A Distributed UWB-based Localization System in Underground Mines

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Abstract—The location of people, mobile terminals and equipment is highly desirable for operational enhancements in the mining industry. In an indoor environment such as a mine, the multipath caused by reflection, diffraction and diffusion on the rough sidewall surfaces are the main sources of range measurement errors. In this paper, a UWB time of flight based localization system is proposed to address the multipath effect in underground mines. To reduce the communication cost and time delay of localization in such a chain type wireless network, a distributed localization algorithm based on particle swarm optimization (PSO) is proposed and implemented on the blind node (the node to be localized). Without extra hardware needed, an accurate but low cost localization system has been achieved. Experimental results verify the proposed scheme.

Index Terms—Ultra Wideband; Wireless Sensor Networks; Localization; Particle Swarm Optimization; Underground Mines

I. INTRODUCTION

Underground mining operations are considered as hazardous industrial activity because of the poor ventilation/visibility, the danger of collapse/gas explosion, and the presence of toxic gas. Accidents often happen and cause severe casualty and capital lost. It is of great significance to establish advanced monitoring system, which can obtain the real-time information about the miners and the environment, especially the real-time location of the miners, to safeguard them in case of emergency.

In emergencies wireless communication may become vital for survival, for example, during a disaster (such as a fire, rock falls), the conventional wired communication system may become unreliable, necessitating a wireless radio system. In fact, the idea of using wireless underground sensor networks, can be traced back to [1]. The utilization of WSNs to implement the monitoring system benefits from rapid and flexible deployment. Additionally, the multi-hop transmitting method conforms to the mines structure and provides more scalability for system construction. Another important reason for choosing WSNs to monitor mines is that it can also be used to localize the miners or equipments, where infrastructures needed for other localization method such as Global Position System (GPS) are not available.

The Ultra Wideband (UWB) technology has been the subject of extensive research in last two decades. It has emerged as promising candidate for many wireless personal area network (WPAN) applications, sensor networks and ubiquitous computing. It has been also selected as a viable candidate for precise ranging and geolocation, due to the high time resolution (large bandwidth) of UWB signals, which enables accurate Time of Flight (TOF) measurement between nodes [2].

In this paper, we focus on designing localization system based on UWB wireless sensor networks in underground mines, however, it can be also generalized to different underground environments such as, underground city, tunnels, subway, etc.

The remainder of the paper is organized as follows: Section 2 reviews the localization techniques in mining industry. A UWB time of flight based localization algorithm is proposed in Section 3. Section 4 details the localization scheme and the implementation of the system. Section 5 demonstrates the experimental results and conclusions are presented in Section 6.

II. LOCALIZATION TECHNIQUES IN MINING INDUSTRY

A. Traditional Localization Method

The traditional localization techniques are based on a procedure of manual reporting of miner’s location (i.e., using talky–walky). However, the precision are limited to the knowledge of the level, gallery name, segment or section number where the miner is located. Infrastructure based wireless techniques, such as RFID, 802.11, are reported for localization in mine [3-5]. However, the precision depends on the deployment of RFID readers or access points, and the cable part makes the localization system less scalable.

B. Wireless Sensor Network Based Localization Schemes

Another kind of wireless network, ad-hoc wireless sensor network, has attracted extensive interests for monitoring in underground mines, due to its low cost, flexibility, and the capability of localization service. In this paper, we focus on the localization function of WSN.
Localization in WSNs refers to estimating the location of a target node (a node with unknown location, i.e. a blind node) according to the relationship between itself and several anchor nodes (nodes with known location). It has received considerable attention, as data collected from sensors makes sense only if the location of those sensors is known, and sometimes the location itself is the information of interest, such as the asset localization, target tracking etc[6].

Underground mine is a quite special indoor environment, with lengths of tens of kilometers and widths of several meters. WSNs deployed there are usually line or chain type networks with low density. Data transmission from sensor nodes to central server costs more energy because of the multi-hop manner. The network topology is dynamic with the advance of production. The surface of the tunnels is usually rough and the multi-path effect of radio propagation is severe. These factors make underground mines quite challenging environments for WSNs localization application.

With regard to the mechanisms used for estimating location, localization based on WSN can be divided into two categories: range-based and range-free. Reference [7] provided an extensive review of range measurement techniques and algorithms for WSN localization.

1) Range-based Localization Schemes

Range-based localization schemes consist two steps: 1) measurement of the relative distances or angles between the blind node and the anchor nodes; 2) estimation the position of the blind nodes with the information collected in the first stage. Several techniques have been researched for physical distances/angles measurement in WSN, such as the Angle of Arrival (AOA), the Received Signal Strength (RSS) and the Time Of Arrival (TOA) etc. In the second stage, trilateration or triangulation algorithms are often used to calculate the position of the target node. We will discuss it in section 3.

The necessary of antenna arrays for AOA mechanisms makes it unpractical to implement while maintaining the low-cost demands of node. RSS is considered as useful information to estimate the distance, because it is a mandatory standard in IEEE 802.15.4, which means every node can get RSS when receiving a package, without additional hardware required. It has been used in underground mines [8, 9]. The main challenge is that the RSS ranging method relies on a path loss model, which is very sensitive to the channel parameters, especially to multipath channel in indoor environment. TOA method measures the time of the flight of acoustics or radio signals, and then the distance between the two nodes can be calculated because the speeds of acoustics and radio in the air are known as constants. Acoustic TOA method can get sub-meter accuracy at the cost of additional acoustic hardware requirement on the node [10]. With the same transceiver used for communication, Radio Frequency Time of Flight (RF-TOF) is preferred for ranging in WSN. In narrowband systems, measuring RF-TOF requires accurately resolving the phase offset of a signal. Ref. [11] proposed a method for pair-wise ranging called code modulus synchronizing that did not require either mote to determine the absolute phase offset of system clocks, the correlation function or the TOF in real time. Meter level accuracy could be obtained even in coal mine environment. Jennic embedded a 2.4GHz TOF engine on a SoC JN5148 [12], which could enable a low cost localization system be included on wireless sensor nodes [13].

UWB has been regarded as an ideal candidate for accurate indoor localization application due to its excellent time domain resolution, multipath immunity, and simultaneous ranging and communication capability. Commercial indoor UWB positioning system already exists. A precision-location UWB system has been developed which achieves sub-meter accuracy with Time Difference Of Arrival (TDOA) range measurement [14]. Combining TDOA with AOA measurement, Ubisense’s precise location system [15] can achieve 15-cm accuracy. However, the high accuracy was achieved in a much smaller coverage because of the synchronization requirement of the anchor nodes. Ref. [16] carried out a feasibility study of using UWB based-WSN as a future solution for localization in underground mines. In 2013, DecaWave company published a low cost UWB chip DW1000 [17], which could provide 10cm ranging accuracy. In this paper, we propose an accurate, low cost, large scale UWB localization system in underground mine based on this chip.

2) Range-free Localization Schemes

In order to address the multipath channel character and the None Line of Sight (NLOS), range-free localization scheme are also proposed in underground mines, such as DV-hop [18], weighted centroid localization [19] and fingerprinting scheme (or pattern recognition technique) [20, 21] etc. The former two connection-based might suffer from the localization precision due to the sparse character of WSN in underground mine. And the main disadvantage of fingerprinting method is the requirement that the training database should be large enough and representative of the current environment for accurate position estimation. It could be laborious or even impossible in practice in harsh dynamic underground mine environment.

III. UWB TOF-BASED LOCALIZATION ALGORITHM IN UNDERGROUND MINES

In this paper, we proposed a UWB TOF-based localization algorithm, which could be implemented in a distributed manner to improve the timeliness of localization and save energy. It consists of three stages: 1) the blind node finds out the anchor nodes in its communication range, and chooses three or four (corresponding to 2-dimensional or 3-dimensional localization scenarios) of them that are not on a line as reference nodes; 2) the blind node measures the distances between the reference nodes and itself, and 3) the blind node estimates its location according to the coordinates of the reference nodes obtained in the first stage and the distances measured in the second stage.
A. Discovery of the Localization Reference Nodes

After joining the network, the blind node broadcasts a localization request in its communication range and starts a waiting timer. The anchor nodes that received the request reply with their coordinates and network IDs. When the waiting timer expires, the blind node checks if there are enough anchor nodes that can serve as localization reference nodes (3 or 4, not on a line). If true, the blind node will start the ToF measurement; otherwise, the blind node will broadcast the localization request and start the waiting timer again.

B. Distance Measurement based on UWB ToF

In this stage, the blind node performs TOF measurement with the chosen reference nodes one by one, as shown in Fig. 1.

1) The blind node sends a Poll message addressed to the current reference node and notes the send time $T_{\text{SP}}$. The blind node listens for the Response message. If no response arrives after some period, the blind node will time out and send the poll again.

2) The reference node listens for a Poll message addressed to it. When the reference node receives a poll, it notes the receive time $T_{\text{RP}}$, and sends a Response message back to the blind node, noting its send time $T_{\text{SR}}$.

3) When the blind node receives the Response message, it notes the receive time $T_{\text{RR}}$ and sets the future send time of the Final response message $T_{\text{SR}}$, it embeds this time in the message before initiating the delayed sending of the Final message to the reference node.

4) The reference node receives the Final message and notes the receive time $T_{\text{RF}}$. Now the reference node has enough information to works out the TOF between the blind node and itself according to (1),

$$\text{TOF} = (T_{\text{RR}} - T_{\text{SP}}) - (T_{\text{SR}} - T_{\text{RP}}) + (T_{\text{RF}} - T_{\text{SR}}) - (T_{\text{RF}} - T_{\text{RP}}))/4 \quad (1)$$

5) The reference node reports the result to the blind node with ToF Report message. Multiplying the TOF by $c$, the speed of the light (and the radio waves), the blind node gets the distance between the current reference node and itself. This ranging algorithm does not require clock synchronization between the two nodes and the average of the four trips time removes the effects of each end’s clock frequency differences.

C. Trilateration Based on Particle Swarm Optimization

With the distances and the coordinates information of the reference nodes, the blind node now can calculate its own position (in 2 dimensional scenarios):

$$(x - x_i)^2 + (y - y_i)^2 = d_i^2, \quad i = 1, 2, \cdots, N \quad (2)$$

where $(x, y)$ is the coordinates of the blind node, $(x_i, y_i)$ is the coordinates of the $i^{th}$ reference node, $d_i$ is the measured distance between the blind node and the $i^{th}$ reference node, and $N$ is the number of the reference nodes. In 2 dimensional scenarios, $N$ needs to be greater than 2, while in 3D scenarios, $N$ needs to be greater than 3. And the reference nodes should not be on a line, or the solution of (2) is not unique.

This geometric technique, called trilateration, yields ambiguous solutions in the presence of range error in the system, since the circles defined by (2) may intersect at multiple points due to the erroneous distance measurement, as shown in Fig. 2. A popular statistical localization algorithm is the Nonlinear Least Squares (NLS) techniques, by which the location of the blind node is calculated as follows:

$$[x, y] = \arg \min_{(x, y)} s(x, y)$$

$$= \arg \min_{(x, y)} \sum_{i=1}^{N} \beta_i (\sqrt{(x - x_i)^2 + (y - y_i)^2 - d_i})^2 \quad (3)$$

where $s(x, y)$ is the cost function, $\beta_i$ represents a weight coefficient for the $i^{th}$ measurement, which commonly reflects the reliability of this measurement. The solution of (3) usually requires numerical search methods such as the steepest descent or the Gauss-Newton techniques, which can have high computational complexity and typically requires good initial value in order to avoid converging to the local minima of the cost function [7].

![Figure 1. UWB ToF ranging algorithm](image)

![Figure 2. Trilateration yields multiple intersections due to the distance estimation error](image)

To minimize the cost function, heuristic algorithms such as simulated annealing [22], Particle Swarm Optimization (PSO) [13], Bacterial Foraging Algorithm (BFA) etc. [23], were used in trilateration.
To reduce the computational complexity and enable the algorithm to be implemented in a distributed manner, a global version PSO algorithm is designed to estimate the position of the blind node. The algorithm is described as follows:

1) After obtaining coordinates of the reference nodes and the distances between the blind node and those reference nodes, the blind node can define a searching space for the current localization, shown as the dotted rectangle in Fig. 2, where

\[
\begin{align*}
    x_{\min} &= \min_{i=1,2,\ldots,N} \{ x_i - d_i \} \\
    x_{\max} &= \max_{i=1,2,\ldots,N} \{ x_i + d_i \} \\
    y_{\min} &= \min_{i=1,2,\ldots,N} \{ y_i - d_i \} \\
    y_{\max} &= \max_{i=1,2,\ldots,N} \{ y_i + d_i \}
\end{align*}
\]  

(4)

2) The blind node defines the fitness function as (3) and initializes M particles’ position according to (5),

\[
\begin{align*}
    x_j &= \text{rand}(1) \times (x_{\max} - x_{\min}) + x_{\min} \\
    y_j &= \text{rand}(1) \times (y_{\max} - y_{\min}) + y_{\min} \\
    j &= 1,2,\ldots,M.
\end{align*}
\]  

(5)

where \((x_j, y_j)\) is the position of the \(j^{th}\) particle, \(\text{rand}(1)\) generates a random number with uniform distribution in the range of \([0,1]\) and \(M\) is the number of the particles.

3) Each particle updates its position based on its own best exploration, the best swarm overall experience and its previous velocity according to the following model:

\[
\begin{align*}
    v_{p,j}(k+1) &= w \cdot v_{p,j}(k) + c_1 \cdot \text{rand}(1) \cdot [p_{Best,j} - x_{j}(k)] \\
               &+ c_2 \cdot \text{rand}(1) \cdot [g_{Best,j} - x_{j}(k)] \\
    v_{j}(k+1) &= w \cdot v_{j}(k) + c_1 \cdot \text{rand}(1) \cdot [p_{Best,j} - y_{j}(k)] \\
               &+ c_2 \cdot \text{rand}(1) \cdot [g_{Best,j} - y_{j}(k)]
\end{align*}
\]  

(6)

\[
\begin{align*}
    x_{j}(k+1) &= x_{j}(k) + v_{j}(k+1) \\
    y_{j}(k+1) &= y_{j}(k) + v_{j}(k+1)
\end{align*}
\]  

(7)

where \((v_{p,j}(k), v_{j}(k))\) is the current velocity vector of particle \(j\); \((v_{p,j}(k+1), v_{j}(k+1))\) is the velocity vector of particle \(j\) for the next iteration; \((x_{j}(k), y_{j}(k))\) is the current position of particle \(j\); \((x_{j}(k+1), y_{j}(k+1))\) is the position of particle \(j\) of the next iteration; \((p_{Best,j}, p_{Best,j})\) is the best position particle \(j\) achieved based on its own experience during previous \(k\) iterations; \((g_{Best,j}, g_{Best,j})\) is the best particle position based on overall swarm’s experience during previous \(k\) iterations; \(w\) is the inertia weight; \(c_1\) and \(c_2\) are two positive constants; \(\text{rand}(1)\) is a randomly generated number with uniform distribution in the range of \([0,1]\); and \(k\) is the iteration index. \(p_{Best,j}\) and \(g_{Best,j}\) are selected in terms of the fitness value calculated. The location estimation algorithm based on the global-best version of PSO is depicted in Fig. 3.

IV. DISTRIBUTED LOCALIZATION SYSTEM IN UNDERGROUND MINES

A. Structure of the Proposed Localization System

The WSN deployed in underground mines has a chain type topology because of the special geographic restriction. The WSN deployed in underground mines has a chain type topology because of the special geographic restriction. The communication cost and time delay are relatively high due to the multi-hop transmission. A distributed localization scheme which can be implemented on the blind node is preferred with only the localization result reporting to the sink node.

The coordinator is responsible for establishing the network. It also acts as a gateway to the surveillance PC through a serial port. The surveillance PC is responsible for the configuration of the anchor nodes and localization data management.

Anchor nodes are routers of the ZigBee network. They collect data from the tunnel environment and participate in localization. When receiving a localization request from a blind node in one hop range, the anchor nodes respond with their ID numbers and coordinates.

The blind node must be a ZigBee router, because it needs to communicate with multiple anchor nodes directly within its communication range. The blind node
carries out the localization algorithm. The proposed localization system structure can be directly applied to multiple blind nodes which are moving in the tunnels simultaneously, without any modification. It is because of the mesh topology of the ZigBee network.

B. The Deployment of the Anchor Node

To ensure the network communication is reliable and the blind node can find enough reference nodes that are not on a line, the anchor nodes should be deployed along both sides of the tunnel. The distance between any two adjacent nodes on the same side keeps equal, and is shorter than the valid communication range between two nodes. The anchor nodes on the opposite side should be placed alternately, in other words, one anchor node on one side is to be placed in the middle of two anchor nodes on the opposite side, as shown in Fig. 4.

Each anchor node has a unique ID number and coordinates which can be configured. The ID numbers of the anchor nodes on one side are odd numbers and those on the other side are even numbers. This rule helps the blind node to choose proper reference nodes on both sides, because if all the chosen reference nodes are on the same side, which means they are in a line, it will lead to a failure of our localization algorithm.

V. EXPERIMENTAL RESULTS

To test the performance of the proposed localization system, experiments were carried out in an abandoned air-raid shelter, with the similar environment characteristics to underground mines. The length in X axis is 120 meters and the width in Y axis is 4 meters respectively, as shown in Fig. 4.

As can be seen from the result, the Line of Sight (UWB) ranging errors based on UWB were much smaller than those based on narrowband. It is because the UWB signal has the character of excellent time domain resolution and the immunity to multipath effect in indoor environment. This provides a good foundation for establishing an accurate localization system in underground mines.

B. Localization Experiment

The deployment of WSN in the shelter is shown as Fig. 5. The distance between the adjacent anchor nodes on the same side was 20 meters, and the deployment of the two sides was alternate. The ZigBee localization network consisted of one coordinator and 13 routers, which were all based on DW1000 UWB chip. One of the routers acted as the blind node, which was localized in real time. A localization software was designed on the surveillance PC. Fig. 6 showed the user interface of the software, through which users could configure the parameters of the anchor nodes, including the ID and the coordinates, and inquire the real-time position of the blind node.

The PSO parameters used in the experiment were as follows:

- Population of particles $M=10$ and the target fitness value $f_i = 0.3$
- The coefficients $c_1 = c_2 = 1.494$
- The inertia weight $\omega$ is decreased linearly from 0.9 in the first to 0.4 in the last iteration, i.e.
  \[ \omega(k) = 0.9 - \frac{k}{\max} \times 0.5 \]
- The weighted coefficient for the $i$th measurement $\beta_i$ was defined as follows:
  \[ \beta_i = \frac{r_{ss_i}}{\sum_{i=1}^{N} r_{ss_i}} \]

where $r_{ss_i}$ is the RSS value obtained when the blind node measures RF-TOF between the $i$th reference node and itself.

At each test point, the localization error (the distance between the estimated position and the real position of the blind node) was less than 0.3 meter.

To prove the advantage of UWB ranging method in mine environments, a contrast measuring experiment was carried out in a point to point way, using a pair of UWB evaluation boards EVB100 [17] and a pair of 2.4GHz narrowband JN5148 [12] nodes respectively. One was placed at the entry of the air-raid shelter and the other was moving along the air-raid shelter. At different test points, 20 times of UWB ranging and 20 times of narrowband ranging were performed. The average and the standard deviation of the measuring results are shown in Table 1.

<table>
<thead>
<tr>
<th>Real distance(m)</th>
<th>UWB ranging</th>
<th>Narrowband ranging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average(m)</td>
<td>Standard deviation(m)</td>
</tr>
<tr>
<td>20</td>
<td>11.599.499.391.888.998.2</td>
<td>0.72.12.22.52.62.8</td>
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</tbody>
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mode 2μA[17]. The blind node can work in low duty cycle mode so that it can be battery powered. But the other ZigBee routers (i.e. the anchor nodes) need to be supplied with main power in long-term run because they cannot be put into sleep mode when idle. Schedule-based network protocols taking localization task into consideration may address this problem.

Several research challenges remain to be addressed. None line of sight propagation is not taken into account in our scheme, which can be a main cause of range error. Time delay of communication is another issue that should be addressed when the scale of the system becomes bigger.

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