Accurate Wireless Tracking for Underground Mining

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Abstract—**Improvements in underground wireless tracking technology are critical for improved safety and productivity in underground mines. While the recent focus on technology development has been for underground coal mines, improvements are required for block caving operations which have very different characteristics from coal mines. Block caving is characterized by a large number of draw points from which the mineral ore is extracted from under the ore body, and efficient and safe operation of such a mine requires careful monitoring and control of the distribution of ore extraction from the draw points. In this paper a new algorithm is presented for accurately tracking mine vehicles in an underground mine with a low density of reference nodes. A system is described that was installed at an operation mine, and results from a year long trial are presented. The results showed that the system is capable of accurately tracking ore extraction in an operational mine, and of reliable operation over an extended period of time.**

Keywords- Underground Mine, Wireless Tracking, Time of Arrival

I. Introduction

Block caving is used to mine massive steeply dipping ore bodies with appropriate mechanical properties. It is a large scale technique that is typically applied to massive and low-grade ore bodies [1]. Mining commences under the ore zone by creating a large void underneath an area of unsupported rock. Gravity, in conjunction with the generated internal rock stress, fractures and breaks the rock mass into pieces that fall (cave) into the void and break into pieces that can be handled by mining equipment. A series of extraction drives are established under the ore body, and branch out into a large number of draw points from which the ore is extracted (see Figure 1). As ore is removed from the draw points the void is (again) opened and ore continues to caves in, providing a steady stream of ore. The extraction of ore from the draw points must be carefully controlled for the safe and efficient operation of a block caving operation. Hence for this reason tracking the production, including the weight of ore and the location (draw point) from which it was extracted, are extremely important.

There are a number of other benefits for wireless tracking in block caving operations in particular and underground mines in general, and the most important of these is to enhance miner safety. Mining is an intrinsically hazardous operation, given the unknowns in rock structure and ground stresses as well as operating in confined spaces with large mobile equipment, and has a high injury rate of the small underground workforce relative to most other industries. A number of high profile accidents leading to a multiple casualties have resulted in legislation, such as the MINER (Mine Improvement and New Emergency Response) Act [2] in the United States, to improve mine-safety technology. Wireless post-accident communication and tracking technology is a key part of this [3]. Wireless tracking technology is also starting to be deployed in underground mines to reduce collisions between personnel and mobile plant. Besides improved safety, wireless tracking enables better monitoring of production, vehicle management in the long underground drives to the caving operation, and monitoring and control of autonomous vehicles.

There have been several recent publications on tracking in underground mines, but these have almost entirely focused on post-accident recovery in coal mines. The main classes of techniques are the use of Radio Frequency Identification (RFID) and mesh networks with the use of received signal strength (RSS) [3,4]. These systems provide low tracking accuracy, with the accuracy of RFID systems limited by the density of installed readers, and RSS techniques limited by variability in the propagation environment due to large mobile plant. The accuracy achieved by systems currently installed in operational mines is typically no better than tens of metres. This is sufficient for knowledge of the location of personnel immediately before or after an accident (such as methane explosion), but not for routine productivity and safety enhancement where personnel may normally operate within several meters of mobile plant.

It is also important to note that the propagation environment in a block caving mine is very different from a coal mine. Coal mining follows a continuous seam and uses methods such as room and pillar [1] or long wall mining, resulting in a different tunnel topology compared to a block caving mine. Furthermore the draw points in a block caving mine may be separated by less than ten meters, hence high accuracy tracking is required to monitor the extraction of ore from individual draw points.

We have developed a system for tracking vehicles, and personnel, in underground mines. In this paper we describe the system and report on a trial that was conducted at an operation block caving mine over a period of one year. The system is described in Section II, then in Section III we describe in some detail the tracking algorithm that was developed to allow accurate tracking with a low density of reference nodes. Section IV then presents some results from the trial.

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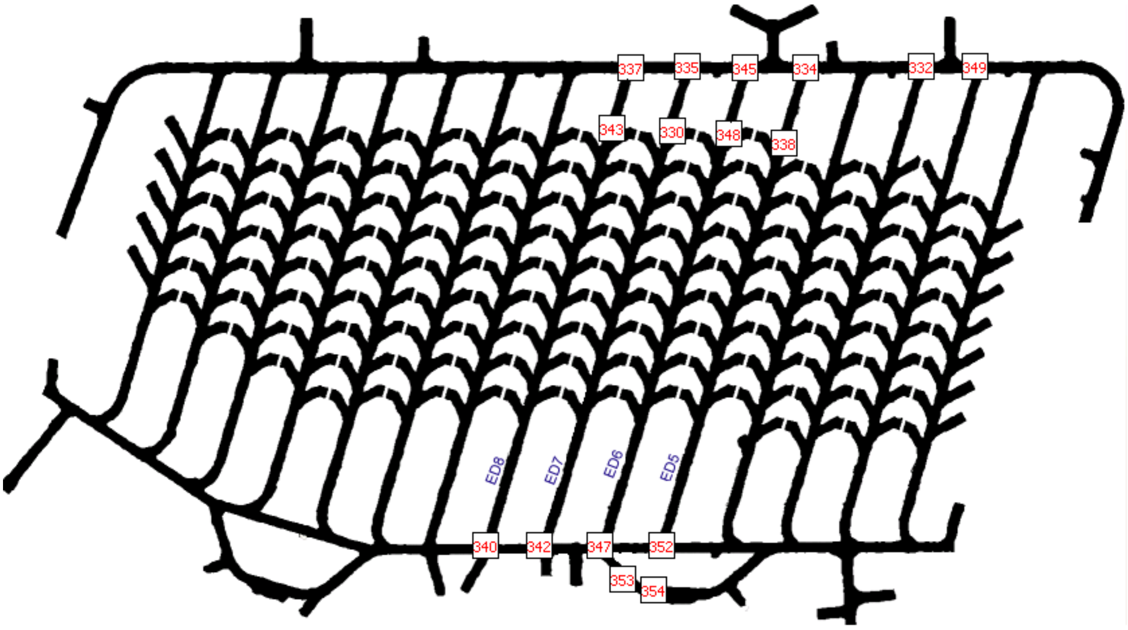

Figure 1: Layout of tunnels for block cave mine in which the trial took place. Four of the extraction drives were instrumented, shown as ED5 – ED8. The location of the WASP anchor nodes are shown as red node numbers in rectangles. The draw points are at the end of the branches from the extraction drives, and terminate at the ore that has collapsed from above (hence they do not provide access between extraction drives). The extraction drives are approximately 250 m long, and the draw point branches are separated by typically 9 m.

II. TRACKING SYSTEM

A. *WASP Technology*

The mine tracking system is based on the WASP (Wireless Ad-hoc System for Positioning) technology that has been previously described in the literature ([5] and references therein). The platform was developed for accurate tracking and high-rate data communications using low-cost hardware in difficult radio propagation environments (e.g. strong multipath interference).

Tracking is based on round trip ranging using time of arrival (TOA). In order to maximize accuracy WASP signaling uses the 125 MHz bandwidth available in the 5.8 GHz frequency band allocated for industrial, scientific and medical (ISM) purposes. The super-resolution TOA algorithm [6] is capable of accuracy down to just half a nanosecond. The transmit power is typically 50 mW, and this can provide a communication rate of up to one kilometer.

B. *System Architecture*

The architecture of the tracking system is illustrated in Figure 2. The small blue boxes in the diagram are anchor nodes that provide the reference for tracking and multi-hop communication links. The larger grey boxes (enhanced node) contain the functionality of the blue boxes, and have additional hardware to support multiple roles:

- Use as a collection point to provide a real-time feed of data. For this support the grey boxes have an Ethernet connection. In the figure box number 11 has this function and is shown providing data to an operator in a control room via the mine network.

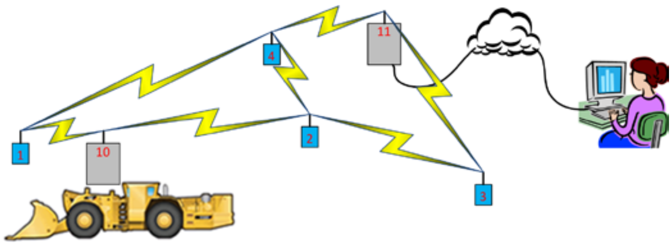

Figure 2: Architecture of deployed system.

- Use on vehicles for tracking, such as node 10 in the figure. For this support the grey boxes also have:
  - A serial port to read load weights from the vehicle;
  - A computational device to calculate range to connected nodes (blue box and grey box), and to periodically transmit this over the WASP network.

The nodes form a robust mesh network, with wireless communication links illustrated with yellow "lightning bolts" in the figure. The grey box in each vehicle periodically computes the range to nodes to which it is directly connected via the WASP wireless network. These ranges, along with the bucket load weight, are transmitted as data packets through the WASP data network where they are received by node 11 (Ethernet gateway node). This acts as a server for the tracking system, and provides the information to a remote client via the mine network (typically with an Ethernet interface). The client is located in the control room on the surface of the mine, and provides real-time information on node locations and network diagnostics.

Figure 3: System anchor (reference) node.

C. System Hardware

The system consists of anchor nodes (shown in Figure 3) that are mounted in the mine at fixed locations and receive the mine 24 V power supply, and enhanced nodes (shown in Figure 4) that are mounted in vehicles (for tracking those vehicles) and at a fixed location in the mine to act as an server.

Both nodes contain a WASP circuit board that provides communication and TOA measurement. The anchor node is mounted in a rugged box with an IP67 environmental rating that has connectors for power (24 V) and an antenna, and internally also contains a DC-DC converter. An externally visible LED shows that the node is powered. In addition to WASP hardware and a DC-DC converter, the enhanced node contains a single board computer (SBC) with an Intel Atom N450 processing running Windows XP. There are external connectors for power, an antenna, Ethernet (when used as a server), and a serial port (that connects to a weigh cell on Load-Haul-Dump (LHD) units to measure the weight of ore transported). The SBC in each vehicle computes the range to each anchor node, and transmits weight and range to the server. Both types of nodes used a vertically polarised monopole antenna with a gain of 7 dBi, which are visible in the figures.

III. Tracking Algorithm

WASP technology uses a previously described algorithm [5] to compute range based on round trip measurements of TOA [9]. Range measurements are transmitted to the server, which computes the locations of the mobile nodes. The dense network of extraction drives and draw points in a block caving mine can required a large number of anchor nodes, and for economic reasons a bare minimum is used. Thus the tracking algorithm must be capable of operation through significant areas where range is acquired to only one or two anchor nodes. This section describes the tracking algorithm. For simplicity only a single mobile node is considered, and all mobiles are tracked independently using this algorithm.

Figure 4: System enhanced node (grey box with antenna) mounted on a light vehicle used in the mine.

A. System Model

The mobile node makes a range measurement to each neighboring anchor node (the set is denoted $\mathcal{N}$) every second, and this set of measurements at time index k is denoted by

$$\mathbf{z}_k = \left\{ r_{k,i} \mid i \in \mathcal{N} \right\}. \tag{1}$$

The state of the mobile at time step k, $\mathbf{x}_k$, is the two-dimensional location of the mobile. As underground vehicles are usually travelling slowly or stationary a constant position motion model is used for simplicity:

$$\mathbf{x}_k = \mathbf{x}_{k-1} + \mathbf{v}_k \tag{2}$$

The process noise is assumed to be normally distributed with a standard deviation sufficient to allow for vehicle motion. The maximum speed is typically about 10 m/s, and for a one second update interval a standard deviation of 5 m in the two components of the state vector is a reasonable choice.

The measurement equation is the distance $r_{k,i}$ from anchor i at location $\mathbf{p}_i$ to the unknown mobile location $\mathbf{x}_k$ at time step k,

$$r_{k,i} = \left\| \mathbf{x}_k - \mathbf{p}_i \right\| + n_{k,i}. \tag{3}$$

The measurement noise n will now be described.

B. Range Measurement Noise

While it is possible for a calculated range to be shorter than the true range due to noise in the TOA measurement or signal processing artifacts, it is more likely to be longer than the true range due to the effects of multipath propagation and an undetected direct path signal. Thus n is biased, and a model that we have found to work well is now given. Let the range error be defined by

$$e_{k,i} = r_{k,i} - \left\| \mathbf{x}_k - \mathbf{p}_i \right\|.$$

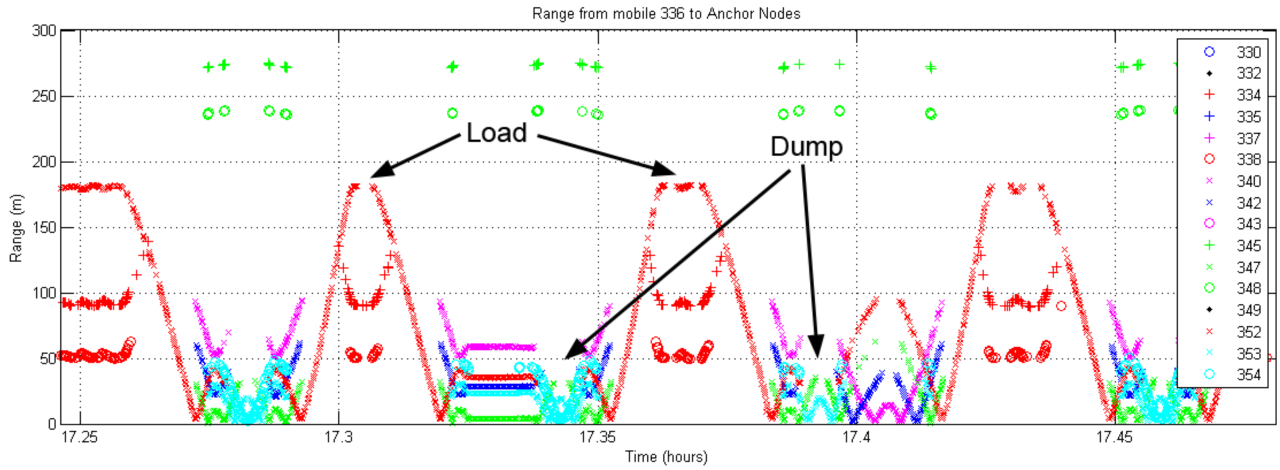

Figure 5: Plot of measured ranges from anchors to LHD while extracting ore from ED5 and dumping it at the crusher.

The simple model for the range likelihood that we have found to work well [8] is

$$p_{R'}\left(r_{k,i} \mid \mathbf{x}_k\right) \propto \begin{cases} 1+\dfrac{e_{k,i}}{R_N} & e_{k,i}<0 \\ 1-\dfrac{e_{k,i}}{R_P} & e_{k,i}\geq 0 \end{cases}$$

The thresholds R_N and R_P define the expected range of errors, with $R_N < R_P$. To allow for the small possibility that a range measurement is an outlier (i.e. large error), as well as preventing negative probabilities, we then apply the following:

$$p_R\left(r_{k,i} \mid \mathbf{x}_k\right) = \max\left(p_{R'}\left(r_{k,i} \mid \mathbf{x}_k\right), 0.01\right). \tag{4}$$

C. *MAP Location Estimate*

A Bayesian approach is used to determine the location of the mobile node. The *a posteriori* distribution is defined by the following recursive equations [7]:

$$p\left(\mathbf{x}_k \mid \mathbf{z}_{1:k-1}\right) = \int p\left(\mathbf{x}_k \mid \mathbf{x}_{k-1}\right) p\left(\mathbf{x}_{k-1} \mid \mathbf{z}_{1:k-1}\right) d\mathbf{x}_{k-1} \tag{5}$$

$$p\left(\mathbf{x}_k \mid \mathbf{z}_{1:k}\right) = \frac{p\left(\mathbf{z}_k \mid \mathbf{x}_k\right) p\left(\mathbf{x}_k \mid \mathbf{z}_{1:k-1}\right)}{p\left(\mathbf{z}_k \mid \mathbf{z}_{1:k-1}\right)} \tag{6}$$

From the model in (2), (5) can be implemented as a convolution of the *a posteriori* distribution with a Gaussian kernel. The denominator of the right hand term in (6) is a normalization value and can be ignored as normalization of the density will be performed at the end of the calculations. The likelihood function is given by

$$p(\mathbf{z}_k \mid \mathbf{x}_k) = p_C\left(\mathbf{z}_k \mid \mathbf{x}_k\right) \prod_{i \in \mathcal{N}} p_R\left(r_{k,i} \mid \mathbf{x}_k\right) p_S\left(\mathbf{x}_k \mid \mathbf{p}_i\right). \tag{7}$$

Range measurements to different neighboring anchors are assumed to have independent errors. This equation consists of the following terms:

- p_R is the probability of the measurement for an assumed mobile location, and was given by (4).
- p_S is the probability that a range can be measured to location $\mathbf{x}_k$ given the location of the anchor node and the map. A shadow map is pre-computed using ray tracing from the anchor node, allowing for diffraction. The map contains a value at a regular grid of locations, which is:

$$p_S\left(\mathbf{x}_k \mid \mathbf{p}_i\right) \propto \begin{cases} 1 & \text{line of sight to anchor} \\ 0.01 & \text{non line of sight to anchor} \\ 0 & \text{rock (invalid location)} \end{cases} \tag{8}$$

- p_C assists with ambiguous locations when only a single range value is available by considering the configuration of nodes and the range measurements that were not obtained. For example if the only measurement for a mobile is a range of 20 m to anchor node 342 in Figure 1, then there are three possible locations for the mobile, two are in the southern drive with nodes 340 and 347 on either side, the other is in ED7. The last is more likely as otherwise we would have expected a range measurement to nodes 340 and/or 347. In this example p_c for locations in ED7 would have a value of unity, and the value would be 0.1 in the southern drive.

Once the *a posteriori* distribution has been determined, the maximum *a posteriori* (MAP) location of the mobile at time step k is determined using

$$\hat{\mathbf{x}}_k = \arg\max_{\mathbf{x}} p\left(\mathbf{x}_k \mid \mathbf{z}_{1:k}\right).$$

D. *Implementation*

The probabilities are calculated on a regular grid of locations. As the probability of being in the rock is zero the probabilities are only calculated at locations within drives. The prior distribution defined in (5) is obtained by blurring the previous *a posteriori* distribution with a Gaussian kernel. The current *a posteriori* distribution is calculated at each valid grid point using the numerator of (6) and (4,7,8). This is normalized to sum to unity prior to the next time step, and the location with the maximum value is the MAP estimate of mobile location.

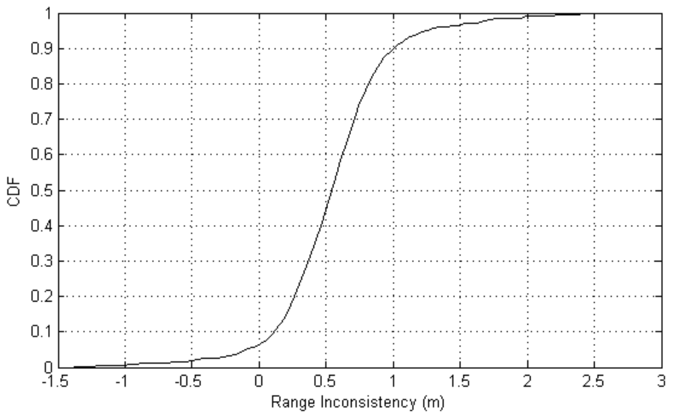

Figure 6: Range inconsistency for vehicle travelling along ED5.

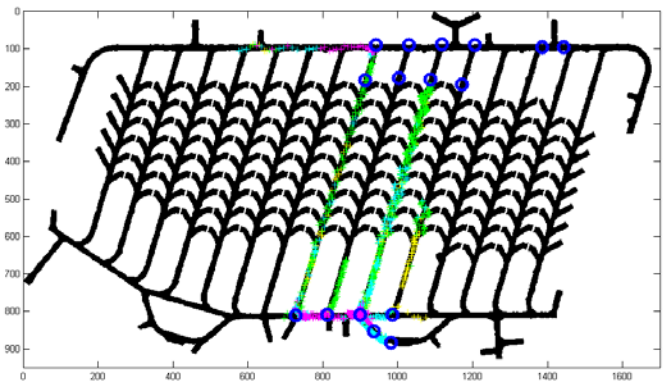

Figure 7: Recorded locations for drive. Blue circles are locations of anchor nodes, + are calculated locations of vehicle, with colour depending upon number of anchors visible at that location (1:yellow, 2:green, 3:cyan, 4+:magenta).

IV. Mine Trial

The trial was conducted in a section of an operational block caving mine. A plan of a section of the mine is shown in Figure 1, and as shown the trial was limited to four extraction drives containing 71 draw points. Anchor nodes were placed at each end of the extraction drives in the perimeter drives. Although WASP is capable of ranging the full length of the extraction drives (roughly 250 m), the non-uniform elevation change along the drives, combined with ventilation closures, prevented these nodes providing full coverage and an additional node was installed in each extraction drive. Two servers were installed, nodes 332 and 349, the second for redundancy. The location was dictated by access to the mine Ethernet infrastructure.

Mobile nodes were installed in a light vehicle used in the mine (as shown in Figure 4), and in Load-Haul-Dump (LHD) units that extracted ore from draw points and dumped it at the crusher near node 354. The purpose of the trial was to monitor operational vehicles over an extended period of time and to evaluate the information provided by the system.

An example of the raw data extracted from the system for an operational LHD is shown in Figure 5. This shows the range measurements, and is annotated to show where ore is loaded and dumped. Combined with information from the weigh cell, that is also transported through WASP network, this allows the extraction of ore to be accurately monitored. An algorithm was developed to automatically determine when ore was extracted and dumped from this data. The values for R_N and R_P were empirically determined and were 4 m and 6 m respectively.

With no independent measurement of vehicle location available it was not possible to determine the absolute accuracy of the system, however with multiple range measurements available their consistency can be estimated. The distance between pairs of anchor nodes in each tunnel is known, and given the constraints of the tunnel these and a vehicle are almost exactly co-linear. The difference between the sum of the two ranges and the known distance is the estimated error, and is plotted in Figure 6. The error is almost always within 2 m, which is more than sufficient to reliably determine the draw point from which ore is extracted (separated by typically 9 m for this mine). A manual comparison of 253 load cycles demonstrated 100% reliability in determination of draw point.

Figure 7 shows the calculated location of a light vehicle travelling through part of the monitored area. It is seen that tracking is successful even through regions where there are only one or two anchors available.

V. Conclusion

This paper described a new system and algorithm for wireless tracking and communication in underground mining. Results from a long-term trial demonstrate that the system is reliable and capable of achieving sub-meter accuracy.

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