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Investigation of Indoor Positioning Technologies for Underground Mine Environments

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Abstract. Positioning in underground mining environments is a key requirement for ensuring the safety of mine workers. It is also a critical technological capability in resolving mine productivity bottlenecks, which has a great economic impact in Australia. To support the growth of the mining sector, innovative technologies need to be developed, with underground positioning an important though significant engineering challenge. This paper aims to demonstrate a robust high accuracy positioning system for underground mining environments to meet the requirements of worker safety and mine efficiency improvement. Several technologies which could be part of the "mix" in the solution to the challenges have been identified. Tests have been carried out in a metal mine. Radio Frequency signal plus Inertial Measurement Unit, multisensor integration, geomagnetic field positioning and ultra-wide band have been tested. The data are analysed and the results are reported.

Keywords: Indoor positioning, Underground mining

1 Introduction

The safety of mine workers is one of the highest priorities of Australia's mining industry. When an accident occurs, the immediate initiation of a search and rescue response is vital, because the survival rate decreases rapidly as time passes - the so-called "golden 72 hours" [1]. The greatest unknown for the rescue team is to know how many people are trapped and where they are located. If the locations of the victims are known, time could be saved and the chances of success markedly improved. Consequently, knowledge of mine workers' position is highly correlated with their safety. In the worst case, when an underground positioning and communication system is completely disabled, the last known position of the miners is extremely useful.

A key objective of the mining industry is to achieve zero-harm in every work place through continuous improvement, intensive training, introducing advanced work practices and implementing new technologies. Considerable effort has been made to develop safety-related technologies, via new training systems, legislation and regulations [2][3]. However, mine disasters still occur. The ordeal of the two survivors of the Beaconsfield Mine in Australia in April 2006 still resonates. On 19 November 2010, the Pike River Mine accident killed 29 people and injured 2 in New Zealand. Just a few months earlier in the United States 29 people were killed in the Upper Big Branch Mine disaster. In developing countries, mine disasters occur more frequently and are more serious. For instance, in 2014 the Soma coal mine disaster in Turkey killed 301 workers [4]. In China, although the number of deaths has decreased over the past 10 years, it was still almost 1500 in 2012 [5].

In addition, according to [6], position determination has been identified by the mining industry as one of the technologies critical to resolving major mine productivity bottlenecks. Positioning is associated with process optimisation and control, operation and maintenance. For instance, if any equipment needs repair, the location of the equipment is needed before a technician can be sent underground. Knowing the location of people and equipment, and the patterns of their movement can also improve productivity.

For open-pit mines or other surface activities, the Global Navigation Satellite System (GNSS) is the preferred technology. However, positioning in the underground mine environment is a challenge due to the lack of a GNSS-like technology. The positioning systems on the market can be classified as belonging to one of two generations. The first-generation products use radio-frequency identification scanners to monitor the tags carried by the workers passing a scanner. It can only report proximity to a scanner if a worker moves into an area [7]. The second-generation products typically use Zigbee or WiFi to trilaterate the location of the workers using the communications signals. This kind of system requires deployment of many Zigbee nodes or WiFi access points, which typically makes the implementation of such systems more expensive [8].

A new generation system requires quick deployment, positioning on server and client sides, high accuracy, and large coverage area, as well as cost effectiveness. We are seeking an elegant solution: utilising innovation in a variety of fields - including radio frequency (RF) signal, geomagnetic field, low-cost inertial measurement unit, and others - deploy as few as possible of the signal transmitters, develop a novel algorithm to integrate these technologies to achieve global (i.e. whole underground mine area) positioning.

2 Our Approaches

2.1 BLE Signal Propagation Model

Bluetooth Low Energy (BLE) can be used to transmit the RF signal which can give the distance from the transmitter to the receiver. It is a low-cost technology that has low power consumption – an AA size Lithium-ion battery (2700mAh) can power it for over 3 years.

Radio waves are affected by many phenomena such as reflection, refraction, diffraction, absorption and scattering etc. The propagation of radio waves is characterized by several factors. When all the factors are considered, the loss is

$$L = d^{n}\left(\frac{4\pi}{\lambda}\right)^{2} + L_{a} \tag{1}$$

where d is the transmitter-receiver separated distance, L_a is the attenuation caused by obstacles, n is the path loss exponent (2 in the case of free space) and λ is the wavelength (2.45 GHz, the centre frequency of 2.4 GHz band). Expressed in decibels

$$L(dB) = 40.23 + 10 \times n \times \log(d) + L_a(dB) \tag{2}$$

When a signal is propagating along a corridor, normally the wave guiding effect might make the exponent lower than 2. However, since the BLE node was installed 3 meters above the ground and when the range is calculated, the height is not considered, the value of 2.1 was used. If the propagation is LOS, *La* can be ignored. The d can be estimated based on Equation (2).

Obviously, using model to convert signal strength to range is not very accurate, however, based on the signal strength, one can detect if the receiver is close to a BLE node. To estimate more accurate position of the receiver, other technologies are required.

2.2 Using IMU to Estimate the Distance

A low-cost IMU is used to detect the worker's steps, and then used to estimate the distance the person has travelled (using a vehicle is another case to be investigated). RF signal and magnetic field sensors can be used to (re)initialise the IMU.

In order for the step detection algorithm to work independently of the device's orientation, only the amplitude of the acceleration is retained.

$$a_k = \sqrt{a_{x_k}^2 + a_{y_k}^2 + a_{z_k}^2} \tag{3}$$

Then the Earth's gravity is removed from the values by applying a high-pass filter to the acceleration amplitudes. General speaking, there are two types of algorithm can be applied for step detection, one is operating in time domain; the other is operating in frequency domain [10]. A Fast Fourier Transform (FFT) based algorithm and a windowed peak detection algorithm were tested. The FFT based algorithm was chosen as it was more reliable in most of the scenarios.

Once the step frequency has been estimated, the step size is still needed in order to compute the estimated speed of the user. In our context, the step size is defined as the distance from the heel of one foot to the heel of the other foot. There are many different models to estimate the step size. For instance, in [11], the step size is assumed to increase linearly with the step frequency. However, the step size is not only a function of step frequency but also depends on the height of the user. In [12], the step size is modelled as a linear function of the height ls=k*h where k only depends on the sex of the user. In our application k varies linearly with the step frequency following this model:

$$\begin{cases} l_s = (a + b \cdot f_s + \varepsilon) * h \\ \varepsilon \sim N(0, \sigma_s) \end{cases} \tag{4}$$

The parameters of the model (a,b,σ_s) are estimated from empirical data.

2.3 Magnetic Field Positioning

The magnetic field can be utilised to improve the positioning accuracy between two RF signal transmitters. When some of the RF transmitters are switch off, due to an accident or a flat battery, magnetic field positioning can be used instead. However, a smart way must be developed to create and maintain the magnetic field database.

Previous research [9] has revealed that the stability of the magnetic field implies that travelling along the same path will generate the same curve and applying fingerprinting technology is not reliable as in reality only two elements (the vertical component and horizontal component of the magnetic field) can be used.

As the tunnel restrains a worker's movement, it is more reliable to apply pattern matching for positioning. The magnetic curve matching algorithms is required using magnetic field for positioning. A few matching algorithm have been investigated.

2.4 Other Technologies

Barometers can detect the change of air pressure, and the change can indicate the movement of the sensor in the vertical direction [13]. Ultra-wideband (UWB) systems can provide 10cm level positioning accuracy.

3 Testing and Analysing

3.1 Testing Bed

The testing bed was selected in a copper and gold mine located in New South Wales, Australia which is a block cave underground mine. The area chosen for our test is about 5km away from the entrance of the mine and 500m under the surface level. The part highlighted with green is chosen to deploy our BLE tags and carry out most of the tests (see Figure 1). The drill drives along the tunnel have been mined out; it is quiet and ideal for testing. The straight line part of the highlighted tunnel is about 100m and the curve part is about 70m. The floor of the first 90m is relatively flat, the altitude only decreases slightly, however, the change of altitude is significant although the exact value is unknown. The tunnel is about 5m wide and 5.5m high (refer to Figure 1).

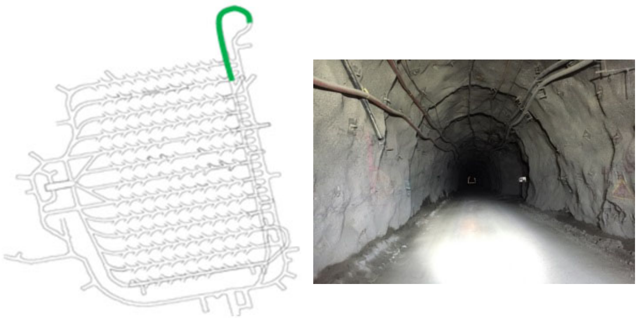

Fig. 1. The location of the testing bed (the tunnel marked green)

3.2 Testing setup

For this test, two data logging system has been developed. One is based on a STM32 development board, the other is based on Raspberry Pi 3B, details can be found in Figure 2. The reasons that two loggers were developed are to evaluate more IMU unites and to make sure at least one set of data can be collected successfully. 170m was measured using tap measure and every ten meters a mark was painted on the wall. A BLE tag was installed on the square plates attached to the ground support (bolt) on the side-wall about 3.5m above the floor. The tag was installed align with the mark as good as possible. In total, 17 BLE tags were installed.

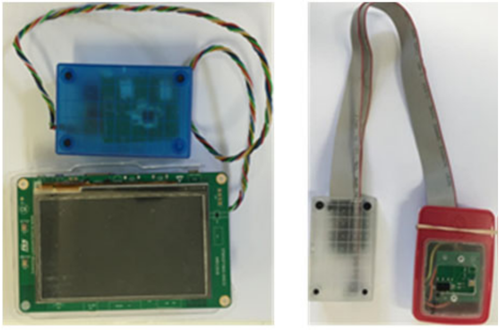

Fig. 2. Data loggers: Data logger A based on STM32F746NG Cortex M7 Discovery Development Board, IMU (BNO055), BLE, temperature and air pressure (BMP180); Data logger B based on RPi 3B with IMU(LPMS-ME1), BLE (RPi 3B built in), temperature and air pressure (BMP180)

3.3 BLE positioning

Figure 3 shows the BLE board used for this test (left) and the relationship between signal strength and distance (right). The signal strength drops quickly with distance increasing below 10m, then the rate decreases and the curve gradually becomes flatter. This is a typical RF signal propagation phenomenon.

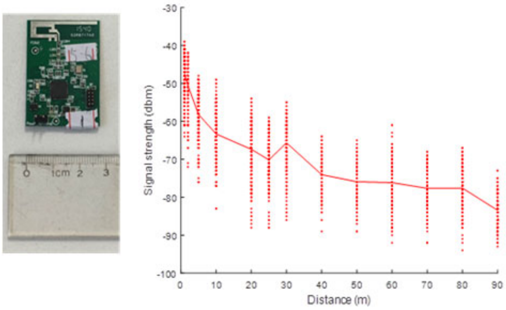

Fig. 3. An BLE transmitter and the relationship between signal strength and distance.

When there are a few BLE transmitters deployed in a line (as in the case of a tunnel), a moving receiver (carried by a person) can detect the change of the nearby BLE transmitters' signal strength, and these changes should be useful for locating the receiver. Two testers carried data logger A and B respectively (the rectangular box was attached to the waist of a tester), walked along the testing path started from 0m mark to 170m mark and then turned around, back to 0m with a speed that was judged as constant as possible. The tests have been done four times and then the testers swapped the devices, carried out another three rounds of tests. Figure 4 (left) shows the variation in received signal strength of one of the test. Clearly, there are 33 peaks of signal strength, which indicate the location when the BLE receiver passed by a transmitter. These peaks, together with other signal strength measurements, can be used to determine the receiver's range from a reference location. Figure 4 (right) compares the estimated range based on the received signal strength and the true (known) range.

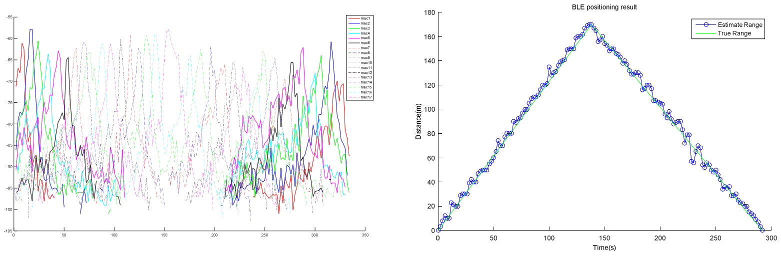

Fig. 4. The received signal strengths when a receiver moved along a tunnel with a constant speed (left) and the estimated range vs true range (right).

3.4 Dead Reckoning

"Dead reckoning" is a well-known relative navigation technique. Starting from a known position, successive position displacements are estimated and then accumulated. Pedestrian Dead-Reckoning (PDR) solutions integrate step lengths and orientation estimations at each detected step, so as to compute the final position and orientation of a person. Inertial Measurement Units (IMU) typically comprises several accelerometers, gyroscopes, and perhaps magnetometers. A low-cost IMU can be used to estimate a person's relative position by implementing a PDR-type solution.

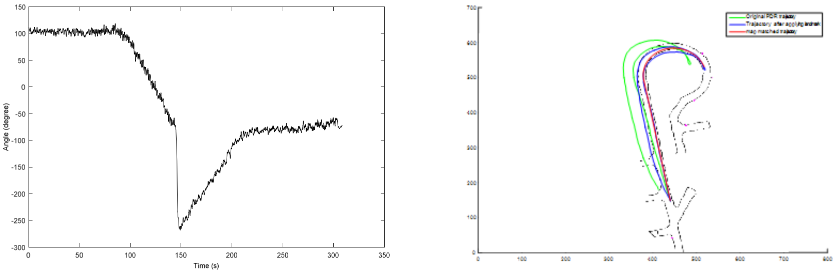

Fig. 5. The angle data collected by an IMU (left) and the trajectory of the IMU (right)

Figure 5 (left) is a plot of the angle data collected during the test. It can be seen that the tester walked along the straight line first, and then started to turn in the curve part. The significant change indicates that the tester turned around and moved back to the start point along the same path. After applying the step detection and step length estimation, the trajectory of the IMU (the tester) is shown in Figure 5 (right) (the green line). Obviously, the trajectory gradually drifts away from the real path. After applying landmark (where the turning around was detected) correction, the result can be improved significantly (the blue line). The further improved red one is the final trajectory after applying map matching. BLE and magnetic field positioning can be used as landmarks to correct the drift of the PDR solution.

3.5 Magnetic Field Based Positioning

The main issues of magnetic field positioning are the database creation and the positioning algorithm. The proposed database creation will be separated into two phases. In the first phase, when the system is deployed, the magnetic field data will be collected. This is the basic database. In the second phase, while the positioning system is running, the mine workers will collect the data which will be used to refine the database.

The test was carried out in the same testbed. An Xsens Mti-100 was used to collect the magnetic field data. A tester carried the IMU, walked from start point to end point and back to start point, twice. The data collected in the first traverses were used as the reference dataset, and that of the second traverse was used as the testing data. After applying a low-pass filter to remove the noise and using an averaging window to reduce the sampling frequency (from 100Hz to 20Hz), the dynamic time warping (DTW) [14] pattern matching algorithm was applied. Only the magnitude (total intensity) was calculated. Figure 6 illustrates the results. The blue, green curves in figure denote the reference data and testing data respectively. The testing data were divided into small fractions (every 10s) to apply pattern matching separately. Most of the matching of the fractions is successful; however the matching of the first and the last fraction is failed. There could be two reasons: At the start point or end point, the tester changed his status from static to dynamic or vice versa, it is much harder to control the speed; also, the tester's gesture might be different at each test.

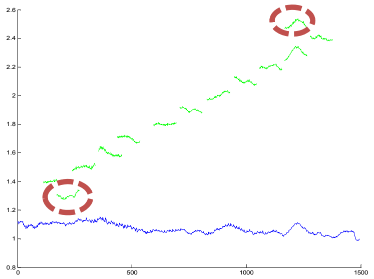

Fig. 6. Magnetic field pattern matching (based on the magnitude matching only, DTW matching algorithm applied), only the first and last piece was mismatched.

4 Concluding Remarks

The testing in a typical metalliferous mine has demonstrated the feasibility of a cost-effective positioning system for underground mining environment based on multiple technologies. The received signal strength of BLE beacons alone can be used for positioning if there are densely deployed beacons. Applying the step detection and step length estimation based on IMU can generally provide an accurate estimation of the position if re-initialisation based on landmarks and map matching can be applied. A sparsely deployed BLE beacons can be used as a type of landmark as well as the magnetic field. Collecting magnetic field data for underground mine is not an easy task; however, crowd sourcing is a possible solution. After several rounds of iteration, it is possible to build a reliable database. Other sensors such as a barometer which can obtain the change of the height can also be used to provide the landmarks. Although UWB can provide accurate range estimation, the requirement of external power supply for the base stations and high power consumption of the tags makes this technology not cost-effective.

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