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Underground mining intelligent response and rescue systems

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Abstract

Coal mine industry, which produces the most abundant and widely-distributed fossil fuel, is the deadliest in casualties. A recent report shows that the casualty rates of coal production per million tones are 4.36 in China, 2.14 in Ukraine, 2.03 in Russia, 0.088 in USA and 0.08 in Australia respectively. Consequently, safety is a critical issue for the mining industry, especially for the underground mining companies. The modernization and informatization of mining companies have significantly improved the operational environments (and hence safety) for the underground miners. Some advanced technologies, such as the intelligent response and rescue systems, have contributed significantly to the reduction of mining fatalities and accidents. Typical underground positioning and three dimensional (3D) modelling techniques are discussed in this paper first. A RFID/INS integrated positioning system has been tested to evaluate its performance and different positioning algorithms have been implemented. Experiments show that the simple centre of origin (CoO) positioning algorithm can achieve a positioning accuracy of 7.9 m. The integrated fingerprinting algorithm can achieve 1.7 m accuracy by using an Extended Kalman Filter. A new underground structure modelling method and a collision detecting method are developed. A prototype intelligent response and rescue system has been implemented in Da Zhuang coal mine, China. The results indicate that both the underground positioning technique and the 3D modelling and representing technique developed can satisfy the requirements of underground rescue in an emergency situation.

Keywords: coal mine industry; response and rescue system; underground positioning; 3D modelling

1. Introduction

Tunlan coal mine which boasts one of the best mining facilities in China, blasted on 22 February, 2009 and killed 78 miners[1]. This is just one month after Mr Lin Luo, the chief of the China State Administration of Work Safety, said that China launched a "Year of Work Safety" to keep the fatalities of mining industry falling[2]. Coal is believed to be the most abundant and widely distributed fossil fuel. However, working in an underground coal mine, especially in China, is one of the deadliest occupations. According to [1], "official sources have put China's cumulative coal mining fatalities at more than 250,000, and independent estimates are much higher since 1949". Australia, as the country with the safest working conditions, has also claimed an causality rate of about eight per 100,000 workers[3] in the past 17 years. Consequently, mining safety is one of the most essential issues in the world and the development of efficient search and rescue techniques for mining industry is critical.

We discuss an intelligent response and rescue system for mining industry and the critical technologies which can be used to establish this system, including the underground positioning techniques and 3D modelling and representing algorithms.

2. The structure of the intelligent response and rescue systems

In general, an intelligent response and rescue system for mining industry contains four major parts. They are: (1) a database, (2) a monitoring centre, (3) a fixed underground sensor network, and (4) mobile devices (see Fig. 1). The database should contain the information about the ground plants and facilities, underground environments, the positions and status of the underground miners, etc. The monitoring centre is to acquire the information both from the database and the underground sensor network, present the "real-time" situations to the rescuer or the decision maker and send the information or commands back to the underground mobile users. The fixed underground sensor network is mainly for communication between the ground and underground sections and performing positioning. The mobile device is used to present the information to the end users underground and provide tracking. Two major challenges in developing such a system are the positioning underground and representing and simulating the "underground scene" in 3D models.

3. Integrated indoor positioning techniques for underground mines

The challenges of indoor or underground positioning are: on one hand, the accuracy required for people tracking and automotive device navigation is generally higher than most of the outdoor positioning requirements. On the other hand, the "unfordable" underground environments due to obstacles and reflectors of the positioning signals can potentially significantly degrade positioning accuracy underground. Consequently, various techniques have to be tested and the cons and pros of each have to be evaluated.
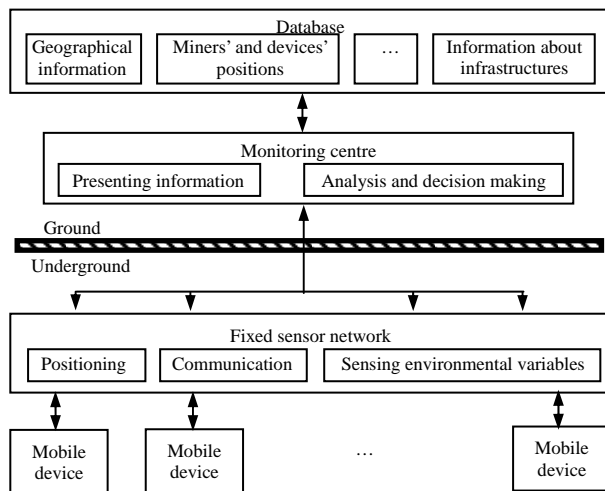

Fig. 1. A typical structure of an intelligent response and rescue system

3.1. Review of the indoor positioning techniques

Table 1 presents a comprehensive comparison of popular indoor positioning techniques. The positioning techniques include micro-machined electromechanical system (MEMS) Inertial Navigation System (INS), dead reckoning (DR), infrared, ultrasonic, pseudolite, Ultra Wide Band (UWB), WiFi and Radio Frequency Identification (RFID) positioning technique [4].

According to Table 1, inertial sensors are neither limited by the effective range nor affected by the signal propagation problems which are inherent to the infrared, ultrasonic and radio-based positioning systems. However, they

are seldom used standalone for personal indoor positioning. The main problem using inertial sensor standalone is, however, their significant drifts either with time (in INS) or with moving steps (in DR) [5, 6]. Except the inertial sensor techniques, the radio-based positioning techniques have the longest covering range and strongest penetrating ability among all the reviewed techniques. The benefits of using RFID positioning technique for personal positioning rather than using other radio-based techniques are that the user device of RFID system is portable, the RFID tags do not need the external power supply in contrast with the WiFi access points and the entire system is economic than using pseudolites and UWB systems.

3.2. RFID/INS integrated positioning techniques

Two positioning techniques are chosen for further investigation for positioning and tracking miners underground based on the above comparisons. One is RFID, which uses received signal strength (RSS) to estimate the absolute positions. Another is INS which uses accelerometers and gyroscopes to estimate the relative positions.

Table 1. Comparison of various positioning techniques

Positioning Methods		Examples	Effective Range	Complexity of Instruments	Positioning Accuracy
Inertial sensors		MEMS INS	• Unlimited range	• Portable device	Accuracy degrade with time
		DR	• Unlimited range	• Portable device	Accuracy degrade with steps
Infrared positioning techniques	CoO	Active Badge	• Not to be able to penetrate walls	• A few number of devices required	Locating people in a room
	AoA	Indoor GPS	• Not to be able to penetrate walls	• A few number of devices required	Millimetre level
Ultrasonic positioning techniques	ToA	Active Bat & Cricket	• About 5 meters • Not to be able to penetrate walls	• Large number of devices required	Centimetre level
Radio-based positioning techniques	ToA/TDoA	LOCATA	• Over 20 meters indoor • To be able to penetrate walls	• A few number of devices required	Meter level
		UWB	• Over 20 meters indoor • To be able to penetrate walls	• Large device • A few number of devices required	Decimeter level
	RSS	WiFi	• Over 20 meters indoor • To be able to penetrate walls	• A few number of devices required • Existing access points can be used • Require external power supply	Meter level
		RFID	• Over 20 meters indoor • To be able to penetrate walls	• A few number of devices required • No external power supply required for RFID tag	Meter level

3.2.1. RFID probabilistic cell of origin algorithm

This algorithm is a combination of the conventional CoO and the RSS loss model. A relationship between the RSS and the distance is modelled based on the experimental data (see Fig. 2). Mobile user's position is then estimated by joint probabilities of the distance measurements and other aided measurements (see Equation 1), such as the relative position estimated by INS measurements [7].

$$
\begin{cases}
p_{pos}(\bar{x}) = p_{RFID}(\bar{x}) \cdot p_{INS}(\bar{x}) \\
\bar{x}_{pos} = \arg\max(p_{pos}(\bar{x}))
\end{cases}
\tag{1}
$$

This means the positioning solution ($\bar{x}_{pos}$) by RFID probabilistic CoO assisted 2D MEMS INS positioning algorithm is the argument of the maximum product of INS positioning probabilities ($p_{INS}(\bar{x})$) and RFID positioning probabilities ($p_{RFID}(\bar{x})$).
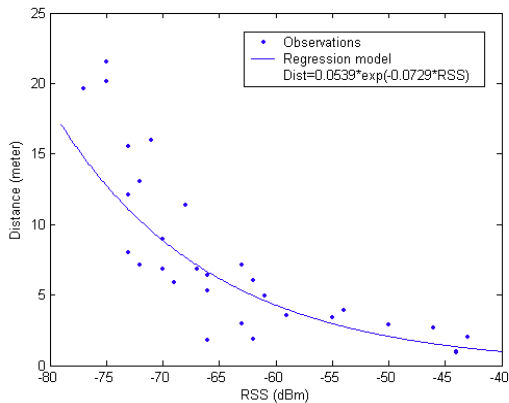

Fig. 2. An exponential function models the relationship between RSS and the distances between the reader and tags

Although this method is simple and can offer positioning services in a large area with a small number of infrastructures, the accuracy and the reliability are concerned in the areas where the number of detectable transmitters is limited. Accordingly, another RFID positioning algorithm is investigated below.

3.2.2. RFID fingerprinting algorithm

This method was first implemented in *RADAR* system [8] which is an RF-based indoor tracking system developed by *Microsoft Research*. It estimates the mobile user's position by matching the on-line sampled RSS with the pervious off-line RSS database then searching for the most possible position of the user receiving the similar RSS pattern (see Equation 2).

$$P(M|L_r) \sim \prod_{i=1}^{n} P(RSS_{Tag_i} = s_i) \tag{2}$$

where $P(M|L_r)$ is the conditional probability of the RSS vector M at the position L_r, $P(RSS_{Tag_i} = s_i)$ is the probability of the measured RSS (s_i) from the tag (Tag_i) at the position (L_r).

This method provides a more continuous and more reliable result than using the CoO algorithm. However, the instability of the RFID signals transmitted often causes a big variance in the positioning estimation. In order to achieve a stable result, the integration with INS is introduced below.

3.2.3. RFID/INS integrated algorithm

To improve the positioning performance, the RFID/INS integrated positioning method is applied. On one hand, the INS is a self-contained, high sampling rate device, which does not suffer any signal propagation problems, such as the multipath effects and obstructions, and can produce more continuous positioning estimations. On the other hand, the RFID positioning method is drift-free so it can be used to correct INS errors. To overcome the respective problems mentioned above, an Extended Kalman Filter (EKF) based algorithm is developed to integrate these two systems (see Fig. 3) [9].
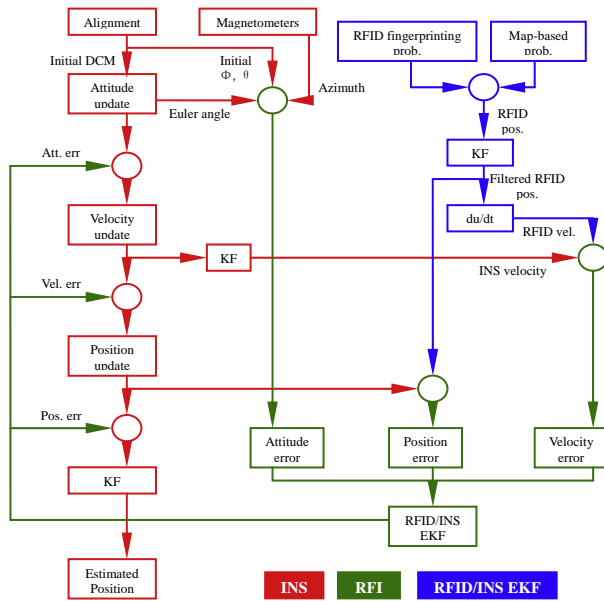
Fig. 3. A schematic structure of the RFID/INS positioning algorithm based on Kalman filtering

A basic 9-state dynamic model [10] is used as the RFID/INS EKF model. In this model, the state vector $\tilde{x}$ contains three position errors (Δx, Δy, Δz), three velocity errors (ΔV_x, ΔV_y, ΔV_z), and three Euler angle errors ($\Delta \phi$, $\Delta \theta$, $\Delta \psi$) (see Equation 3). The state transition matrix $\tilde{\phi}$ represents the tri-axis inertial error model as shown in Equation 4. The observation vector $\tilde{z}$ equals to the INS estimations and the reference measurements. In this case, the RFID positioning and velocity estimations are used as the position and velocity references. The initial pitch and roll angles from the alignment stage and the azimuth estimated by the tri-axis magnetometers are used as references of the Euler angles since the mobile user itself does not contain significant changes in pitch and roll (see Equation 5).

$$\tilde{x} = \begin{bmatrix} \Delta x & \Delta V_x & \Delta \phi & \Delta y & \Delta V_y & \Delta \theta & \Delta z & \Delta V_z & \Delta \psi \end{bmatrix}^T \qquad (3)$$

$$\tilde{\phi} = \begin{bmatrix}
1 & \Delta t & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & g \cdot \Delta t & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \Delta t / R_e & 1 & 0 & 0 & 0 & 0 & 0 & \omega_x \cdot \Delta t \\
0 & 0 & 0 & 1 & \Delta t & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & g \cdot \Delta t & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \Delta t / R_e & 1 & 0 & 0 & \omega_y \cdot \Delta t \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & \Delta t & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix} \qquad (4)$$

where g is the vertical component of the gravity, R_e is the radius of the Earth and ω_x and ω_y are the pitch and roll angular rates respectively.

$$\tilde{z} = \begin{bmatrix} x - x_{RFID} \\ V_x - V_{RFIDx} \\ \phi - \phi_0 \\ y - y_{RFID} \\ V_y - V_{RFIDy} \\ \theta - \theta_0 \\ z - z_{RFID} \\ V_z - V_{RFIDz} \\ \psi - Ori_{mag} \end{bmatrix} \qquad (5)$$

where (x, y, z) and $(V_x, V_y$ and $V_z)$ are the position and velocity estimations of the mobile user respectively. ϕ, θ and ψ are the pitch, roll and yaw angles estimates of the mobile user respectively. x_{RFID}, y_{RFID}, z_{RFID}, V_{RFIDx}, V_{RFIDy} and V_{RFIDz} position and velocity estimations by RFID positioning respectively. ϕ_0 and θ_0 are the pitch, roll estimated in the alignment stage respectively. Ori_{mag} is the azimuth estimated by the tri-axis magnetometers.

The velocity estimated by RFID, V_{RFIDx}, V_{RFIDy} and V_{RFIDz}, are assigned as the average velocity between the current RFID position estimation and the previous RFID position estimation. It may not represent the mobile user's current velocity accurately but, these values provide a significant contribution in eliminating the INS drifts. That is because the kinematics of the user is relatively low (with the speed of less than 10 m/s) and the measurements by RFID are drift-free even though they contain errors caused by the RFID positioning errors and the arbitrary assignment of the RFID velocity estimations.

The EKF is implemented to provide error estimations in position, velocity and attitude determinations according to the referencing measurements generated from the RFID positioning system, magnetometers and the alignment. These estimated errors are then used to correct the INS positioning estimations.

3.3. Experiments and results

The experiment was conducted in the Yarra Bend Park, Melbourne, Australia [7]. Seven RFID tags were placed in an open area with different intervals. The tags' positions were accurately measured by the *Trimble R8* GPS. This RTK system is also used as a real-time reference to evaluate the RFID CoO positioning algorithm. The synchronisation of the RFID positioning system and the RTK reference system is based on the GPS time generated by the *MinimaxX* GPS receiver, a portable GPS/INS integrated device, and the *Trimble R8* GPS receiver (see Fig. 4).

The 3D RFID fingerprinting/INS positioning experiment was conducted between levels 9 and 11 in Building 12 of RMIT University [9]. Eight RFID tags are mounted on the walls and 2 meters above the floor. Eleven RFID fingerprinting off-line reference points are chosen along the centre line of the stairway from the intermediate level between levels 9 and 10 to level 11. The off-line database contains the RSS and the corresponding sigma with one-cubic-meter resolution grids are interpolated by Kriging method according to the 11 reference points' measurements (see Fig. 5).

Fig. 4. The prototype RFID-assisted 2D MEMS INS positioning system used in the experiments
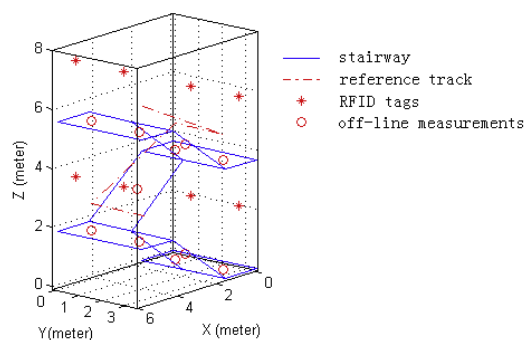
Fig. 5. A schematic plot of the experimental stairways at RMIT University (building 12, levels 9-11)

Experiment results show that the RFID CoO method can provide a high accuracy in the central area of the RFID tags' reading ranges with the simplest instruments and algorithms but it can not provide the continuous and reliable positioning estimations without the integration of other positioning techniques in the far end or outside the reading ranges. The positioning accuracy of the system will highly depend on the technique integrated between RFID cells. In addition, it is anticipated that better integration algorithms can improve the accuracy, continuity and reliability of the RFID positioning methods (see Table 2).

Table 2. Numerical comparisons of different RFID positioning methods

Method	Accuracy RMS (m)	Updating Rate (Hz)
INS/RFID Probabilistic CoO	7.9	100
RFID Fingerprinting	2.4	1
INS/RFID Probabilistic Fingerprint	1.7	100

4. Representing positions in the underground mine by a 3D modeling system

One of the important aspects in mining modernization is to model and visualise the complex 3D structure. According to this demands, an innovative mining surface plant and underground roadway 3D modelling system has been developed and tested in China University of Mining and Technology, China [11]. This system provides both query and calculation of mining related items in an interactive environment and it is established based on geographical information systems and virtual reality techniques.

4.1. Development of 3D models

The first step of establishing the entire system is to model the structure. This step includes two main sections, i.e. modelling the mining surface plants and the underground roadways.

The mining surface plants are modelled by integrating both *ArcInfo* and *SiteBuilder3D*. It shows the efficiency and simplicity of using this method. The information is gathered from a series of two dimensional (2D) *ArcInfo* datasets, including geographic features, satellite images and elevations. Consequently, these pieces of information are transferred into a 3D model by *SiteBuilder3D*, an extension of *ArcInfo* for 3D GIS developments, using model replacing and converting methods. For simple structures, such as roads and cubic buildings, the model converting method is applied with elevation data. In contrast, the model replacing method is applied to the complex structures, such as offices and houses. The usage of information from existing 2D database significantly reduces the workload of building the models for a large area of a mining surface plant. In addition, the converting and replacing methods provide an efficient way to represent the surface constructions (see Fig. 6).

Fig. 6. 3D models of the surface plant buildings

In contrast of the conventional underground roadways modelling method, which constructs roadways like 3D line sections by *Creator* and then recreates its geometry in *AutoCAD*, the method developed is more efficient. This method firstly categorises the underground roadways into three classes, i.e. the even cylindrical roadway, the uneven cylindrical roadway and the even non-cylindrical roadway. Secondly, to those even roadways, the attributes, such as the shape of the profile and the coordinates of the central lines, are extracted from a 2D *AcrInfo* database by *ArcObjects* then the 3D model is built by *OpenFlight API*. Finally, the structures are rendered by *Vega Prime* (see Fig. 7).
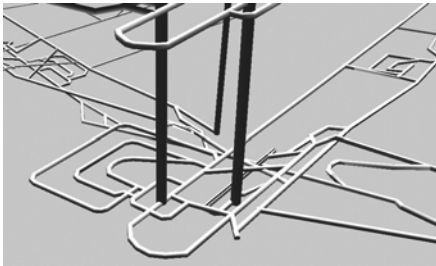

Fig. 7. A sample of roadways models

4.2. Interactivities

With the establishment of 3D models of the mining surface plants and underground roadways, interactive functionalities of the system are developed. These functionalities include 3D simulation, querying, calculation and shifting representations between 2D and 3D, which are essential to organizing activates underground or making decision in emergency situations.

Simulating a smooth walking through 3D underground models is a challenge due to the complexity of underground roadways. One of the major problems is to avoid the collision between the virtual camera and the structures. Most of the traditional methods prefer to apply the line crossing test to avoid the collisions, whereas this method requires the additional thread for each test. In contrast, an efficient method is developed for this system. An object, which contains six line-shaped sections in three positive and negative orthogonal directions, is defined to calculate the possible collision. The dimension of this object is obtained from the instance (c.f. Figs. 8 & 9).
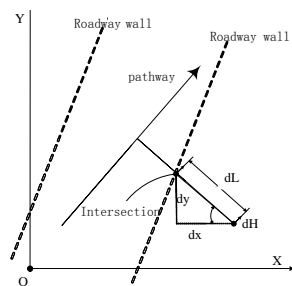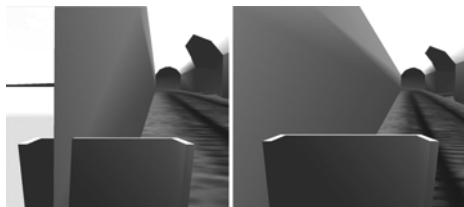
Fig. 8. The collision detecting method developed

Fig. 9. Examples with (left)/without (right) collision effects

4.3. Prototype

To evaluate the design of the system, a prototype system has been tested in Da Zhuang coal mine, China (Fig. 10). A 1:1000 terrain map is used to establish the surface plant models. The comparison using conventional and the method developed to build the underground roadways is conducted. A software package having all the functionalities mentioned above is tested. The interactivities via mouse and keyboard are available and view points can be moved freely. The objects can be queried from both the view port or attribute tables. This study suggests that the method developed is efficient and it has satisfied the requirements of project.
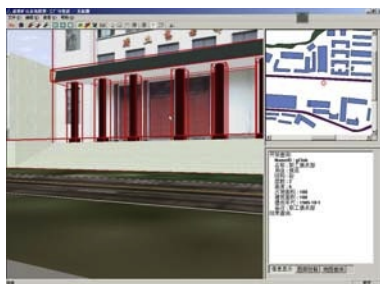

Fig. 10. Prototype software package's interface

5. Conclusion and discussion

A prototype underground mining intelligent response and rescue system has been designed and implemented. The techniques investigated can satisfy the requirements for positioning the underground miner and providing the critical information needed for the rescuers or decision makers on the ground. The integrated RFID/INS units with the developed algorithm can provide 1.7-meter accuracy in indoor environments. The 3D modelling and collision detecting methods simulated can provide an efficient way to represent the underground situations. Future work will be focused on improving the accuracy of the positioning accuracy in the underground sections and enhancing the spatial analysis functionalities in the central monitoring section.

Acknowledgements

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