem can be formulated as follows: given a multihop network, represented by a graph G = (V, E), and a set of beacon nodes B, their positions {xb, yb} for all b ε B, we want to find the position {xu, yu} for all unknown nodes u ε U.

Related Work

Localization in WSN is an active area of research and so there are some existing literature surveys [23], [24] on this topic. In these literatures the authors discuss most important localization techniques and critique those techniques. But there are some existing techniques which use two localization techniques such as multidimensional scaling (MDS) and proximity based map (PDM) [16] or MDS and Ad-hoc Positioning System (APS) [17]. These techniques have not been mentioned in any literature but these techniques give new directions in WSN localization as these schemes give high accuracy in low communication and computation cost. On the other hand interferometric ranging based localization has been proposed in [18], [19], [20] which have not been discussed by any existing literature.

Moreover due to channel fading and noise corruption error propagation comes in picture. To suppress this error propagation a localization scheme has been proposed in [21] which was not been discussed by any literature. This literature gives comprehensive summary of these techniques along with other existing localization schemes. At the same time this paper also compares all localization techniques and also provides future research directions in this area.

Different Location Discovery Approaches

Existing location discovery approaches basically consists of two basic phases: (1) distance (or angle) estimation and (2) distance (or angle) combining. The most popular methods for estimating the distance between two nodes are described below:

Received Signal Strength Indicator (RSSI): RSSI measures the power of the signal at the receiver and based on the known transmit power, the effective propagation loss can be calculated. Next by using theoretical and empirical models we can translate this loss into a distance estimate. This method has been used mainly for RF signals. RSSI is a relatively cheap solution without any extra devices, as all sensor nodes are likely to have radios. The performance, however, is not as good as other ranging techniques due to the multipath propagation of radio signals. In [26], the authors characterize the limits of a variety of approaches to indoor localization using signal strengths from 802.11 routers. They also suggest that adding additional hardware or altering the model of the environment is the only

Time based methods (ToA, TDoA): These methods record the time-of-arrival (ToA) or time-difference-of-arrival (TDoA). The propagation time can be directly translated into distance, based on the known signal propagation speed. These methods can be applied to many different signals, such as RF, acoustic, infrared and ultrasound. TDoA methods are impressively accurate under line-of-sight conditions. But this line-of-sight condition is difficult to meet in some environments. Furthermore, the speed of sound in air varies with air temperature and humidity, which introduce inaccuracy into distance estimation. Acoustic signals also show multi-path propagation effects that may impact the accuracy of signal detection.

Angle-of-Arrival (AoA): AoA estimates the angle at which signals are received and use simple geometric relationships to calculate node positions. Generally, AoA techniques provide more accurate localization result than RSSI based techniques but the cost of hardware of very high in AoA.

Hyperbolic trilateration: The most basic and intuitive method is called hyperbolic trilateration. It locates a node by calculating the intersection of 3 circles.

Triangulation: This method is used when the direction of the node instead of the distance is estimated, as in AoA systems. The node positions are calculated in this case by using the trigonometry laws of sines and cosines.

Maximum Likelihood (ML) estimation: ML estimation estimates the position of a node by minimizing the differences between the measured distances and estimated distances.

Advantages

WSNs bring several advantages over traditional wired industrial monitoring and control systems as expressed in the following:

No Wiring Constraints

Wireless sensor nodes are installed on industrial devices and equipments to monitor the measurements such as proximity, temperature, pressure, level, and power quality, and to transmit/receive control signals for activating the device accordingly. Without the wiring constraints, devices can be utilized in applications that previously are either physically unreachable or cost prohibitive. For example, adopting wireless transmission greatly reduces the complexity of implementing monitoring and control devices for rotary equipments. Furthermore, the industrial process system becomes highly scalable and flexible due to the device autonomy.

Easy Maintenance

After the installation of wired device, control engineers have to deal with various wiring maintenance problems such as corrosion, water in the conduit, burned cabling, freezing, wild animal damage, physical wear caused by frequent movement of instrumentation, and unexpected power outage. Wireless device is almost care-free, only a battery change is necessary after years of operation. In addition, it is also possible to relocate current wireless devices or deploy additional wireless devices on the control system after it has been installed with minimal changes to the existing configuration.

Reduced Cost

Cabling and installation for an automation project in an existing facility can run as high as 80% of total system cost and can exceed $1,000 per linear foot in regulated environments, like a typical power plant [12]. Going wireless eliminates the wiring, conduit and installation cost. What's more, for some applications, sensing nodes can put their radio in off mode when necessary, this will save lots of energy compared to wired devices, which requires constant power supply.

Better Performance

Industrial WSNs have the potential to outperform the existing process control network with wired devices. Firstly, it has higher data transmission speed. For example, the most popular control protocols HART (Highway Addressable Remote Transducer) has a data rate of 1.2 kbps and FF (Foundation Field bus) has a data rate of 31.25 kbps, while Wireless Hart has a data rate of 250 kbps based on the IEEE 802.15.4 standard. Secondly, unlike wired control systems, where devices share a single bus, multiple wireless communications can act simultaneously if there is no mutual radio interference [3]. Thirdly, more sensors/data points can be used to beat the performance of traditional wired control system.

Challenges and Solutions

Quality of Service: Class 5: Monitoring without immediate operational consequences.

Class 4: Monitoring with short-term operational consequences
Class 3: Open-loop control
Class 2: Closed-loop, supervisory control
Class 1: Closed-loop, regulatory control
Class 0: Emergency action

Network Topology:

The network topology is the backbone for any network based systems. When choosing the communication topology for a WSN, in addition to the responsiveness and reliability discussed in Section 7.1, the following aspects need to be considered according to different scenarios: connectivity, adaptability, mobility, and scalability.

TABLE I. INDUSTRIAL WSN PRODUCTS

Company	Accutech	Honeywell	Emerson
Example application	Pressure, temperature, level measurement, discrete input	Pressure, temperature, level, position measurement, discrete input/output	Pressure, temperature, level, position, vibration measurement, discrete input
Communication Technology	Star Point to Point Communication - Base station that transmits and receives data from multiple field units	Star Mesh Network - The Honeywell OneWireless network is formed with mutli-protocol communication nodes, called multinodes, which support both 802.11 and field sensor-based transmissions.	Mesh Network The Dust Mesh network with self healing and self organization features.
Transmission Technology	900MHz Frequency Hopping Spread Spectrum (FHSS)	2.4 GHz Frequency Hopping Spread Spectrum (FHSS)	2.4 GHz Direct Sequence Spread Spectrum (DSSS)
Maximum Transmit/Receive Range	Up to 5000ft (~1500m)	Up to 6 miles (10 km) multinode to multimode communication; sensor to multinode designed for over 2,000 ft (600m)	200m
Fastest Update Time	1 second	1 second	4 second
Wireless Standard	Uses proprietary protocol	ISA100.11a	WirelessHart
Number of Field Units per Network	Up to 100 wireless field units per base radio	Each multinode accepts signals from up to 20 wireless transmitters reporting at 1 second, and up to 400 transmitters reporting at slower rates.	Up to 100 devices for a single wireless gateway
Gateway Interface	Modbus	802.11 Wi-Fi	Ethernet, Modbus

There exist three types of network topology for industrial WSN applications: star, star mesh and mesh. In star network, each node has a designated forwarding path. If there is a failure between two nodes, the information is lost, so that site surveys and link-level configuration are performed during system installation. Compared to star network, star mesh network has increased adaptability, mobility, and scalability by providing multiple routing nodes but they do not offer full end-to-end redundancy. In mesh network, each end nodes are also routing nodes, so that all nodes are fully connected to provide full redundancy. The self organizing and self healing features make the mesh network highly adaptive to node failures/relocation and easily scalable for network expanding. Only for mesh network can a new node be added anywhere without sophisticated site surveys as long as it is within transmission range of at least two other nodes. It requires less manual configurations for each node and provides greater expandability when more nodes are to be added in the future. This makes it a more suitable choice for deployments that are subjected to changes. The drawback is that extra delay and processing time is introduced due to multiple hops and paths.

Resources

The architecture of a wireless node for process monitoring and control is shown in Fig. 2. For the design of this device, there exist multiple resource limitations, such as processing power and memory limitation, bandwidth limitation, and constrained energy capacity.

 ISSN: 2277-9655

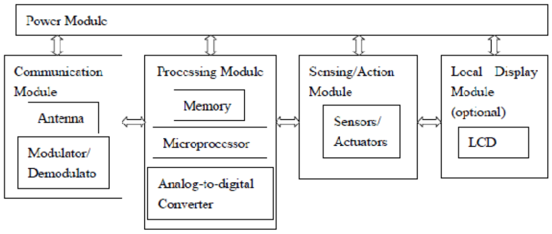


Figure 2. The architecture of a wireless node for process monitoring and control

Hardware limitation: As shown in Fig. 4, the processing module supports the operation system, the network protocol, and handles the data processing and control algorithms. The selection of the microprocessor is critical to the whole design. The ideal microprocessors are those that have large memory and powerful computation capability, consume ultra-low power, and are also energy efficient. An introduction and comparison of available microcontrollers can be found in [25]. [26] Provides an interesting heterogeneous multiprocessor sensor node with staged wakeup to keep the device energy efficient. As the technology advances, it is promising to have powerful processor and large memory in the sensor nodes with reduced cost.

Bandwidth limitation: Sensor nodes may provide significant redundant data, for example, multiple signals generated from two or more temperature monitoring nodes, or from different sampling period of the same sensing unit. Similar data information can be aggregated by certain functions such as duplicate suppression, minima, maxima, and average to reduce the number of transmissions. Thus, data aggregation is a good technique to achieve required. Network capacity within the limited bandwidth [5]. By aggregating multiple packets into one packet, the network through will be increased with the reduced overhead for each packet, the drawback is that may introduce extra delay. Coding is also applied in data transmission to increase network capacity [27][28]. Furthermore, it is mentioned in [29] that instead of transmitting the raw data, only the processed data such as estimation results are transmitted over the WSNs.

Conclusions

WSN is a technology with promising future and it is presently used in a wide range of applications to offer significant advantages over wired system. However, WSN technology is not considered mature enough to be widely implemented in process control applications. The demanding constraints for process monitoring and control applications pose many challenges to the implementation of WSNs to the industrial field. In this paper we have surveyed various issues relating to implementing the WSN technology to process monitoring and control. Future research and development may continue to be focused on further improvements of the reliability and responsiveness, and technology advancements on energy saving, power management, fault tolerance, and smart routing. In addition, software tested can be developed to evaluate various functions of WSNs such as the self organization, self healing capability.

It may also be commercialized as an adds-on software component to evaluate the overall system performance, predict potential problem, and provide suggestions for meeting the desired customer selectable criteria based on the existing system performance. Also, control over wireless is still an emerging research area. The usage of WSN technology within feedback control loops raises lots of challenges to be explored.

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