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Tunnel personnel positioning method based on TOA and modified location-fingerprint positioning

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ABSTRACT

To position personnel in mines, the study discussed in this paper built on the tunnel personnel positioning method on the basis of both TOA and location-finger print (LFP) positioning. Given non-line of sight (NLOS) time delay in signal transmission caused by facilities and equipment shielding in tunnels and TOA measurement errors in both LFP database data and real-time data, this paper puts forth a database data de-noising algorithm based on distance threshold limitation and modified mean filtering (MMF), as well as a real-time data suppression algorithm based on speed threshold limitation and MMF. On this basis, a nearest neighboring data matching algorithm based on historical location and the speed threshold limitation is used to estimate personnel location and realize accurate personnel positioning. The results from both simulation and the experiment suggest that: compared with the basic LFP positioning method and the method that only suppresses real-time data error, the tunnel personnel positioning methods based on TOA and modified LFP positioning permits effectively eliminating error in TOA measurement, making the measured data close to the true positional data, and dropping the positioning error: the maximal positioning error in measurements from experiment drops by 9 and 3 m, respectively, and the positioning accuracy of 3 m is achievable in the condition used in the experiment.

1. Introduction

Mine accurate positioning, a vital technologic means to ensure personnel safety in mine production, is one of key technologies in researches concerning "six systems" for mine safety protection [1–4]. The location-finger print (LFP) positioning method, an accurate positioning method and suitable for studying indoor accurate positioning, is mainly achieved through the ranging-based received signal strength indication (RSSI) and time of arrival (TOA) [5–9].

Some fundamental researches, mainly RSSI based, have been used on the LFP-positioning-based mine personnel accurate positioning method. The paper presented a WiFi-based mine positioning algorithm and proposed a RSSI-based LFP positioning method to estimate positions of individuals [10]. The paper put forth a RSSI-based kernel-function matching algorithm to carry out the mine LFP positioning [11]. The paper brought forth a modified mine LFP positioning matching algorithm based on RSSI and combining the K-nearest neighbor algorithm and the shortest historical path matching algorithm [12]. The paper presented the experiment on the mine LFP positioning algorithm on the basis of Wi-Fi and RSSI, and the result indicated that within the range of 25 m, more accurate positioning could be attained [13].

There has so far been limited research on application of TOA-based technology in mine positioning, mainly because TOA technology needs high temporal synchronization among nodes and thus imposes high requirement on hardware [11,12]. This led to few papers on TOA-based tunnel LFP positioning methods. However, the paper came up with a mine TOA positioning method on the basis of Kalman filtering and fingerprint positioning, and discussed applying TOA-based LFP positioning in mines [14]. However, more parameters found in further research have to be determined if a Kalman filter is applied in mines, which may affect the final positioning result to some degree.

There are some shortcomings in researches on mine LFP positioning methods presented in papers. Because there are many factors affecting transmission of electro-magnetic waves (EMW) in tunnels, processing the real-time measurements alone cannot assure the method is reliable, and on the contrary, the error suppression of the real-time measurements and de-noising of data in the database are required synchronously [10–14].

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By analyzing the impact of mine environment on RSSI and TOA technologies, the paper demonstrated that TOA technology is better-suited for positioning in tunnels and the LFP positioning method, which is feasible in the current condition of technology. By studying and improving TOA-based tunnel LFP positioning methods, considering the tunnel environment's effect on TOA ranging, the paper presented a real-time measurement error suppression method and a database data de-noising algorithm both of which require fewer parameters, to position personnel in tunnels at high accuracy.

2. Comparison between TOA and RSSI

2.1. Resolution

RSSI is calculated with the formula below using the received strength of wireless signals:

$$P(d) = -10n\log\left(\frac{d}{d_0}\right) + P(d_0) + A \quad (1)$$

where $P(d)$ is the received strength of wireless signal; $P(d_0)$ the strength reference at d_0; and A the additional loss due to environment, i.e., due to tunnel. Ideally, the free-space transmission model may be applied in analysis and the relation between RSSI value and the result from ranging is presented as shown in Fig. 1.

It is evident from Fig. 1 that in the ideal condition, the RSSI-based ranging resolution decreases with increase in the distance between the receiver and the transmitter, and the accuracy is high when the distance is small.

TOA is calculated with the formula below using the travel time of wireless signals:

$$d = c \times t_{\mathrm{TOA}} \quad (2)$$

where d is the traveling distance, i.e., the result from ranging; c the light's speed; and t_{TOA} the travel time of wireless signals. The relation between TOA and the result from ranging in the ideal condition is shown in Fig. 2.

The TOA-based ranging result is linearly corresponding to TOA at a constant rate of change and the obtained ranging accuracy, which correlates with the temporal resolution of TOA, is expressed as follows [15]:

$$P_{\mathrm{Range}} = \tau \times c \quad (3)$$

where P_{Range} is the ranging accuracy; and τ the temporal resolution.

2.2. RSSI in mine environment

There are many factors leading to losses in EMW transmission in tunnels, including conventional free space losses, EMW tunnel waveguide losses, the tunnel wall roughness and inclination losses, metallic facilities shielding losses. With all factors considered, RSSI distribution of 2.4 GHz band EMW in tunnel is shown in Fig. 3. The analysis method is the mode superposition of EMW transmission in tunnel [16,17].

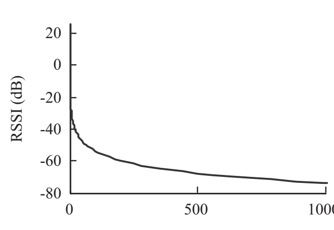

Fig. 1. RSSI curve in the ideal condition.

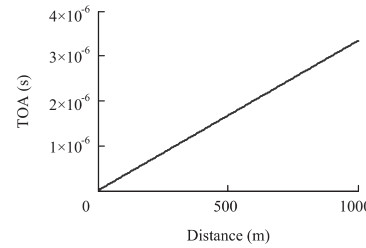

Fig. 2. TOA curve in the ideal condition.

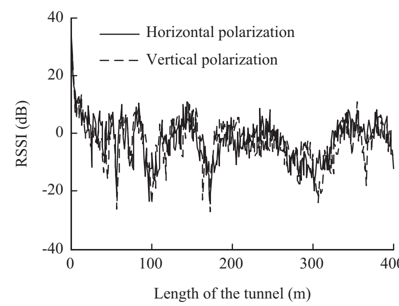

Fig. 3. RSSI curve in mine tunnels.

From the Fig. 3, it is obvious that RSSI resolution drops with increasing wireless signal influenced by tunnel losses. For 2.4 GHz signal polarized whether horizontally or vertically, ranging cannot be carried out with losses to a certain degree. The curve with wide fluctuation range results in the same received strength corresponding to multiple ranging distances. For the case shown in the Fig. 3, it is very difficult to distinguish the specific locations of the positioning targets in the area beyond 30 m.

2.3. TOA in mine environment

Cui et al. concluded that TOA technology requires high temporal synchronization among nodes. However, GPS is capable of high temporal synchronization in ground TOA positioning but cannot be applied in mines [11,12]. For this reason, few researches have been conducted concerning TOA application in mine positioning.

In the tunnel environment of mines, errors in TOA technology include the synchronization time-delay error inherent to the technology, the timing error and NLOS time-delay error attributive to shielding of facilities and equipment inside the tunnel.

$$t'_{\mathrm{TOA}} = t_{\mathrm{TOA}} + t_{\mathrm{SYNC}} + t_{\mathrm{e}} + t_{\mathrm{NLOS}} \quad (4)$$

where t_{TOA} is the actual travel time of signals from the transmitting end to the receiving end; t_{SYNC} the time-synchronization error, i.e., the synchronization time-delay between the devices at the transmitting end and at the receiving end; t_{e} the timing error, dependent on the biasing of frequency of the crystal oscillator in the timer; and t_{NLOS} the NLOS time-delay. All of the three factors act independently of each other.

The two-way ranging method can get rid of t_{SYNC}, and the symmetric double-sided two-way ranging (SDS-TWR) TOA method can eradicate t_{SYNC} and mitigate effect of t_{e} on positioning [14,18].

Therefore, with the currently available technologies, the key to application of TOA technology in tunnels is to restrain the NLOS time delay. The NLOS time delay is present in EMW traveling due to shielding of facilities and equipment in tunnels, including the fixed ones such as signboards, overhead lines and ventilation devices, and the mobile ones that appear in tunnels any time such as vehicles. Aiming at the effect of the two kinds of NLOS time