Third Generation Positioning System for Underground Mine Environments: An update on progress

Binghao Li
ACSER, School of EE&T, UNSW Australia
+61-2-93850783, binghao.li@unsw.edu.au
Kai Zhao, Serkan Saydam
School of Mining Engineering, UNSW Australia
Chris Rizos
School of Civil & Environmental Engineering, UNSW Australia
Jian Wang
School of Environment Science and Spatial Informatics, CUMT, China
Qiang Wang
College of Applied Science and Technology, CUMT, China,

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. Australia is one of the world's largest mining nations and a significant player in mining-related research and development. To support the growth of the mining sector, innovative technologies need to be developed, with underground positioning an important though significant engineering challenge.

An Australian Research Council Linkage Project (ARCLP) granted in 2015 aims to demonstrate a robust high accuracy positioning system for underground mining environments to meet the requirements of worker safety and mine efficiency improvement. This paper reports on the latest progress of this project.

KEYWORDS: Underground; Indoor positioning;

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 (RFID) 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 Wi-Fi to trilaterate the location of the workers using the communications signals. This kind of system requires deployment of many Zigbee nodes or Wi-Fi access points (APs), which typically makes the implementation of such systems more costly [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.

The ARCLP awarded to the authors aims to design a prototype robust, high accuracy, wide-area positioning system for underground mine environments to meet the requirements of emergency tracking and mine productivity improvement.

2. REVIEW OF RELATED TECHNOLOGIES

Positioning in underground mine environments is a technically challenging problem [9]. Underground mine environments have numerous obstacles that prevent the use of the same techniques typically used for outdoor and other indoor environments. For instance, it is impossible to receive satellite signals underground. High sensitivity GNSS and assisted GNSS [10] cannot be used under such conditions.

Several techniques that have been widely used for indoor positioning, such as RF-based trilateration and triangulation, have been found to be extremely difficult to deploy underground [11]. Trilateration is a technique using range measurements, while triangulation uses angle measurements to estimate the position of the miners or device [12][13]. Underground mine environments generally consist of long and narrow tunnels, typically 100s of meters of length and 5 by 5 m width and height. Using RF-based trilateration/triangulation systems has at least two significant problems. One is that the signal cannot penetrate rocks, hence the coverage is very limited, and the deployment of a large number of transmitters is rarely feasible [8]. The other is that the geometric distribution of signal transmitters is generally very poor due to the limited locations available for their installation. This means that the positioning accuracy is invariably poor [14]. Other problems such as non-line-of-sight (NLOS) signals and multipath are more severe underground because of the nature of the narrow tunnels, hence RF-based (or ultrasound, infrared-based) trilateration/triangulation systems rarely find application in underground mines.

A common system investigated for its potential for underground positioning is the so-called “sensor network” – an application of the concept of the “Internet of Things” (IoT) [7][15]. However, there is a fundamental problem with using sensor networks – a large number of sensors need to be deployed. Considering that a typical underground mine can span an area of $100km^2$, it is very difficult, if not impossible, to deploy enough sensors to cover the entire area of interest.

The “fingerprinting” technique, especially as applied to Wi-Fi signals, is widely used in non-GNSS environments. Measurements of received signal strengths from several Wi-Fi APs are used as the signal “fingerprint” at discrete pre-mapped locations. However, one of the major disadvantages of this technique is the difficulty in creating

the fingerprint database [16]. Methods have been investigated to make the training phase a less burdensome task in terms of labour and time. However, it is still difficult to apply such methods underground. Furthermore, installing sufficient APs underground is not feasible.

Compared with current fingerprinting systems, positioning systems based on RFID are less complicated, and as a result many operational systems have been deployed [17]. Passive RFID systems are generally used for access control. RFID can also provide the user's location by using the "cell ID" or proximity method. When a RFID scanner detects the signal from a RFID tag, the scanner's position can be substituted as the tag's position. Sparsely deployed RFID scanners can only report the area the tags are within. On the other hand, a dense network of RFID scanners is not a realistic proposition.

An Inertial Measurement Unit (IMU) typically consists of accelerometers, gyroscopes and magnetometers. IMUs have been used for GNSS-unfriendly environments. However, the accumulated error quickly makes IMU-derived position accuracy unacceptable, and hence, reinitialisation of the IMU sensors is periodically required [18]. In the case of low-cost microelectromechanical systems (MEMS), the intervals between reinitialisation are very short, of the order of seconds to tens of seconds, which means a large number of reference points (RPs) with known coordinates is required. Such a condition may be difficult to satisfy in many circumstances. Combining an IMU with other positioning sensors is a common solution [9] .

In [11], a map-based "global positioning system" is described. It is necessary to drive a vehicle equipped with sensors to collect data for mapping. To some extent this technique is similar to fingerprinting [16]. The training phase (i.e. data collection) is not a trivial task. Furthermore, this system can only be used for a vehicle equipped with comparatively heavy and expensive sensors.

For many years investigators have been attempting to use very-low frequency (VLF) electromagnetic waves (3kHz to 10kHz) to navigate underground. The main advantage of VLF signals is that they can penetrate much deeper into the ground than higher frequency signals. However, there are difficulties when using either naturally occurring VLF signals (such as those produced by lightning strikes) [19] or artificially generated VLF signals [20].

Recently, using the geomagnetic field for indoor positioning has attracted attention from researchers [21][22]. The use of magnetic field disturbances for underground positioning has several advantages: no pre-deployed infrastructure is required; the magnetic field is everywhere and relatively stable. However, there are also significant challenges, such as: the number of elements that can be used to create the fingerprint database is small, maximum three, though the number could fall to two in many applications [23]; magnetic interferences should be considered, especially in areas close to large equipment.

Clearly no single technology can address the challenge of underground positioning,

and hence integration of several technologies may be the best option.

3. NEW APPROACHES

Based on our previous research, several technologies which could be part of the "mix" in the solution to this challenge have been identified. RF plus IMU, multi-sensor integration and geomagnetic field positioning are the technologies investigated in this paper.

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.

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.

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.

Barometers can detect the change of air pressure, and the change can indicate the movement of the sensor in the vertical direction.

It is unlikely that Ultra-wideband (UWB) systems will be included in the proposed system because of the relatively high cost and complexity. However, it is useful to investigate the performance of UWB positioning systems.

4. TESTING

4.1 UWB Testing

UWB refers to radio technology with a bandwidth exceeding the lesser of 500MHz or 20% of the arithmetic centre frequency. 500MHz bandwidth results in pulses of 0.16ns width, which means that it is possible to do accurate ranging indoors with a lot of reflectors. The range measurement accuracy can be of the order of centimetres. For a typical underground mining environment, an accurate range measurement is enough to position a person or device. Hence a test of Pozyx's UWB system was carried out.

The first test was carried out in an outdoor environment to determine the maximum range of the system and the best accuracy it can achieve without multipath and NLOS propagation. The transmitter's power was set to a maximum. A tripod was set up to host the base station and a rover station was used to make range measurements at 1m, 2m, 3m, 5m, 10m, 15m, 20m, 25m, 30m, 40m, 60m, 80m, 100m and 120m distances. Figure 1 gives the details of the test results. The average measurement error is below 10cm and the maximum range can be up to 100m, although it is still possible to

occasionally make a measurement at 120m.

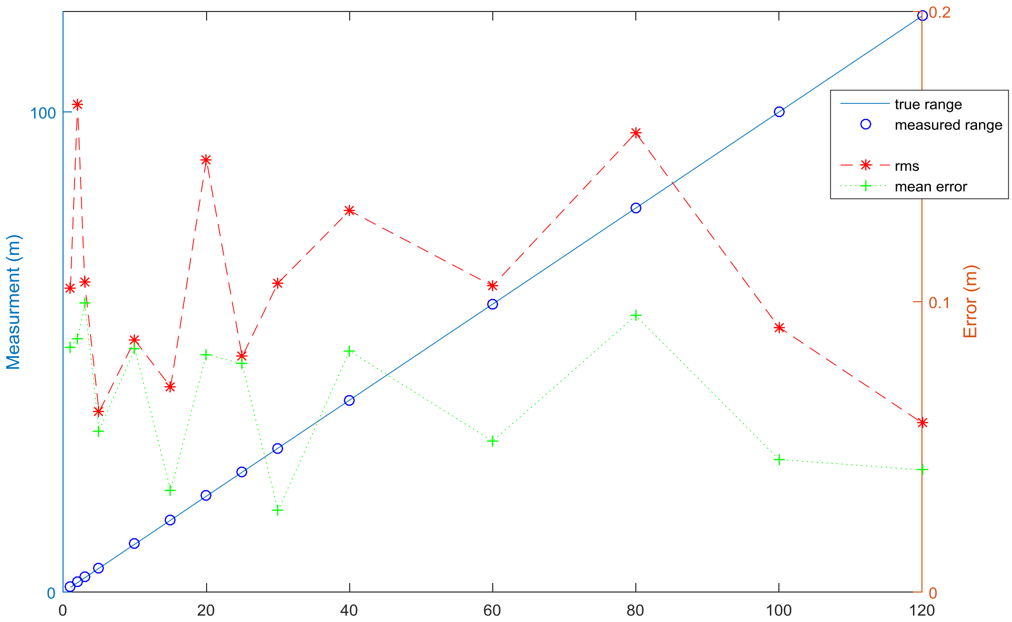

Figure 1. Ranging in an outdoor open area (UNSW Village Green)

As we are more interested in the performance of the system in an indoor environment, a 90m long tunnel-like corridor (UNSW Old Main Building Level Ground) was chosen for this test. The setup was similar to the outdoor test. A researcher moved a rover station to 1m, 2m, 3m, 5m, 10m, 15m, 20m, 25m, 30m, 40m, 50m, 60m, 70m, 80m and 90m distances from the transmitter. Figure 2 shows the test environment and the results. It is obvious that the ranging accuracy is worse than for the outdoor test, but still within 20cm most of the time. The worst ranging error is about 30cm.

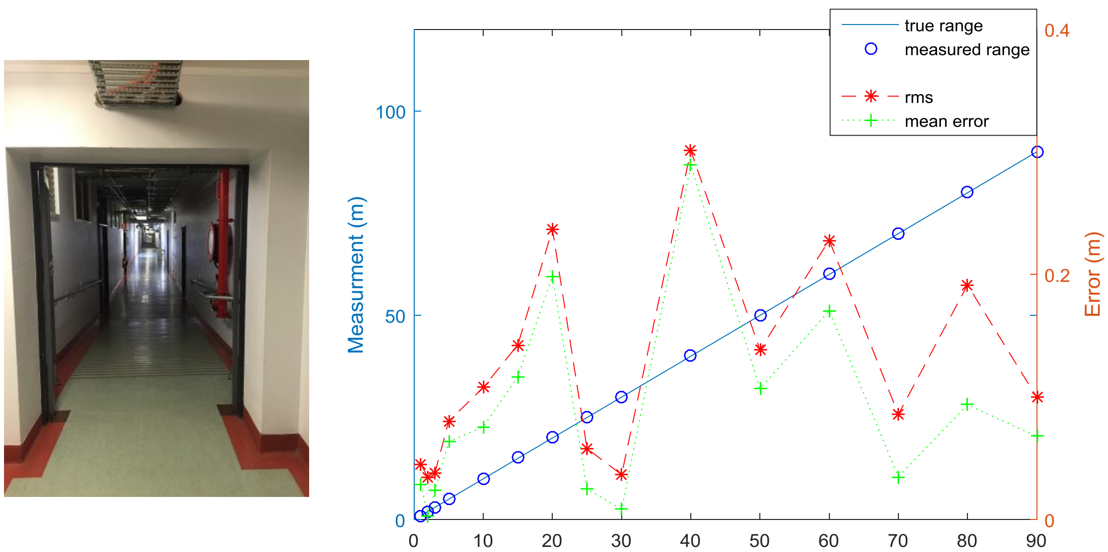

Figure 2. Ranging in a corridor (90m long tunnel-like environment, OMB LG UNSW).

To investigate the performance of the UWB system in NLOS propagation scenarios, the transmitter was set up between two concrete walls (refer to Figure 3, the star denotes the base station). The thicknesses of the two walls are 25cm and 48cm. The rover station was placed on the opposite side of the wall to collect the range measurements – the results are listed in Table 1. Then the base station was setup on the left side, the rover was moved to the right side so that there were now two walls between the two stations – see Table 1. The UWB signal can penetrate the two walls to give range measurements, however the results show that the thickness of the wall may affect the range measurement error. Other issues may also affect this performance such as the presence of signal multipath.

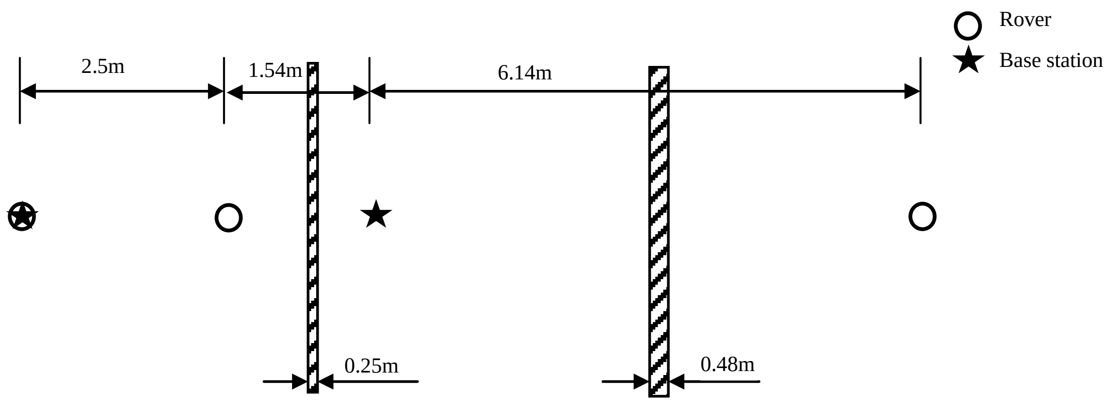

Figure 3. Ranging in a NLOS environment.

Table 1. NLOS environment ranging test results.

True range (m)	1.54(thin wall)	4.04(thin wall)	6.14(thick wall)	10.18(two walls)
Mean error(m)	0.46	0.64	0.42	0.70
RMS(m)	0.49	0.65	0.42	0.71

To investigate the influence of human bodies on signal propagation, and therefore ranging accuracy, another test was carried out in a corridor which connects to several lecture rooms. The test was started a few minutes before the end of a lecture and ended a few minutes after the end of a lecture. The traffic in the corridor was light in the first few minutes, then becoming heavy for about 4-5 minutes and gradually reducing again. Figure 4 shows the test environment and the results. No difference can be detected during the testing period, which implies that human traffic has no significant impact on range measurements.

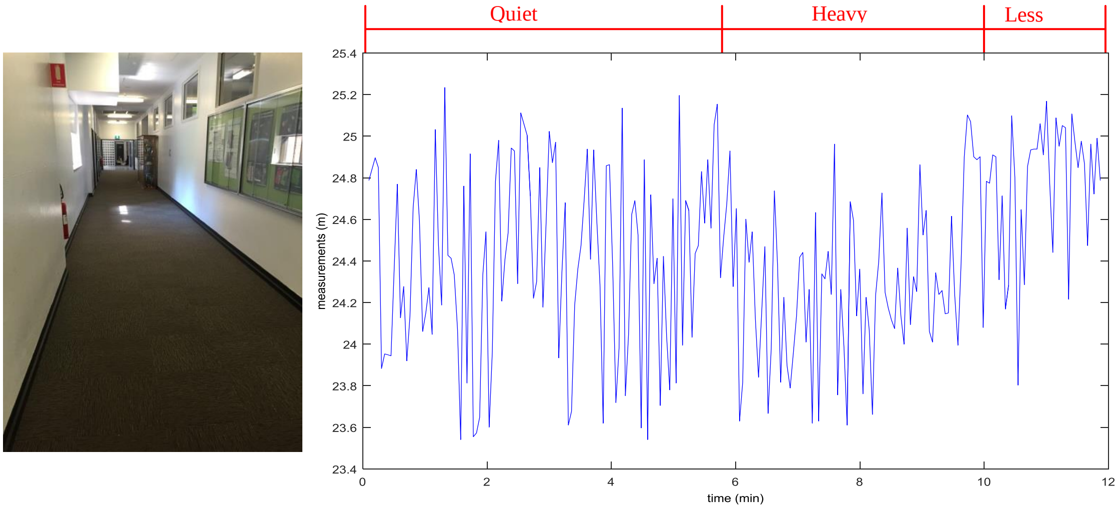

Figure 4. Ranging in an environment with human traffic (many students moving around).

4.2 BLE Testing

Figure 5 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.

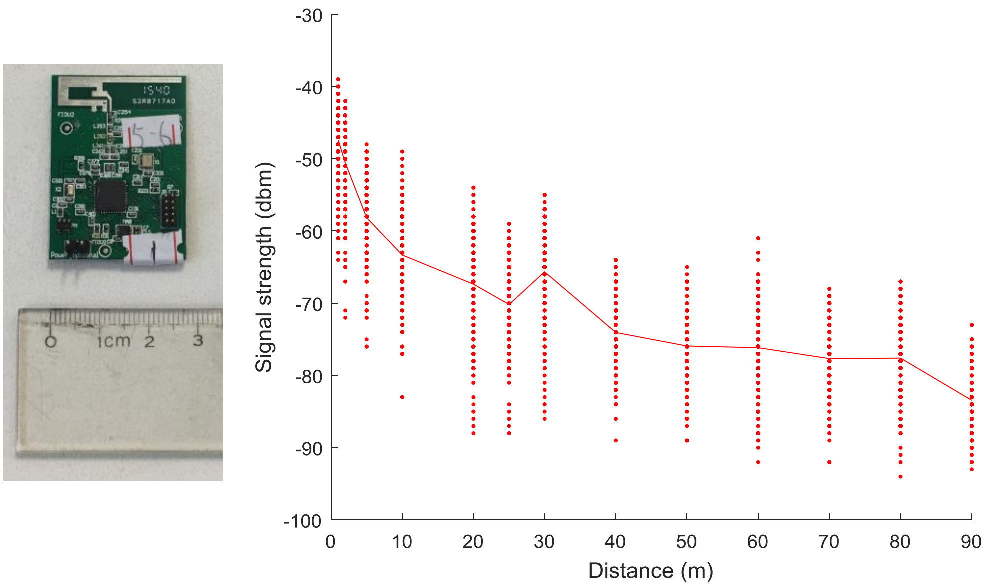

Figure 5. An BLE transmitter (left) and the relationship between signal strength and distance (right).

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. 8 BLE transmitters were deployed every 10 metres on the ceiling of the corridor (shown in Figure 2). A BLE receiver was carried from one end of the corridor to the other end, and then back, with a speed that was judged as constant as possible.

Figure 6 shows the variation in received signal strength. Clearly, there are 16 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.

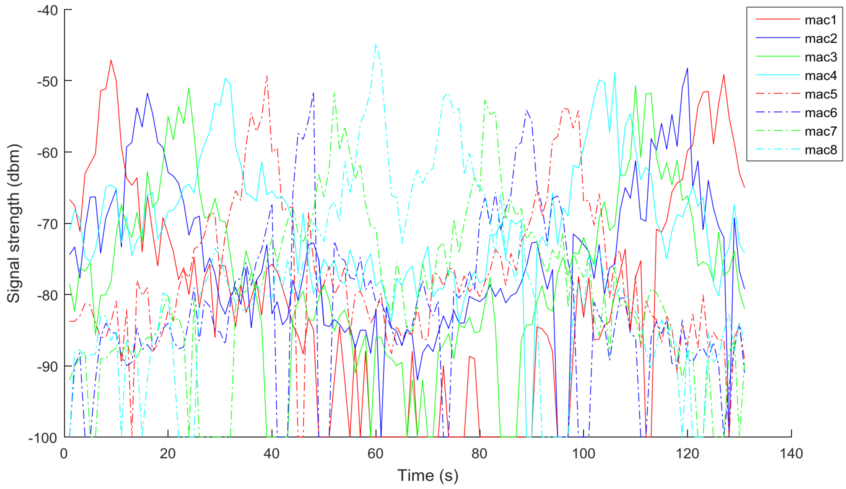

Figure 6. The received signal strengths when a receiver moved along a corridor with a constant speed.

Figure 7 compares the estimated range based on the received signal strength and the true (known) range. As the speed of the receiver was not truly constant, the ranging errors cannot be estimated. Nevertheless, the figure indicates that the error is reasonable.

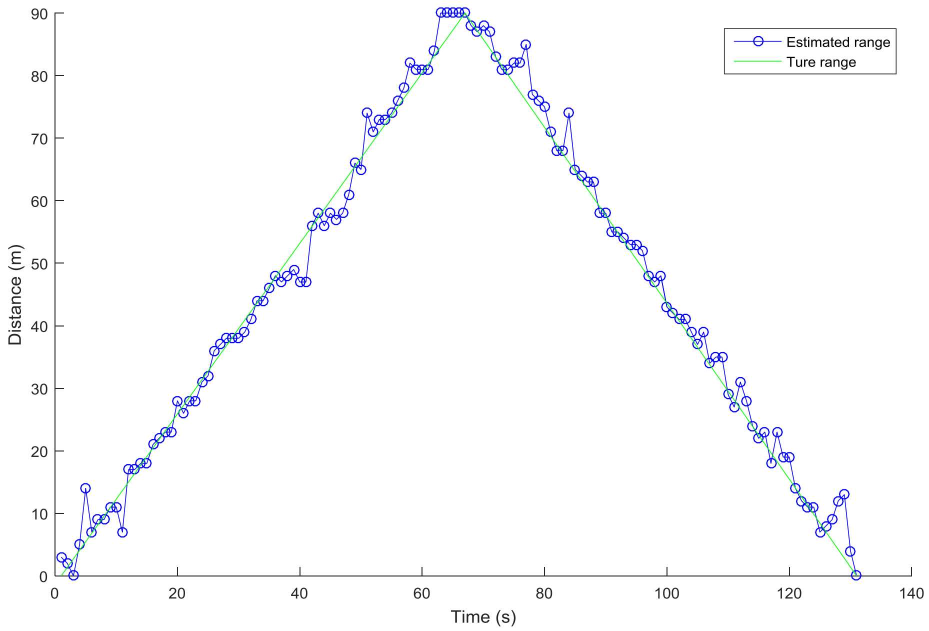

Figure 7. The estimated range vs true range.

4.3 IMU Testing

“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 comprise 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.

An Xsens Mti was attached to the waist of a researcher to collect the data on the same testbed as shown in Figure 2. Figure 8 is a plot of the angle data collected during the test. The significant change indicates that the researcher turned around and moved back to the start point. After applying a simple algorithm, the trajectory of the IMU is shown in Figure 9. If no map-matching algorithm is applied there will be up to 20m positioning error. BLE and magnetic field positioning are necessary to correct the drift of the PDR solution.

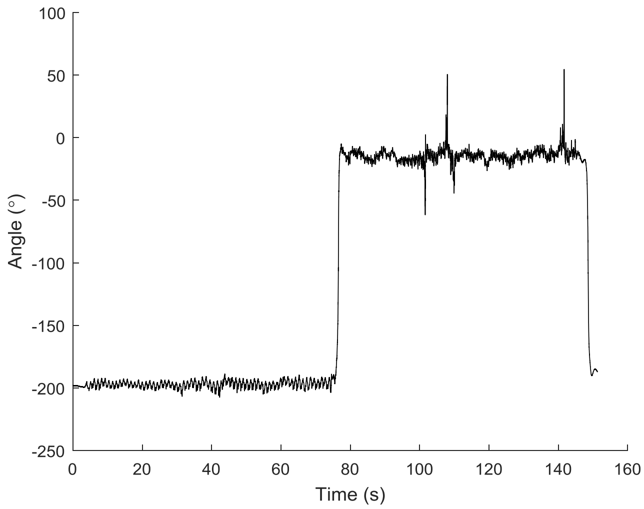

Figure 8. The angle data collected in the IMU testing.

Figure 9. The trajectory of the IMU.

4.4 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.

As discussed in previous work, 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 [23]. However, the stability of the magnetic field implies that travelling along the same path will generate the same curve [21]. As the tunnel restrains a worker’s movement, it is more reliable to apply pattern matching for positioning.

The test was carried out in the testbed mentioned earlier. A researcher walked along the centre of the corridor from start point to end point, and returned to the start point, for a total of three times. The data collected in the first two traverses were used as the reference dataset, and that of the third 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), a simple pattern matching algorithm was applied for two cases. In case one, the vertical component and horizontal component of the magnetic field were separated based on the gravity data. In case two, only the magnitude was calculated. Figure 10 (with the vertical component and horizontal component) and Figure 11 (magnitude only) illustrate the results. The blue, green and black curves in the two figures denote the horizontal component, vertical component and magnitude respectively. The testing data were

divided into small fractions (every 10s) to apply pattern matching separately. The red curve indicates the location where a best matching was detected. It is clear that the pattern of the curves of the two reference data is very similar. In addition, the matching based on the vertical component and horizontal component is better than that based on magnitude alone.

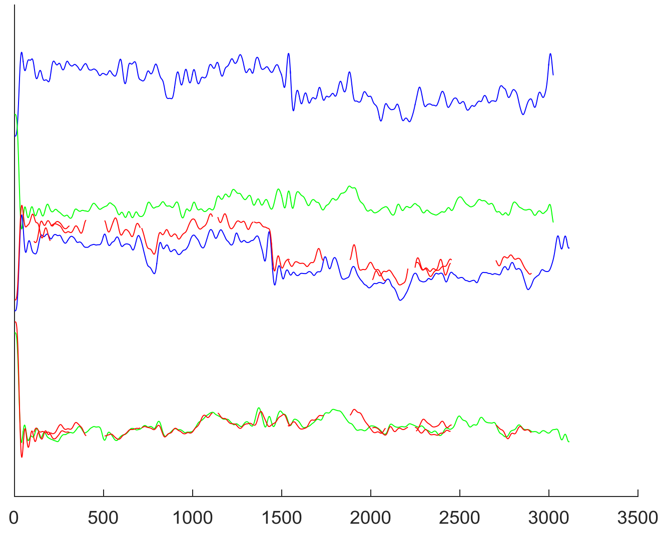

Figure 10. Magnetic field pattern matching (based on the vertical component and horizontal component matching).

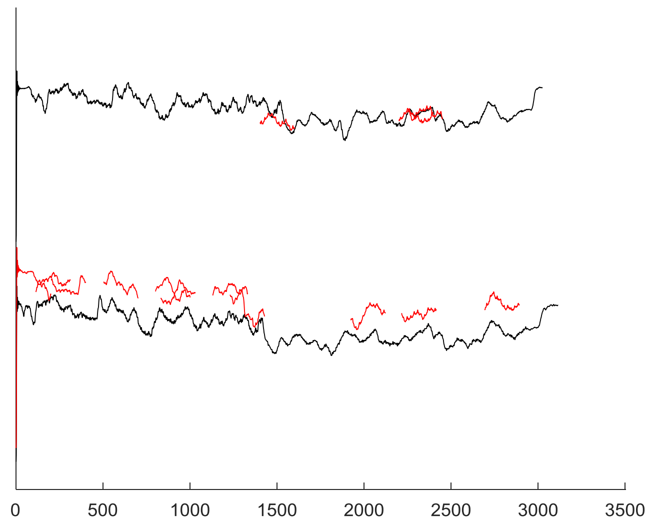

Figure 11. Magnetic field pattern matching (based on the magnitude matching only).

5. CONCLUDING REMARKS

Preliminary testing has demonstrated the feasibility of a cost-effective positioning system for underground mining environment based on multiple technologies. Testing will be carried out in several mines in the coming months. The algorithms for each positioning technology will be improved based on real data, and a fusion algorithm will be developed to integrate the outputs of all technologies.

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You need to put ack to the ARC LP project. This is a requirement for the publications

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