Research on Key Technologies of High-precision Location Based Service System for Intelligent Mines

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Abstract

Aiming at the common application requirements of intelligent mine construction for high-precision location based service, this paper analyses the present status and development of mine positioning technology, explains the technical bottlenecks and construction goals in the existing system, discusses in detail the key technologies such as location based service system architecture, multi-source fusion positioning method, distributed service oriented system, high-precision map and 4D visualization, and finally puts forward the technical standard requirements of location based service and related mine application system research directions.

Introduction

The precise location information of various targets in the mine plays an important role in the construction of intelligent mines. On the one hand, the precise position monitoring and real-time tracking of various moving targets in underground mines can effectively improve the safety management level of mines. On the other hand, the development trend of intelligent mines with fewer people and unmanned operations requires the autonomous collaborative operation of underground mining and transportation equipment. To realize autonomous collaborative operation, The primary demand for the equipment is to perceive the precise position of itself and each other^[1-2].

Location Based Service (LBS) refers to the service that provides the geographic location information of the target, which includes three main parts: location acquisition, location transmission and information service^[3]. As underground mines cannot receive GPS signals, the existing underground positioning systems cannot meet the technical requirements of intelligent mine construction. A high-performance MLBS (Mine Location Based Service, MLBS) system is not only an important technical foundation for realizing the safety of mine personnel, but also a key technical support for realizing efficient and intelligent mine production.

This paper investigates the status and development underground positioning technologies, explains the main technical bottlenecks in the current system, analyzes and discusses in detail the key technologies for constructing a high-precision MLBS, Provides technical reference and research direction for the key infrastructure construction of intelligent mines.

1. Mine Positioning Technologies

1.1 Radio positioning

Radio positioning technology can be subdivided into categories such as WIFI, GSM/LTE, Blue tooth, ZIGBEE, UWB, millimeter wave radar, etc. based on the carrier radio^{[4]-[6]}. WIFI wireless local area network positioning has the advantages of low deployment cost and integration with communication system, but the tag power consumption is high; the GSM/LTE uses underground mobile communication network to

realize mobile phone positioning, since the underground mobile communication base station has less cross coverage, the positioning accuracy is low; Blue tooth is characterized by low power consumption and short coverage distance. In most situation, The underground blue tooth beacon was used to achieve regional positioning; ZIGBEE has been mainstream technology for current underground personnel positioning system, with the characteristics of low power consumption and short distance, it can achieve meter-level precision; UWB has the advantages of large capacity, low power consumption, and centimeter-level accuracy which is currently dominant the high-precision positioning application; millimeter-wave radar has millimeter-level accuracy which is generally used for obstacle recognition and accurate ranging of underground mobile equipment.

Based on the positioning principle of radio technology, the mainstream methods include RSSI(Receiving Signal Strength Indication, RSSI), AOA (Angle Of Arrival, AOA), PDOA (Phase Difference of Arrival, PDOA), TOA (Time Of Arrival, TOA), TDOA (Time Difference Of Arrival, TDOA) and other methods^{[7]-[8]}. RSSI calculates the distance between the mobile node and the anchor node based on the radio signal transmission loss model. In underground mines, the radio signal transmission loss model is greatly affected by the environment which results in more than 10 meters positioning accuracy; the AOA method measures the angle of the target node, this method generally requires an integrated antenna array, which is difficult to apply in underground mines; the PDOA method measures the phase difference of the arrival of the radio signal and calculates the distance to the target node. This method is susceptible to interference from multipath effects; the TOA method measures the propagation delay of radio signals and uses the constant speed of light to calculate the distance, the coordinates can be calculated based on distances from the tag to more than three anchors using trilateral least squares and other algorithms. TOA related methods are simple and easy to implement, but the round-trip measurement between nodes increases the congestion of the radio transmission and reduces the number of concurrency and real-time performance of the positioning system; TDOA calculates the position of the mobile node by measuring the difference in the arrival time of the radio signal from the tag to several anchors, This method requires highly consistent clock synchronization of base stations, TDOA has high positioning accuracy, large system capacity, and short response time, but the technology is relatively complex and high-cost to implement in underground mine.

1.2 Geomagnetic positioning

Geomagnetic positioning collects geomagnetic characteristic parameters at any locations in the space to be measured and establishes a characteristic database^[9]. In actual positioning, the parameters are collected by sensors and matched and retrieved with the geomagnetic data collection in the database. Ideally, the geomagnetic positioning accuracy can reach about 2 meters.

The advantage of geomagnetic positioning is that there is no need for additional infrastructure support such as positioning base stations, and only the tag needs to support geomagnetic feature collection, which is relatively low cost. To achieve ideal geomagnetic positioning performance,

geomagnetic characteristic parameters from all physical spaces on the site need to be collected in database. Once the characteristics change, the parameter records need to be updated again, which make it hard and complex to implement on site.

The underground mine is a special place with a relatively complex environment. Electromagnetic interference of various electromechanical equipment, metal shielding and reflection of mining equipment and protective nets, etc. make the underground geomagnetic parameters extremely unstable, and even unable to effectively extract characteristic parameters. It's difficult to rely only on geomagnetic information to achieve accurate position in underground mine.

1.3 Inertial Positioning

Inertial positioning uses IMU (Inertial Measurement Unit, IMU) such as multi-axis acceleration sensors, gyroscopes, and magnetometers to measure the directional velocity and acceleration of the measured tag in three-dimensional space, and calculate the tag position according to certain rules^[10]. The advantage of inertial positioning is that it does not require the support of additional hardware infrastructure, but it has the problem of starting position drift, and small errors in the measurement will cause big positioning estimation error over time.

Because of the high cost, high-precision inertial positioning technologies such as lasers and optical fibers are only used in a few scenarios such as positioning for shearer. For most underground positioning applications, MEMS (Micro-Electro-Mechanical System, MEMS) inertial positioning technology is used. MEMS inertial sensors have the advantages of small size and low power consumption, but generally have low accuracy, especially temperature changes can easily cause measurement and calculation errors to accumulate, causing speed and position to diverge, which has big impact on the final positioning accuracy.

1.4 Visual Positioning

Visual positioning uses computer image processing technology to estimate the distance and position of the target to be measured from the digital image. Visual positioning can be divided into monocular visual positioning, binocular visual positioning and RGB-D visual positioning^[11]. Monocular visual positioning has low cost and poor accuracy; binocular visual positioning are more accurate depending on more complicated calculations; RGB-D has even better performance which can realize three-dimensional position calculations and avoid light effects.

Visual positioning has been partially applied in underground mines, such as underground video surveillance, Intrusion into dangerous area monitoring. Due to the limitation of the capturing range of camera, the visual positioning is only suitable for the target positioning in narrow directional and small range area in underground mine, and is not suitable for the whole mine positioning with large capacity

and multiple targets. The positioning accuracy of visual positioning can generally reach the meter level, but due to the influence of underground mining dust, the accuracy and reliability of the actual scene still have space to be improved.

1.5 Comparison of positioning technologies

Comprehensive comparison and analysis of the advantages and disadvantages of various underground positioning technologies, as the following Table 1, among different underground positioning methods, UWB has obvious advantages, and each method has certain shortcomings. From the perspective of the application requirements of MLBS, it's difficult for a single technology to meet all the needs. Combining the advantages of one or more technologies especially the fusion method can further improve the positioning accuracy and reliability in the complex underground environment.

Table 1 Comparison of performances of underground positioning methods

Mine Positioning Technology		Accuracy	Distance	Price	Advantages	Disadvantages
Radio Positioning	WIFI	3m-10m	100m-600m	Low	Mature technology and easy to deploy	Low accuracy and high power consumption
	GSM/LTE	25m-50m	100m-400m	High	Integration of positioning and communication	Low accuracy and high terminal price
	Blue Tooth	1m-3m	3m-15m	Low	Ultra-low power consumption	Small coverage
	ZIGBEE	1m-3m	30m-250m	Low	Low power consumption and easy to deploy	Unreliable accuracy
	UWB	0.1m-0.3m	200m-800m	Low	High accuracy and Ultra-low power consumption	NLOS issue
	Millimeter Wave Radar	0.02m-0.05m	20m-100m	Medium	High accuracy	Small coverage
Geomagnetic Positioning		1m-3m	–	Low	No need base station	Unstable positioning feature
MEMS IMU		0.2m-1m	–	Low	No need base station	Error accumulation
Visual Positioning		1m-3m	10m-50m	High	Integration of positioning and video surveillance	Limited application scenarios

1.6 Current Status and application requirements

Most of the positioning systems currently used in mines are designed for single application and only meet partial services. With the further development of intelligent coal mines, the demand for less humanized and unmanned underground operations has become increasingly obvious. At the same time, higher performance requirements such as accuracy, capacity and response time have been put forward for the underground positioning system. Some problems of the existing positioning system include the following:

(1) Insufficient positioning accuracy, capacity and real-time performance. The current positioning accuracy is generally less than 3 meters. The concurrent capacity of a single base station is 80 tags. The positioning interval is generally greater than 1.5 seconds, which cannot be satisfied the requirements of large-capacity nodes, fast movement and high-precision positioning.

(2) The centralized system structure cannot meet the demand of real-time response. The server on the surface is the center of the existing system which collects all the positioning data and implements calculations, the tags cannot sense the location information directly, which makes it impossible to respond immediately for some mine application scenarios such as personnel vehicle collision avoiding and collaborative mining operation.

(3) Only supports one-dimensional positioning. The mining equipment not only moves in the horizontal direction, but also has a multi-degree-of-freedom movement. It is important for mining equipment to sense accurate position of each other while collaboratively mining, two-dimensional and three-dimensional positioning service will be necessary.

(4) Does not have open service application interface. Different underground applications have different functional requirements for the accuracy, dimension, and response time. Lack of unified access standards and universal application interfaces which enables multiple application systems requirements to be satisfied are becoming the bottleneck of positioning system development.

Therefore, the construction goal of the high-precision MLBS should be set as the public infrastructure of intelligent mines. Through the establishment of an open service and unified architecture underground GPS-like system, it can meet the positioning, tracking, navigation and coordination of different scenarios and different application requirements in underground mines.

2. System Architecture Of Mlbs

The overall system architecture of the MLBS shown as following Figure 1, which can be divided into four layers: location acquisition, location transmission, location service, and location application.

The location acquisition layer is composed of positioning infrastructure, including distributed area controllers, various positioning base stations and devices, mobile tags, etc..

The location transmission layer is generally connected to the existing high-speed wired Ethernet network or wireless communication network of the mine, also positioning data can be exchanged by the integrated network of the positioning base stations which includes the switch units form an optical fiber or wireless cascading network.

The primary functions of the location service layer are divided into coordinates management, clock synchronization, base station configuration, equipment status monitor, and location data exchange, with the support of high-precision map database and positioning and navigation algorithms library.

The location service layer provides four-dimensional space-time location visualization services to the upper application system and supports the operation of all location-related subsystems. The upper location application layer does not need to be concerned the specific details of the positioning realization, only need to focus on the realization of various intelligent mining and management applications.

3. Reliable Location Acquisition Method

UWB positioning can meet most of the positioning requirements in the underground mine. However, the frequent appearance of NLOS (None Line of Sight, NLOS) problem reduces The accuracy and reliability of positioning performance due to the undulating underground space terrain, the bent roadway, and the shielding of various equipment for mining and transportation.

There are many technical solutions to solve the NLOS problem. Among them, the weighted Levenberg-Marquardt method can effectively reduce the influence of NLOS^[13]. Set the weight matrix as a diagonal matrix and construct the following calculation formula as shown in formula (1):

$$w_i = \begin{cases} 1 + 0.01(|d_i - d^{ref}| + 1) & , d_i < d^{ref} \\ \frac{1}{|d_i - d^{ref}| + 1} & , d_i > d^{ref} \end{cases} \quad (1)$$

$$d^{ref} = D_{\lfloor (n+1)/2 \rfloor}, \quad D$$

In the formula D is the ranging sequence arranged from small to large, and the weighted LM method is combined with the weighted least square method for positioning calculation, which can achieve obviously better results.

In-depth solution to the NLOS problem must also rely on the fusion of different positioning methods^[14]^[15]. A more effective strategy is to use UWB positioning and DR (Dead Reckoning, DR) based on fusion strategy. The steps are shown in Figure 2. First, perform NLOS detection on UWB and DR positioning results. If the NLOS parameter does not exceed the set threshold, take the UWB positioning result; otherwise, take the previous positioning results according to the positioning reliability and combine the inertial parameters to calculate the position then perform the DR positioning data as the positioning result using the weighting process, and finally the selected result is subjected to an extended Kalman filter (Extended Kalman Filter, EKF) to obtain the final fusion result.

4. Distributed Service Deployment

The surface server is the center of the entire system, and all location information is centrally stored in the server center database. Obviously, such a single centralized architecture cannot meet the requirements for high response time in the application scenarios such as operator-machine proximity detection and equipment collaborative operation, because possible network transmission delays and transmission Failure will lead to system out of service and unreliability. The use of edge computing architecture^[16] can effectively solve the problem.

MLBS adopts a unified service system of both centralized and distributed architecture, as shown in Figure 3. The MLBS base station has absolute geographic coordinates. The moving targets and the base stations realize two-way ranging and positioning calculation. The MLBS area controller acts as the edge computing unit processing the regional location information. The neighboring controllers distribute and exchange real-time locations and map information to each other. The area managed by each controller can be completely separated from the centralized control of the surface server to provide location service information independently. This distributed service deployment using edge computing technologies avoids instability and unreliability of centralized systems, improves the real-time performance and the robustness of the application systems.

5. High Precision Map And 4d Visualization

High-precision map^[17] is an essential technical support for MLBS. Technical requirements are mainly reflected in three aspects: high-precision geophysical coordinate system, three-dimensional model of underground space and map dynamic real-time information.

(1) High-precision geophysical coordinate system. The coordinate accuracy of the MLBS positioning the base station itself will determine the overall precision of the system. The entire system should be built on a precise three-dimensional geographic coordinate system, and each positioning reference node has high-precision geophysical absolute coordinates.

(2) Three-dimensional model of underground space. At present, mine GIS systems mostly use roadway centerline combined with cross-section stretching to build data models. This method lacks three-dimensional spatial location details. In order to support services such as underground navigation and unmanned driving, the data model of the MLBS requires accurate information on the direction and distance changes of underground roadway undulations, bends, and crossings, as well as complete contour information such as the height, width, and convexity of the underground roadway section.

(3) Map dynamic real-time information. There are two main sources of dynamic real-time information. One is from the information provided by the MLBS centralized servers, including transportation navigation signals, access to specific areas, coordinates, directions and speeds of the moving targets around, and the other from MLBS area controller, which obtains distributed area location and environmental information through local positioning tags, cameras, millimeter wave radar, etc.

LiDAR laser scanning is used to precisely model the underground space and extract the cross-section profile information of the roadway. The real photo and video image splicing modeling technology is used to form part of the real and part of the virtual field operation underground scene^[18]. In addition to the three dimensions of the physical space, the MLBS has time stamps for all location information. It uses time-sharing compression storage and optimized indexing technology based on spatial location in the database space to classify and store present and history data, which can perform 4D visualization based on virtual reality technologies as shown in Figure 4.

6. Future Development

The high-precision MLBS is the primary infrastructure to realize the efficient and safe mining of intelligent mines, and accelerating the scientific and technological research of its related technologies is an inevitable choice to realize the intelligent mine construction. Although some progress through unremitting efforts have been made, key technologies are still not mature enough to fully meet the technical requirements of intelligent mine .

In addition to the needs for further research on key technologies of MLBS, The Relevant technical specifications and standards for MLBS is also critical, such as positioning devices interface standards, Positioning radio communication protocols, map information transmission specifications, System service application interfaces, etc.

Looking forward to the mine application scenarios of the high-precision MLBS, the system should be able to meet various technical requirements such as positioning, tracking, navigation and coordination of different scenarios and different targets, including: 1) Accurate positioning and safety management of underground personnel; 2) Underground search and rescue autonomy tracking and path planning; 3) Underground locomotive traffic guide; 4) Underground logistics and transportation control; 5) Underground operator-machine approach safety monitoring; 6) Direction correction of underground tunneling equipment 7) Automatic coordinated operation of mining equipment; 8) underground unmanned equipment navigation and so on.

With the further development and application of advanced intelligent technologies and equipments in present mine construction, high-precision MLBS will play an increasingly important role as a primary technical infrastructure.

Declarations

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Authors' contributions: BAO Jianjun designed the system architecture, wrote the draft and WANG Haibo provided important guidance and gave a detailed revision. All authors have read and approved the final manuscript.

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Figures

Figure 1

System architecture of MLBS

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Figure 2

UWB/DR Fusion method

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Figure 3

MLBS Distributed Service Deployment

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Figure 4

MLBS high precision map and 4D visualization

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