GPS-less Positioning, Tracking and Navigation Services for Underground Mining Applications

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Abstract: - The paper briefly presents practical applications of positioning and navigation services based on wireless ranging technologies suitable to operate in confined space environments with special attention paid to underground workings of mines. Results of the recent work related to underground location and tracking in day-to-day as well as emergency situations are described, together with the achievable performance and problems that are typically encountered. A recently implemented mining vehicle tracking system based on IEEE 802.15.4a is presented as an example of a practical application. Additionally, an experimental underground navigation system, employing a sensor fusion combined with an augmented reality user interface, is also briefly reported on, as an example of possible emerging applications.

Key-Words: Real Time Location, Navigation, Tracking, Mining Applications, Augmented Reality

1 Introduction

Location, navigation and tracking services based on the Global Positioning System are becoming more and more popular in consumer applications and are also finding their way into more demanding industrial usage. Positioning accuracy offered by the GPS system is sufficient for most of the applications especially since the more accurate civil version has become available. However, use of the GPS technology is limited to open space environments where the reference signal from the satellites is available. There is a large niche in the market for reliable positioning in confined spaces such as indoor areas or interiors of industrial facilities. Underground mining is one of the branches where reliable positioning is demanded in many situations. In the case of conditions present in the typical mine, a class of GPS alternatives must be used. A number of solutions, based on various wireless technologies, are available commercially as products at various development stages in terms of the performance offered. There are also some emerging solutions in the pre-commercial or research stage. These systems and devices use propagation properties of radio frequency (RF) signals, as well as light or ultrasound, or their combination. In this paper we focus on RF solutions based on contemporary wireless sensor network technologies that offer location-aware services. Special attention was paid to the performance of modern IEEE 802.11 and IEEE 802.15.4(a) transceivers.

2 Wireless Positioning in mines

2.1 Conditions affecting EM based positioning in underground mining

In general, the propagation of electromagnetic waves in underground mines is, in most cases, limited to line of sight. This is equally true for HF and VHF bands. The interesting exceptions are very low frequency bands (ELF/VLF) where through-the-earth transmission is possible and the middle frequency band (MF) where infrastructure coupled transmission is likely to occur.

This is due to the high stratum attenuation, rapidly increasing for higher frequencies. This paper focuses on applications based on wireless technologies operating in microwave bands, therefore, apart from line of sight free space attenuation, the most important factor is multipath fading. There are areas that are characterized by a strong multipath propagation impact due to the presence of highly reflective metal structures. These are typically such obstacles as roof support components, rails, pipes, frameworks, large machines etc.. The cross-sectional apertures also differ and in some cases the roadways may be very wide and high whilst in others they may be narrow and low . The available aperture has a direct impact with regard to deterioration of the first Fresnel zone, especially for frequencies from the microwave band.

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Underground mines vary with regard to their spatial topology. Typically you will find there a multilevel network of roadways, crossroads, shafts, chambers etc. Despite the quite complicated three dimensional structure of such a network, the wireless positioning in a mine is actually, in the vast majority of cases, reduced to a '1-D' linear location problem. It is as a result of the spatial limitations of the environment that the problem is reduced to finding the position in a 'tunnel'. This is true for the most common applications such as vehicle or personnel tracking in a roadway system. A solution, which is the position of the located mobile node, can be found by means of bilateration based on the distance measurements to adjacent reference nodes.

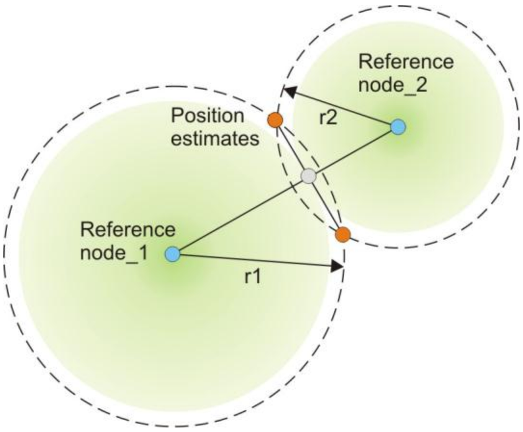

Fig. 1 Bilateration method

There are many methods of wireless distance determination (aka ranging). Some of them were found to have practical applications for underground mines as described in later paragraphs. An example of a specific case where a 2-D positioning is required is the underground tracking in the area of extraction with the room and pillar method. In such a case the position of the objects must be determined in a chess-board like, spatially limited pattern. It should be noted however, there is also a separate class of mining applications which would require precise 3-dimensional positioning, such as the guiding of extraction machines (e.g. road-headers). In this case a dedicated lidar-based solution is typically utilised but a description of this method goes beyond the scope of this paper.

2.1 Wireless positioning methods suitable for use in underground mining

There are a number of wireless technologies used for indoor positioning that offer different degrees of performance. They are based on a broad span of physical principles. An interesting set can be found in contemporary low power, wireless sensor network (WSN) technologies.

For the sake of practical implementation in mining (as described in the paragraph above) we focus here on the following methods:

- Received Signal Strength Indication (RSSI),
- Time of Flight/ Time of Arrival (TOF/A),
- Time Difference of Arrival (TDOA)

Note: the angle of arrival method is not practical for the mining environment due to tunnel like topological structures.

RSSI - the simplest, however the least accurate method utilised in WSN, is based on a received signal strength measurement (RSSI). For example some implementations of ZigBee and WiFi transceivers offer an estimation of the distance between adjacent nodes based on RSSI distance. This method gives relatively good results in 'open space' environments, but in practical interior applications the performance is degraded to a large extent due to the impact of multipath effects. Numerous trials have been carried out with sub-gigahertz and 2,4GHz ISM WSN in diverse conditions of the underground mine environment. The results clearly indicate that, with regard to the performance of RSSI based ranging, the distance measurement errors limit applicability of this method only to coarse positioning. As a result it is possible to have a practical extension of so called ‘zonal location’ so that it is possible to determine whether the mobile node is 'near' or 'far' from the particular base station or coordinator/router node. However, it is important to note that, in the case of standard WSN implementations such as ZigBee or WiFi, we get that coarse distance estimation at no additional cost as RSSI is typically used for medium access procedures (i.e. CSMA/CA).

TOF – a second group of distance determination methods is based on the amount of time the modulated signal travels between the wireless nodes (hence the name - Time of Flight). In contemporary digital transceivers it is realised in a way that the initiating frame is sent to the adjacent node which, after the determined processing delay, responds with an acknowledgement. The time of the complete operation is used for calculation of the distance. It is important to take into account the processing delays at both nodes as well as to compensate for (any) local oscillator inaccuracies. The main sources of inaccuracy, in ideal conditions, are the drifts of local oscillators. To improve the results, this

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operation is sometimes done symmetrically by 'swapping' the initiating node with the responding node, and a number of subsequent measurements are then averaged. In practical conditions the limiting factor is the environment. Due to the multipath propagation, in many cases the signal that is received is a reflected copy and this leads to distance calculation errors. In the case of narrowband implementations, such as those which can be found in contemporary IEEE 802.15.4 transceivers with a time of flight engine, the channel bandwidth is 2MHz. Practical measurements carried out in mining environment with those transceivers show that the average accuracy achieved over the whole radio coverage distance is typically in range of 10-15m absolute error. Such a performance is absolutely sufficient for some applications. Much better performance can be achieved when wider bandwidth is used. The tests carried out with wideband transceivers using an alternative PHY that complies with IEEE 802.15.4a in similar conditions, result in much better accuracy. This is due to the fact that these transceivers utilise an order of magnitude higher transmission bandwidth and therefore the impact of multipath propagation is less significant. The example results of the distance measurements (raw data, straight roadway section, 0dBm transceivers with the alternative PHY) are presented in the figure below.

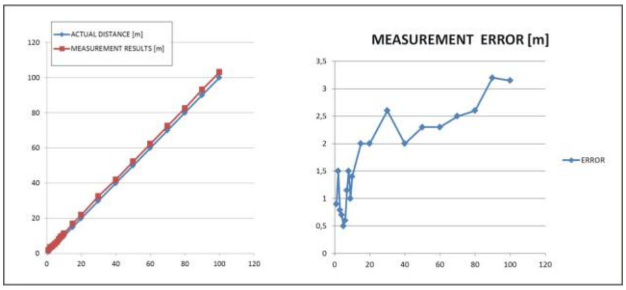

Fig. 2

It should be noted, that the accuracy of the distance determination can be further improved when instead of simple averaging use of Kalman filtering and is applied.

TDOA – even better performance can be achieved when a Time Difference of Arrival method is used. In this scheme the distance calculation is derived from the difference of two TOF measurements carried out simultaneously by the adjacent reference nodes (two or more.) However, to achieve good results it is necessary to synchronise the reference nodes precisely. This can be easily done in the case of systems in which the nodes are interconnected by a transmission backbone. The only drawback from the point of view of a mining application is the failure of the backbone communication link (e.g. cable breakdown) which disables local positioning services and may be crucial in the case of emergency applications.

3 Applications

3.1 Personnel tracking

An interesting solution for personnel tracking was developed in ITI EMAG in the course of RFCS project EMTECH. The solution can be used for day-to-day purposes as well as providing information regarding pre-incident personnel deployment locations. Information regarding where to send the rescuers is critical especially in first stages of the rescue operation. The developed tracking system consists of reference nodes which are distributed along the underground workings of a mine. The communication range of used WSN technology makes it possible to space them up to 500m apart on straight sections of the roadways. The mobile tag is integrated within the mining cap lamp (see the figure below).

Fig. 3 Cap lamp with integrated location tag

The tag also has a digital VLF transmitter which is used in the case of roof fall to transmit an encoded beacon signal through-the-earth. That signal can be used during the assisted search action to find location of the trapped miners through the overburden. The device is also equipped with a simple user interface consisting of a small OLED display, a buzzer and an 'alarm' button. Thanks to these features it was possible to implement paging functionality. What is more, such a configuration can be used for automatic emergency guidance/ way finding in limited visibility conditions (i.e. smoke caused by underground fire). For that purpose the system detects whether the movements of a person carrying the tag are following the correct evacuation direction. Additionally, the information on valid escape routes is shown on the display to facilitate decision making in stressful situation. Shall the system detect incorrect moving direction a warning

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is generated both visually and by means of loud sound beeps.

3.2 Vehicle tracking

In contemporary mining, various transportation means are utilized. In some of the transportation processes vehicles such as floor-mounted trains or suspended monorails are used. One of natural and straightforward applications for WSN-based wireless positioning a is real time tracking of moving vehicles. In ITI EMAG a system of such functionality has been developed and successfully put into practice in Polish copper mining company the KGHM Polska Miedz S.A. The system was dubbed 'WLSS' which is an acronym of 'Wireless Logistics Support System' as in fact it constitutes a significant support for personnel managing the underground transportation (i.e. dispatchers). Structure of the system is shown in the figure below.

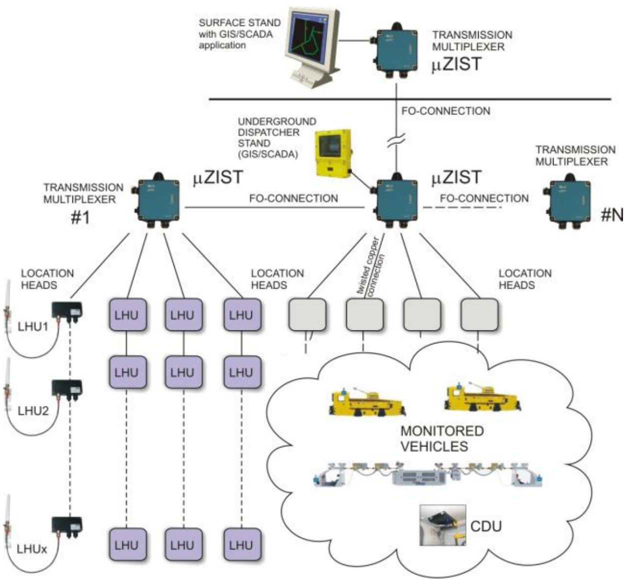

Fig. 4 Structure of the WLSS system

All the vehicles monitored by the system are equipped with wireless tags (CDUs). Their positions are tracked in 'real time' by a network of reference nodes (LHUs) distributed along the underground roadways. For wireless positioning the TOF ranging method with advanced filtering is employed. The locations and heading directions of the vehicles are displayed in a dedicated GIS/SCADA application which runs on a computer in the underground dispatcher's room. The system features an important safety related functionality which is automatic detection of potential collisions of vehicles. For that critical feature a pin-point location with accuracy below 1m was necessary. It was achieved by use of a hybrid method employing auxiliary passive RFID tagging. Additionally, the system offers capabilities of text messaging and diagnostic data transmission. The main hardware components are shown in the figure below.

Fig. 5 (a) – vehicle tag, (b)- robust antenna (c)- RFID reader

3.3 Navigation and information services

In course of the recently finished RFCS project EMIMSAR an interesting application of underground wireless positioning was developed. The application takes advantage of Augmented Reality (AR) display technology that operates in a see-through mode to provide navigational and informational aids for underground personnel. For that purpose a novel, wearable AR display that complies with requirements of use in mining environment has been developed - see figure 7a. The application is compatible with the wireless positioning subsystem based on the previously described WLSS solution. However, in this case the navigation subsystem operates in 'autonomous' mode in a manner that all the geographical information data is stored in the local database of the mobile node. The infrastructure reference nodes are used only to locally calculate the valid co-ordinates. In the developed prototype navigation computer module, see figure 7b, an Attitude and Heading Reference System (AHRS) was also implemented. It provides the AR visualisation engine with the current spatial orientation data. The device works on a sensor fusion principle where signals from the nine degrees of freedom (9DOF) MEMS based sensor module and wireless positioning subsystem are used to determine both the current position and heading direction. Signal processing algorithms in the module are based on Extended Kalman filtering to obtain smoothed and reliable data. The calculated co-ordinates and heading information are then passed to the visualisation engine.

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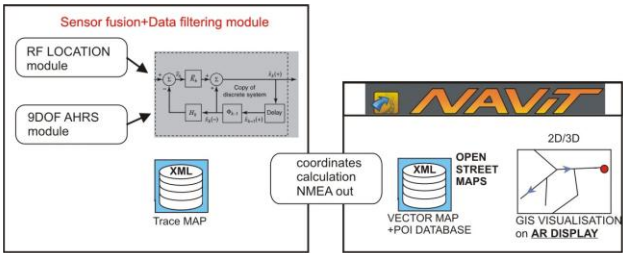

Fig. 6 The sensor fusion navigation scheme

For the purpose of visualisation an open source ‘Navit’[6] engine was utilised. It uses an open standard – ‘osm’ GIS data format for storage of vector maps with convenient point of interest definition. The high level software works in embedded Linux environment and runs on a low power, however high performance hardware platform which is based on Cortex-A8 processor with hardware 2D/3D graphics accelerator. All the subcomponents of the navigation subsystem were integrated together with a battery power supply in a small, high IP rated belt strapped enclosure, resulting in a smart wearable device in figure 7b.

Fig. 7 (a) – AR display, (b) – navigation computer

During the final stage of already mentioned EMIMSAR project the complete system prototype was tested in underground conditions. The tests were carried out in a test installation deployed in historical mine Guido (Poland) [7]. The tests proved the developed prototype system works without major flaws. It is important to note that the developed navigation computer prototype can be further optimised in terms of size and weight reduction.

4 Conclusion

We discussed here a few wireless positioning methods capable to operate in conditions of underground mines. From practical point of view the contemporary low power ‘location-aware’ WSN technologies, especially the wideband types, were found as an appropriate solution for personnel and vehicle tracking in underground. Such an approach, apart from location and tracking alone, provides with set of useful features derived from inherent WSN capability which data transmission is. These features include safety (personnel, machines) and conditions monitoring. The achievable performance of WSN-based wireless positioning was determined in numerous in-situ trials as well as during the observation of behavior of the systems that have been recently put into practice (i.e. WLSS). A number of software techniques such as sophisticated filtering can be used to improve ranging accuracy and offer additional benefits especially in the case of sensor fusion based navigation.

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