The Detection of Abandoned Mineshafts Using GPS and Capacitively Coupled Resistivity Imaging

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ABSTRACT

The re-development of derelict land in the built environment frequently encounters potential geohazards, such as old mine shafts and workings, which pose serious risk to health and safety. Apart from the physical risk to new structures from subsidence, people are also at risk from mine contaminants. Trial pits and boreholes test only a statistically small volume of ground, therefore, a technique is required that is non-invasive and provides ultra-high density volumetric images of the subsurface.

The research underway at the University of Nottingham and the British Geological Survey investigates the integration of single frequency RTK GPS with a novel capacitively coupled resistivity imaging (CCRI) system. The system is designed to enable the real time positioning and resisitivity of the ground to be determined, and hence the characteristics to be evaluated.

The following paper details the work, and focuses on the research into the integration of GPS into such a high voltage system.

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1. INTRODUCTION

Mining is one of man's oldest industrial activities. Subterranean exploration for materials such as flint and clay extends back at least to the Neolithic period. The growth in demand for raw materials, fuelled by the Industrial Revolution and population increases brought with it a massive increase in mining activity between the 17^{th} and 20^{th} centuries.

In the United Kingdom today, only a small number of mines remain active but there is a massive legacy of abandoned mines. Extensive underground mining has exploited deposits of metals, fuels and other mineral resources for thousands of years. The modern industry is characterised by small numbers of capital intensive, large volume and highly mechanised operations. In the past many mines were small operations using multiple excavations often in haphazard places with no consideration of subsequent land use nor for the safety of the subsequent users. Shafts were often abandoned with no capping or perhaps a few planks or other scrap laid across the opening. Prior to the Mining Acts of the 1870's there was no requirement to retain any plans of the location or extent of abandoned workings. Where records do exist they have often proven unreliable and incomplete. The intensity of past mining has left some areas of the country with as many as 200 abandoned shafts per hectare. Subsequent levelling and re-use of the ground has often eradicated any surface indications of the location of these shafts. Because of the very poor or non-existant capping, these shafts present a very high risk to those using the land and there have been numerous incidents involving to loss of property, livestock, pets, vehicles and people through falling into these workings.

2. BACKGROUND

Faced with this legacy and the increasing pressure to re-develop brown field sites, a means of detecting and mapping abandoned mine shafts becomes highly desirable. In this context the detection of mineshafts is very similar to the detection of any shallow sub-surface feature which might present a risk to the development and use of the land, for example, voids, burried waste, pipes, contaminant plumes. Since in the UK there are large numbers of mine shafts over a large geographical area generating a significant number of 'events', they have been chosen as the target for this study.

2.1 Definition of the problem.

Because of the diversity in the scale and nature of mining operations there is a huge variation in the characteristics of the resulting abandoned mine shafts. The factors influencing these characteristics include; age, mineral type and distribution, geological and geographic setting, methods of working, size of operation and the abandonment procedure.

The imoprtant charactreristics of the abandoned shaft from the point of view of the developer or site user are; location, depth, diameter, direction, nature and depth of capping, fill material, lining and the surrounding rock characteristics.

2.2 Detection options

The only definitive way of determining the characteristics of abandoned shafts is to excavate, but this is an expensive, hazardous and impractical approach in all but extreme circumstances (figure 1). The only other option is to derive as much information as possible through combination of historical data, 'expert' knowledge on abandoned mines and data determind by 'geophysical' probing of the sub-surface. It is beyond the scope of this paper to give a full review of all of these aspects and the various geophysical techniques and their potential in determining the characteristics of abandoned mine shafts. The choice of technique was based on its ability to detect the important features of the target and on it's suitability for deployment in the target areas. Every geophysicist has their 'pet' technique(s) and a wide variety; resistivity, magnetics, electromagnetics, gravity, seismic and soil gas flux have all been used with varying degrees of success for shaft detection.

2.3 Resistivity and CCRI.

Resistivity is one of the oldest and best developed of the geophysical techniques and is based on the ability to detect small changes in the resistivity of rocks and soils caused by changes in their structure, mineral and fluid content. Because of this, within a host medium it has the potential to detect voids, fill, water saturation and disturbance of the host. It is also capable of building a 3-dimensional portrayal (tomograph) of these changes. One of the major drawbacks of resistivity mapping is a slow data acquisition rate. This is because it generally requires 'ohmic' contact to be made by sinking metal spikes into the ground for each reading. The method developed during the programme reported here utilised 'capacitive' coupling with the ground enabling much faster data acquisiton. This, in turn, gives much higher resolution (resistivity and positional). The data quality and density allows detailed tomographs to be produced. This Capacitively Coupled Resistivity Imaging (CCRI) enables good visualisation of sub-surface features and well as their precise positioning.

2.4 Positioning requirments.

The other major drawback with all geophysical techniques is that the time taken to conduct a survey is heavily influenced by setting out of acquisition grids or determining the position of data. In many cases positional information was derived from 'pacing out' or tape and compass. It is clear that a more rapid precise and accurate serveying technique is required. The specification for the positioning system is driven by the capabilities and requirements of the CCRI hardware and software. In practical terms the CCRI sensing array is towed behind a vehicle and the maximum anticipated ground speed is of the order 6km hr^{-1}. The geometry of the CCRI array has been chosen to optimise the system response to targets typical of mineshafts and the closest useful spacing between samples is of the order 10cm. These figures yield a maximum sampling rate of 16.7 Hz.

For the CCRI interpretation software operating on a 10cm grid a position error of 20% (2cm) would not seriously degrade the data. This degree of accuracy is also adequate for the positioning of any target.

3. SURVEYING TECHNIQUES

There are two types of systems capable of dynamic surveying, these are GPS and tracking theodolites/total stations.

3.1 Tracking Theodolite

Tracking theodolites use distance and angle measurement from the total station to a reflector to determine relative position. Data logging at the target end is possible using radio communication with the theodolite, so triggering of the CCRI in a similar way to that investigated would be possible. Dynamic positioning requires that a 360° reflector be used, these are less accurate than standard prisms and have a much shorter, but adequate, range (13000m). The requirement for a small sampling separation (10cm) and the lowest speed that a Land Rover (or similar vehicle) will maintain, creates a need for a fast update rate of position data. For an accuracy of 5-2mm the time per measurement of the theodolite is 0.3s and using rapid tracking the accuracy is reduced to 10-2mm in 0.15s. Thus much more than 10cm will be travelled in between updates and the errors introduced in the interpolation of 10cm will be significant. The cost of a tracking theodolite is about £5000, but radio equipment, and possibly a laptop, computer would also be needed. However the main problem with this approach is that the positioning is relative and would need to be tied back to a known point bringing about the issue of how that point could be established and how accurately.

3.2 Global Positioning System (GPS)

GPS uses range information from satellites to calculate the position of the antenna in space and using an ellipsoidal model of the Earth (WGS84) converts this cartesian position into latitude, longitude and height above the ellipsoid. This provides an absolute position which, can be referenced back to maps i.e. British National Grid (with further transformations).

The satellites emit radio signals. The receivers are able to measure the fractional part of the wave and track/count the whole waves as the antenna and or the satellites move. Using the information from several satellites and complicated On The Fly ambiguity resolution techniques, the whole number of waves (integer ambiguities) between satellite and antenna is calculated. The positions of the satellites are broadcast in the radio signal (they are tracked by a ground control network, which updated their position and direction) and by simple geometry the position of the antenna is found.

3.2.1 GPS errors

However there are many sources of error in the system. There can be errors in the broadcast position (satellite dither). Accurate timing is also an important part of positioning, the receiver clock is synchronised to the satellites, so delays of the signal while passing through the ionosphere affect this. Multipath is another cause of position error. Mitigation of these error sources is possible. Multipath is minimised by using a choke ring antenna, which has several concentric metal rings to baffle reflected signals. The effects of the ionosphere and error in satellite position can be over come by using two GPS antennas and receivers. If one is on a known point and the other is within moderate proximity the effect of the ionosphere and dither can be said to be the same at both stations and thus the error in position is the same, this correction can then be applied to the unknown station. This can be done in real time by sending corrections by radios link or by post-processing.

Because of the geometrical position of the satellites in relation to the antenna i.e. all satellites above and none below, the calculation of the height will be the least accurate. This position dilution of precision is call VDOP with reference to the height, HDOP with reference to plan and DDOP with reference to both at once.

3.2.2 Dual frequency receivers

The satellites emit signal on two carrier frequencies L1 and L2. As the name suggests dual frequency GPS uses both frequencies whereas single frequency only uses L1. Because the wavelength of the two carriers are different from each other, at approximately 19 cm for L1 and 24 cm for L2, the ionosphere effects them differently, which can be used to calculate the error induced. But more importantly the use of both greatly reduces the time taken to resolve the integer ambiguities.

However dual frequency GPS receivers are much more expensive than single frequency and once the integer ambiguities are resolved single frequency provides accurate enough results for the application considered in this paper.

3.3 Sharpe XR6 Single Frequency Receiver

The single frequency receiver that was chosen for this project was the Sharpe XR6. It was designed mainly for military use thus it is small (175 x 80 x 57mm), light (less than 1kg), robust and well shielded. It has a sun-spark chip, 32M of memory and 12 channels (can track up to 12 satellites at once). The programming and interrogation of the receiver is conducted through an external computer connected to the Comm port. The interface program is DOS based with several screens for control, using multiple choice options, or viewing one second updates of aspects such as the state of the Kalmen filter or the position.

There are several standard ASCII and NMEA strings that can be output from a separate port, these contain data such as position, quality, satellite, depending on which is chosen. There are also multiple options for sending correction data i.e. base position, raw data, corrections. All these can be output at a range of rates up to 10Hz. It has two ports that such data can be output on and an internal memory that can record them (or raw data) for down loading onto a computer later. Thus the session can be post-processed as well. The 'binary macro 2' when converted by 'bin2gpb' or 'Navbin' (in real time) is compatible with Waypoint GPS program GraphNav and can also be converted to RINEX.

3.3.1 Receiver peripherals

There are two main types of antennas; choke rings and navigation/patch. The former (mentioned earlier) aids multipath mitigation, but is heavy and expensive. The navigation antenna however is small, light and costs much less. On this basis it was chosen for the project.

Half watt Satel radio modems were also selected, they have easily programmable baud rates and handshaking protocols. The power and data transmission is through a single cable.

4. GPS TESTING

An assessment of the receiver performance and the system as a whole was carried out.

4.1 24 Hour Test

During a 24hour stand alone test (just one receiver by itself) the XR6 performed well within the manufactures claims of 15m accuracy. The period of the satellites orbit is just under a day, so all the satellite positions for the area and diurnal changes in ionospheric effects were experienced. This also revealed that this mode of operation the receivers accuracy was much better than the estimated accuracy. The horizontal error estimate was either 10 or 20m but in reality the error was never greater than 6m. The vertical error estimate gave a similar range with a few peaks at 30 and one at 50m but was never greater than 10m in error. This is due to the removal of a deliberate error in the signal (selective availability).

4.2 Bungy Experiment

A bungy rig consisting of a rigid platform with antenna mounts at each corner, suspended by heavy-duty elastic from a frame, was used to provide movement for multiple antennas while maintaining a constant vector between them. The resolution of the vectors reveals errors in position and noise. The post-processed performance of the XR6 was compared to that of dual frequency Leica receivers in a test where the motion was mainly up and down (this was required by the other participant in the experiment). There were three Leica receivers so a zero vector (the position of one rover resolved by two base stations) position analysis was possible. This revealed an average error of only 7mm and a standard deviation of 3.6mm for both periods of induced motion and stillness, showing no significant deterioration due to the motion. However the vector between the bungy mounted XR6 and Leica showed greater error with standard deviations of about 7mm in the periods of motion and 5.5mm when still. Obviously not all but most of this variation is due to the XR6 and demonstrates the superior accuracy of the dual frequency system. However, it does also show good maintenance of satellite lock and acceptable positioning for the purpose of this project.

4.3 Post-Processed And Real Time Compared.

During the bungy experiment both real time data and raw data for post-processing were collected. The calculated positions for both were compared. The greatest difference was in the height that varied greatly in comparison to the latitude and longitude, the latter two showing more stable offsets. However the greatest difference was only ± 2.5cm (in height) and the longitude was always between 1 and 2cm, and the latitude from1.2 cm to negative 0.3cm. Thus indicating that the use of post-processed data where real time is not possible is valid and will yield similar results.

4.4 Assessment of Internet Based Resources

The Ordnance Survey has a network of active RINEX format base stations positioned accurately throughout the country. These provide dual frequency GPS data at intervals of 15s with a latency of about a day. These can be used in post-processing as base stations for establishing the co-ordinates of a local base station for use in RTK GPS. The length of the baseline and the duration of occupation were investigated for average accuracy.

The improvement in accuracy due to the duration of occupation was greatest on the longer baselines. The quality of the solution after 2 hours of observations was unpredictable, the longest baseline (103km) yielded an error of only 40cm on one occasion but failed to find a solution to the integer ambiguities on another. The improvement over a short baseline (2.5km) from 2 to 4 hours was negligible. But the mid-distances improved by about 20cm.

The International GPS Service provide a more accurate ephemeris than that broadcast from the satellites. These can also be utilised, post mission to improve position quality, this would only be useful when establishing a local base, but the latency in publication (up to two weeks) would delay further field work. A test was carried out to assess its usefulness but the results were inconclusive.

A satellite predictor program will display the satellites available for an area if the co-ordinates are roughly known. When establishing a local base this can be used to find the time when the same satellites are visible at both the local base and the Ordnance Survey station. It can also be used to determine the time of day that most satellites are available for local kinematic GPS surveying. The usefulness of this is demonstrated by the variation in solution quality of the 2 hour occupation over the 103km baseline, which was due to the number of satellite visible at both the base and the remote.

4.5 Radio Modem Range Testing

The radio modems were tested for the maintenance of radio contact over varying conditions of line-of-sight, obstructions and separation distance. The base was positioned on top of a tall building and the remote on a van. They performed well, maintaining contact up to 7000m with line-of-sight. Without line-of-sight the link was good for about 300m radius, but poor when obscured by buildings, trees and a small hill at greater separations.

5. INTEGRATION OF THE CCRI AND GPS

5.1 Physical Integration

There were only a few options when considering the physical integration of the geophysics and GPS. The position of the antenna is important, it must be afforded a clear view of the sky in a stable position. The suggestion of mounting it on the array was quickly dismissed due to the occlusion of the sky by the towing vehicle and the increased potential of multipath. Raising it on a pole would make it too unstable, but would overcome the other problems. Placing it on the top of the towing vehicle provides an extended ground plane and stability, but introduces an offset that will have to be accounted for in the calculations. Interference from the electric fields of the CCRI on the GPS signal or receiver could mean degradation of position accuracy or inability to maintain lock on the satellites. So the effect of the proximity of the CCRI transmitter on the GPS receiver was assessed with respect to the placing the antenna.

5.1.1 Interference Testing

Interference from the CCRI is very important, if it has significant effect on the receivers then the position accuracy could be degraded such that integration would not provide the required accuracy. The receivers were set up in RTK mode (but the remote was stationary) and after the ambiguities were resolved, the transmitter of the CCRI was brought closer to the remote receiver and antenna in stages from 15m to 2m. At each stage the transmitter was switched on for a few minutes and then off for a few minutes. There was no discernible effect of the CCRI transmitter on the GPS.

The utilisation of a common CCRI/GPS power supply was considered but rejected because of radio frequency interference concerns.

5.2 Interface Program

As mentioned in section.2.4 the fastest steady speed of movement (about 4mph, 6km hr^{-1}) requires a fast position update rate to measure the sample spacing of 10cm. This would be over 16Hz and the fastest available refresh rate from the receiver is 10Hz. Therefore forward prediction of position is needed.

It is clear that an intermediate program is required to trigger the CCRI, compensate for the antenna offset, forward predict the position, tie the real and predicted position to the geophysics data, and perform transformations if needed.

The programming language Visual Basic was used to create a program that was capable of receiving ASCII text on the Comm port, interpreting it and calculating the appropriate sampling rate to generate a grid of the required spacing. The timing data was to be communicated through the parallel port to an exterior timing device, which generates pulses on which the CCRI will collect data

5.2.1 Data Handling

The program separates a string of text from the GPS receiver, which contains time, position and quality information, into is component parts. It then calculates local northing and easting values using a flat earth model based on the user input base station co-ordinates. It also calculates the speed and hence the pulse rate needed for the grid spacing. This information is written to a text file and the pulse rate is communicated, in binary form, to the timing device through a piece of shareware. The pulse is then fed back to the comm port on the carrier detect line and counted, the predicted position for that pulse and the count number is written to a separate file. The count of the return pulse ties the position and geophysics data together.

5.2.2 Trigger pulse generation

It is not possible to generate reliable timing pulses from software in a windows environment without complex management of interrupts. It was decided to generate data acquisition trigger pulses external to the laptop at a rate programmed through the parallel port. A 1MHz, crystal controlled oscillator was divided down to produce a 100 Hz reference into a wideband phase detector. The second input to the phase detector is derived form a programmable 8-bit divider. The input to the divider is generated by a voltage controlled oscillator (VCO) which is controlled by the voltage output from the phase detector. The divider consists of and 8 bit down counter which is preset by the data on the control computer parallel port. Using this Phase Locked Loop (PLL) arrangement the VCO output can be set from 100Hz to 25.5kHz in 100Hz increments. This was then divided by 2^8 to give a trigger output in the range 100Hz down to 0.4Hz. At a 10cm sample interval this corresponds to speeds between 36 and 0.141 km hr^{-1}. This range can be easily changed by moving the tap on the final divider.

5.3 Mapping Reference Frames

The reference frame used by GPS is WGS84 as it provides the best-fit model of the whole Earth, there are however many well established ellipsoids that give best-fit for specific areas of the Earth. For the UK the OSGB36 (Airy) ellipsoid is used. However ellipsoidal co-ordinates are in degrees, which is no use when the grid is in centimetres. The 10cm could be converted in to decimal seconds but that would be mathematically difficult and conceptually complicated. So the ellipsoidal co-ordinates must be projected to a flat Earth model such as the National Grid. The receiver is capable of performing this projection or it can be done in a separate program. Because a projection is a mathematical model it will not be the same as the mapped National Grid because of imperfections in the original measurements, but this is of little consequence over small areas such as a survey site.

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BIOGRAPHICAL NOTES

Dr Gethin Wyn Roberts is a lecturer at the Institute of Engineering Surveying and Space Geodesy, the University of Nottingham. His research interests include the applications of kinematic GPS and its integration with other sensors, and he is currently supervising various projects in this field.