ZigBee-based Positioning and Navigation System for Robot

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Abstract

At present, the research on the technology of mobile robot navigation is under the spotlight. This paper introduces ZigBee technology into mobile robot’s research, and constructs an experimental system for robot navigation based on ZigBee wireless sensor network localization technology.

In this system, robot added a ZigBee module takes the position as a blind node in ZigBee network, which forms a wireless location network, together with other ZigBee reference nodes. Combined with several other algorithms like robot obstacle avoidance algorithm and navigation algorithm, it realizes the position and navigation of mobile robot. The experiment result shows that the ZigBee-based robot position and navigation method discussed in this paper can meet the requirements of mobile robot navigation applications.

Keywords: ZigBee, Mobile Robot, Positioning, Navigation

1. Introduction

Mobile robot is a complex system which rounds up a set of functions, such as environmental awareness, dynamic decision-making, behavioral control and implementation and so on. In the study and application of the robot, its position and navigation is the most basic and important issue, and it is one of the key technologies to achieve real intelligent and completely autonomous mobile robot.

Wireless Sensor Networks (WSN) is constituted by a large number of low-cost micro sensor nodes which are arranged in the monitoring area, forming a multi-hop self-organization network through wireless communication. Therefore, the nodes can collaboratively perceive, collect and process the object’s information in the coverage area of the network, then send it to the observers. ZigBee-WSN technology will expand the perception realm of mobile robot, and provide a new way for robot’s localization and navigation.

This paper combines the advantages of ZigBee-WSN and mobile robot to build a ZigBee-based position and navigation system of mobile robot. In the environment of WSN, this system extends robot’s perception by ZigBee technology, to locate robot accurately and then navigate it.

1.1. ZigBee-WSN overview

WSN is composed of a large number of small sensor nodes. It monitors the object’s real-time information through various micro-sensors, which will be processed by the embedded computing resource and be transmitted to remote users via wireless communication network.

The framework of WSN system is as shown in Figure 1, which generally includes sensor nodes, sink node and management node. Sensor nodes are placed in the examination area and constitute network in a form of self-organization. The data of a sensor node monitored will be transmitted hop by hop along other sensor nodes after preliminary treatment by itself. During the transmission, the data may be multi-processed, spreads to sink node through many hops and finally reaches the management node through the Internet.
Sensor node is usually an embedded system, its processing power and storage capacity are relatively weak, and its communication distance is quite limited. Sink node usually has a strong processing power, storage capacity and communications capabilities. It can be either an enhanced sensor node which has sufficient energy supply, more memory resources and computing power, or a particular gateway device with wireless communication interface. Sink node connects WSN with the external network, achieves the communication between management node and WSN through the protocol conversion. Accordingly, the data collected can be forwarded to the external network, and simultaneously the tasks submitted by management node will be posted.

ZigBee is a new technology of WSN deployment. It is a wireless network technology focusing on low power, low cost, low complexity, low-rate and short-range wireless communications.

ZigBee protocol defines several layers. Each layer is responsible for its own duties and provides services to the upper. Complete ZigBee protocol is constituted by high-level application specification, application layer, network layer, data link layer and physical layer. Its physical and MAC layer adopt IEEE802.15.4 standard, but improved and expanded on that basis. Its network layer, application layer and high-level application specification drafted by the ZigBee Alliance.

According to the protocol, its frequency band is divided into three bands, which are 868MHz, 915MHz and 2.4GHz, the modulation mode and transmission rate on each band are different. 2.4GHz frequency band is divided into 16 channels and its data rate is 250kbps. The channel numbers of 868/915MHz band are correspondingly 1 and 10, transmission rates are 20 and 40kbps.

The main features of ZigBee technology are following:

a) Low data rate. Only 10kbps ~ 250kbps, focus on low-transmission applications.

b) Low power consumption. In the low power standby mode, two common 5 V batteries can sustain more than 6 months.

c) Low cost. Both low data rate and simple protocol reduce the cost greatly.

d) Large network capacity. Each ZigBee network can support at most 255 devices, which means each ZigBee device connects with other 254 devices.

e) Low delay. Delay is usually 15 ~ 30ms.

f) Small effective range. Its effective coverage ranges from 10 to 75 m, depending on the actual transmission power and application pattern.

1.2. Mobile robot overview

Mobile robot is a kind of intelligent robot with highly self-planning, self-organizing and adaptive capacity, which is suitable for working in complex unstructured environments. As one of the important robot branches, mobile robot’s combination and formation are of great flexibility because of its autonomy and mobility. And this gives it greater flexibility and adaptability of applications.

In order to achieve autonomously move, mobile robot must have accurate perception, reliable navigation and good movement system. The key technology involves sensing technology, navigation and positioning technology, mechanical design, motion control, architecture, smart technology and so on. Among which, the navigation is a vital issue in the research of
autonomous mobile robots, and critical to achieve a real intelligent and fully autonomous mobile robot.

Currently, technologies used in location and navigation of autonomous mobile robots can mainly be divided into two categories: (1) Robot itself records the movement by sensors like code discs, electronic gyroscopes and accelerometers, calculating the current location by integrating. (2) Determine the relative position of the robot and the environment by radar, laser range finder, image matching, etc. and then get the location. However, because of the strong mobility and modeling difficulty of mobile robot, the error accumulated in the first method has greater impact on the positioning accuracy. The second approach is of high cost and needs for additional expensive ancillary equipment.

1.3. Integrate ZigBee with mobile robot

WSN can continuously monitor a wide range of the environment, but its data processing and execution ability is quite limited. Mobile robots are with strong computing power and mobility, but their limitations of perception restrict their intellectual development. In view of their respective advantages and characteristics of ZigBee-WSN and mobile robot, people began to seek a combination to form a new system of distributed sensing and control network.

Integrate ZigBee with mobile robot can enhance the robot's perception ability and the sensor network's control to environment. ZigBee can, not only provide global real-time awareness for the mobile robot, but also be a medium between calculation and communication. Meanwhile, mobile robot can be a flexible executor to manage and maintain the network.

Thus it is clear that the research on ZigBee-based mobile robot navigation is of great significance.

2. System framework overview

ZigBee-based mobile robot navigation system is mainly constituted by three components: WSN used for navigation, navigated mobile robot and ZigBee network coordinator. The framework of system is as shown in Figure 2.

ZigBee-WSN consists of many ZigBee wireless sensor nodes with location ability, which are bestrewed in the robot work area, as reference nodes of the network with CC2430 module. Reference node is a known static node; its coordinate \((x, y)\) is fixed, and has no position calculation function.

Mobile robot is a special featured node in WSN, carrying the wireless communications and positioning module, as blind node of the network with CC2431 module. Blind node is a kind of mobile node, which can make any movement in the area encircled by reference nodes, and blind node must use CC2431 chip. The difference between CC2431 and CC2430 is that CC2431 has a wireless location engine, which can calculate the location of the blind node in network to achieve Received Signal Strength Indicator (RSSI)-based positioning. In other words, blind node automatically receives RSSI from the reference nodes, runs location algorithm automatically with these RSSIs, and finally calculates its own position \((x, y)\).
When robot locates itself, it will enable its navigation algorithm and behavior control program to conduct path planning and behavior operation. ZigBee network coordinator serves as the gateway, responsible for the services and coordination of the wireless network. It can connect with the monitoring terminal (PC) by wired or wireless means. Mobile robot’s coordinate is sent to the monitoring terminal by the gateway, and the terminal controls the behavior of mobile robot through the gateway. In addition, the binding table, routing tables and equipment information can be stored in PC, to reduce the burden on the coordinator and improve network efficiency.

3. Key algorithms

3.1. Node localization

In applications of WSN, location information is very important for monitoring network activities, determining the location of the incident and collecting data are two basic functions of WSN.

According to the need for measuring the actual distance between nodes when locating, the location algorithms can be divided into distance-measured location and non-distance location. The former uses actual distance to calculate the location of unknown node, by measuring the distance or the location information between sensor nodes; the latter has no need to measure the actual distance between nodes, it estimates the distance between nodes and calculates the location only by the network connectivity and other information. Non-distance location has nothing to do with the actual distance and orientation, which reduces the hardware requirements of the node. But its positioning accuracy is relatively low. Distance-measured location can provide high positioning accuracy.

At present, the commonly used distance-measure technologies are RSSI, TOA (Time of Arrival), TDOA (Time Difference of Arrival) and AOA (Angle of Arrival). In which, RSSI has advantages of easy realization and low cost, its positioning accuracy is up to 3 m.

The basic principle of RSSI-based location is: knowing the signal strength of sending node, the receiving node can calculate the transmission loss according to the RSSI. Then it will transform transmission loss into distance by use of theoretical or empirical model, and use the existing location algorithm to calculate the location of the node. Details see reference [4].

This paper uses the location engine embedded in CC2431 to locate nodes according to the distances. This engine uses Motorola wireless RSSI-based positioning method. In this method, 3~8 nodes with known address are as reference nodes, which locate the location of the address unknown node. The schematic diagram is as shown in Figure 3-1-1.

![Figure 3-1-1. RSSI location schematic diagram](image)

First, all the nodes in the network communicate with their neighbors, blind node receives the RSSIs and coordinates of its neighboring reference nodes. Then blind node computes its distances from the reference nodes according to the RSSIs received. RSSI is a function of the TX power and the distance between the sender and receiver, the relation is as formulae (3-1):

\[
RSSI = -(10n\log_{10}d + A)
\]  

(3-1)
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Here, \( d \) is the distance between transmitter and receiver; \( A \) is defined as the absolute value of the average power in dBm received at a close-in reference distance of one meter from the transmitter; \( n \) is defined as the path loss exponent that describes the rate at which the signal power decays with increasing distance from the transmitter. The actual parameter \( n \) value written to the Location Engine is an integer index value named \( N \), their mapping table could be found in reference [2].

Finally, after obtaining the distances from the reference nodes, the blind node uses Maximum Likelihood Estimation Method (see reference [4]), to calculate the coordinates of itself. The Maximum Likelihood Estimation Method is as shown in Figure 3-1-2.

**Figure 3-1-2. Maximum Likelihood Estimation Method**

Set: the coordinates of \( m \) reference nodes are: \((x_1, y_1), (x_2, y_2), (x_3, y_3), \ldots, (x_m, y_m)\), their distances to the blind node \( D \) are respectively \( d_1, d_2, d_3, \ldots, d_m \), the coordinates of blind node \( D \) is \((x, y)\).

According to the distance formula between two points, the relationships between nodes are as follows:

\[
\begin{align*}
(x-x_1)^2 + (y-y_1)^2 &= d_1^2 \\
&\vdots \\
(x-x_m)^2 + (y-y_m)^2 &= d_m^2
\end{align*}
\]  

(3-2)

Minus the former \( n-1 \) formulas with the No.\( n \) respectively, getting the following equation set:

\[
\begin{align*}
x_1^2 - x_m^2 &= 2(x_1 - x_m)x + y_1^2 - y_m^2 - 2(y_1 - y_m)y = d_1^2 - d_m^2 \\
&\vdots \\
x_{m-1}^2 - x_m^2 &= 2(x_{m-1} - x_m)x + y_{m-1}^2 - y_m^2 - 2(y_{m-1} - y_m)y = d_{m-1}^2 - d_m^2
\end{align*}
\]  

(3-3)

The equation set can be expressed as: \( AX = B \)

Here

\[
A = \begin{bmatrix}
2(x_1 - x) & 2(y_1 - y) \\
2(x_2 - x) & 2(y_2 - y) \\
& \vdots \\
2(x_m - x) & 2(y_m - y)
\end{bmatrix}
\]  

(3-4)

\[
B = \begin{bmatrix}
(d_1^2 - d_m^2) - (x_1^2 + y_1^2) + (x_m^2 + y_m^2) \\
(d_2^2 - d_m^2) - (x_2^2 + y_2^2) + (x_m^2 + y_m^2) \\
& \vdots \\
(d_{m-1}^2 - d_m^2) - (x_{m-1}^2 + y_{m-1}^2) + (x_m^2 + y_m^2)
\end{bmatrix}
\]  

(3-5)

\[
X = \begin{bmatrix}
x \\
y
\end{bmatrix}
\]  

(3-6)
Use the least square method to compute the \( X \) estimates: \( \hat{X} = (A^T A)^{-1} A^T B \), obtaining the estimated coordinates of the node \( D = (x, y) \).

3.2. Navigation algorithm

In the research of mobile robot navigation system, there are two major problems: positioning and path planning. The RSSI-based positioning algorithm mentioned above provides location information for the robot in unknown environment, which means it has solved the positioning problem. In addition, the robot hardware platform-AS-UIII intelligent mobile robot adopted by this experiment, which comes with a collision sensor, can avoid obstacle when moving. This paper combines the above two technologies, figuring out a simple navigation algorithm.

Robot can get its coordinates at any time from the wireless location module during locomotion, and determine its travel direction by comparing with the target coordinates. If the robot encounters obstacles in the locomotion process, its collision sensor will be triggered, and it will automatically change the direction to avoid obstacles, and then re-obtain its current coordinates to determine the direction of travel. Repeat this process until the robot reaches the target. In addition, the robot's current direction can be evaluated by the two consecutive coordinates measured.

The principle of navigation is shown in Figure 3-2-1, the WSN area covered by eight reference nodes is a 64×64 square, and the blind node (blue dots) can make any move in it. The red dot represents the target, its coordinates \( (M,N) \) is set in the behavior control program.

![Figure 3-2-1. Navigation algorithm schematic diagram](image)

Suppose the two consecutive coordinates measured by blind node were \( (X,Y), (X',Y') \), then the current direction can be considered as angle \( \beta \) with the \( X \) axis as marked in the diagram. According to the latest coordinates \( (X',Y') \) and the target coordinates \( (M,N) \), we can compute the next direction should be angle \( \alpha \) with the \( X \) axis as shown, and then we get the angle robot should turn \( \theta = \alpha - \beta \).

When selecting the next direction of travel, this method uses the real-time environmental information of the WSN. So, it can be applied to robot navigation system in dynamic environment.

4. System implementation

4.1. Hardware design of system

4.1.1. Hardware design of ZigBee network
The ZigBee-WSN designed in this paper is constituted by three parts: network coordinator, reference nodes and blind node. Apply ZigBee/802.15.4 wireless SCM (Single Chip Micyoco) development system of C51RF-CC2431-ZDK Series as the hardware platform.

Network coordinator includes a backplane and a CC2430 RF ZigBee module. On the backplane lays graphic and Chinese characters LCD, keyboard, ZigBee module interface of CC2430/CC2431, adjustable resistor, LED, power and RS-232 interfaces. The reference nodes and blind node respectively use ZigBee wireless modules with CC2430/CC2431 chip. SCH (Schematic diagram) of designing them are shown as (a) (b) (c) in Figure 4-1-1.

![Figure 4-1-1. 3 nodes’ SCH of ZigBee network](image)

The CC2430/CC2431 chip integrate CC2420 RF receiver, enhanced 8051 MCU and 8KB RAM. What’s more, CC2430/CC2431 has DMA (Direct Memory Access), programming watchdog timer, AES (Advanced Encryption Standard)-128 security protocol processor, 8 to 14-bit ADC, USART, sleep timer, power on reset, brownout detect and 21 programmable I/O. Additionally, CC2431 has a Motorola’s location engine. So, in ZigBee-based positioning system, CC2430 module can only be used as a reference node, while the CC2431 module can either be a reference node or a blind node.

4.1.2. Hardware platform of mobile robot

The object of this position and navigation system is GuangMaoDa's AS-UIII intelligent mobile robot. AS-UIII is equipped with collision sensors, infrared sensors and other sensors, and it can also expand vision sensors and range sensors, with a strong perception on the environment.

In order to achieve the ZigBee-based position and navigation system proposed by this paper, instead of using the AS-UIII vision and ranging sensors during the experiment, we only take the AS-UIII as a program-controlled mobile robot platform.

Three main components of the mobile robot are the main controller, wireless communication module and motion-control sensing module. Framework of the mobile robot system is as shown in Figure 4-1-2.

![Figure 4-1-2. AS-UIII structure sketch](image)
Motion-control sensing module is responsible for transmitting the information collected by each sensor to main controller, receiving the command from main controller, and controlling the rotation of the motors. The collision sensors contribute to obstacle avoiding by getting local obstacle information.

AS-UII uses NXP's LPC2132 MPU as the core for control. LPC2132 is based on a 32/16-bit ARM7TDMI-STM CPU which supports real-time emulation and embedded tracing. With a high-speed 64 kB Flash memory embedded, it can provide a huge buffer space and strong processing power. The main controller will process the information received from the motion-control sensing module and the wireless communication module, then return the corresponding results and orders.

The wireless communication module chooses Chipeon's wireless SoC-CC2431, which is not only responsible for the transceiving of data, but also computing the coordinates of blind node by its location engine. The wireless communication module is connected with the main controller through the ASBUS expansion card on AS-UII control panel.

4.2. Software design of system

4.2.1. Software design of ZigBee network

The software design of the network nodes is modularized into three layers, including hardware layer, software layer and application layer. The hardware layer is responsible for the collection of data, delivery of commands and localization. Its core is CC2430/CC2431 which is with an 8051 core and a RF transceiver in it. Software layer transplants the Z-stack to achieve the data processing and transmission. Application layer runs programs written by ourselves, including the positioning function, control to the robot, management of network data and so on.

The hardware layer of ZigBee wireless module on CC2430/CC2431 is compatible with 802.15.4/ZigBee. The MAC layer and physical layer protocols are up to IEEE802.15.4 standard; network layer and security layer is formulated by the ZigBee Alliance, provided in the form of library. Thus, the software design of the entire system is mainly about the implementation on AF (Application Framework) layer and APS (Application Support sublayer) layer. Next, the detailed design of the network nodes will be presented.

**Reference node:** Reference node is static and knows its own location, whose location in the region must be configured correctly. Its role in the system is to provide a packet with its own coordinates and RSSI to the blind node as a reference. Usually, location area is constituted by eight reference nodes, at least 3–4, the more reference nodes the higher the positioning accuracy. Reference nodes in the network are with routing function, using chip CC2430, Figure 4-2-1 is its flowchart.

![Reference node flowchart](image-url)
Blind node: Role of blind node in this system: Calculate its own coordinates by receiving all the RSSI of reference nodes in the region and applying location algorithm. As it involves computation of coordinates, chip in this node must be CC2431.

The flowchart of blind node is as shown in Figure 4-2-2. Blind node contacts its neighbor reference nodes to collect their coordinates and the RSSIs, and calculates its own location according to these information and input parameters ($A,N$), both of which have been mentioned in formulae (3-1). Then it will send appropriate information to the gateway, simultaneously to the robot control center through ASBUS expansion card to control the robot's movements.

![Blind node flowchart](image)

Figure 4-2-2. Blind node flowchart

Network coordinator: Coordinator (Gateway) is the central controller, all the valid data will be transmitted through it to the PC, reference nodes and blind node. Coordinator plays a vital role in the whole system, using chip CC2430. First Coordinator receives the configuration data of reference nodes and blind node provided by the monitoring software, and sends to the appropriate nodes in different ways. Secondly, it transmits the valid data feedback from nodes to the monitoring software. The flowchart of coordinator is shown in Figure 4-2-3.

![Coordinator flowchart](image)

Figure 4-2-3. Coordinator flowchart

4.2.2. Software design of mobile robot controller
The controlled members of the core controller involve a number of input parts and output parts. The import parts are primarily wireless communication modules and sensors, and the output parts are a variety of servo motor.

AS-UHII use hybrid programming environment VJC2.0 which integrates flowcharts and C language to develop High-level control procedures. VJC2.0 programming environment adopts graphical programming language VJC, providing a simple and powerful platform for the development of intelligent robot projects, procedures and algorithms. Developers can program either by the intuitive flow chart or by C language. To meet the requirements of the navigation, instead of using the existing software of AS-UHII, this paper develops its own control software in VJC2.0, realizing obstacle-avoiding for mobile robot on the basis of positioning and navigation.

The control program flow chart of mobile robot is shown in Figure 4-2-4. The implementation of this navigation algorithm is primarily based on the constant cycle operation of three modules as coordinate measurement, obstacle avoidance and angle rotation, and it will not stop until the robot reaches the target.

5. Experiment and analysis

This paper takes C51RF-CC2431-ZDK ZigBee wireless network/location system as the experiment platform, with integrated development environment IAR Embedded Workbench IDE. The programming environment of AS-UHII is VJC2.0. Experimental steps are as follow:

5.1. Build the hardware platform

Insert a CC2430 module into the network expansion board as the network coordinator, and connect it with PC through a RS232 serial port line, power on. This system sets 4 reference nodes as the reference for the location of blind node. For higher precision, the number of reference nodes can be increased to eight. Each reference node with CC2430 module should connect an antenna and install battery. Insert CC2431 module with an antenna on the ASBUS expansion card of AS-UHII, turn on the power.

5.2. Download program

In a location system, each node can only connect with one coordinator (gateway) to constitute a network. It will go wrong if equipment has joined the other networks. To avoid such case, we should first initialize the physical address of all nodes. Open the project in IAR and
program three modules: coordinator, the reference node and blind node. Connect one side of C51RF-3-ZDS emulator with computer through the USB, the other side with one node module, so that the appropriate program can be downloaded to this module. After downloading, set an unique non-default IEEE address for each node, no repetition between any two nodes.

The high-level control program of robot can be downloaded through VJC2.0. Before downloading, connect the computer with robot by USB.

5.3. Draw map of the monitoring scope

In this system, the map can be set and modified through software, monitored object and its location can be visually seen through PC. The map is drawn in mapping software. Load the map into the monitor software—Z-Location Engine (see reference [2]), after it is finished.

5.4. Position reference nodes and blind node

Reference nodes should be settled according to the actual distance; the more accurate the distance calculated the higher positioning accuracy. It would be best to settle the blind node within the range built by reference nodes. Each node must be placed with the cooperation of monitoring software according to its coordinates, which are set by the monitoring software. Ensure that the actual riding positions of the reference nodes are the same with that on the map. And the blind node (robot) will be detected automatically after power on.

5.5. System debugging

The above steps have constructed the environment of the positioning and navigation system, the next is debugging this system. Place the robot in ZigBee network, after the blind node appears in monitoring software, set the two parameters \( A \) and \( N \) of blind node. Then start the robot, the position variation of blind node (robot) can be seen in the monitoring software.

5.6. Results and analyses

The test site is a 10.5m*5.25m square area, taking the northwest corner of it as the origin of coordinates. Put one reference node at each corner of this field. The coordinates are (0, 0), (0, 5.25), (10.5, 0) and (10.5, 5.25). The navigation task is that the mobile robot should move from coordinates (0, 1) to (10.5, 5.25), avoiding obstacles in the environment. Robot’s locomotion path is as shown in Figure 5-1. In the figure, the distance between each grid is 10m; the black box here stands for artificially constructed environmental barrier.

![Figure 5-1. Robot’s walking path with obstacle avoiding](image)

This experiment shows that the ZigBee-based location and navigation method put forward by this paper can fulfill the navigation task successfully, meeting the requirements for the navigation applications of mobile robot. However, after many experiments, it turns out that the paths of robot are not totally the same and sometimes the location where it stops is not accurate.
This indicates that some errors exist in the system. In this regard, some further research is in need.

6. Conclusion

This paper presents and discusses a kind of location and navigation approach based on ZigBee. The blind node is developed on our own, which combines mobile robot with wireless location module, to construct the ZigBee-based navigation experimental system for mobile robot. Finally, we conduct an experiment and verify that this location and navigation system can meet the requirements of mobile robot navigation.

7. References

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