Underground Tunnel Detection Across Border Areas

K.V. Nibi, K.A. Unnikrishna Menon and Preeja Pradeep

Abstract Tunnels are considered as the oldest method of passageway. Underground tunnels are popular from olden eras for connecting places, travelling, and aid for various surface threats. They are also used for illegal activities like smuggling of unlicensed drugs, weapons, currency, gold, explosives, and even human trafficking is being done through these tunnels. These immoral activities are concentrated in national border areas in order to escape from the border security measures. Hence the detection processes of such tunnels in the national security border areas are necessary in order to protect our homeland security systems. The geology plays an important role in the detection of the underground tunnel system procedures. There is no perfect system for the tunnel detection and localization and even today the tunnels revealed in coincidence. The basic principle to find the hollow space (tunnel) is, by sending an ultrasonic frequency signal into the ground, and study the reflected beam from the tunnel or the hollow space. By analyzing the reflected signal characteristics, preliminary detection of a tunnel/void is possible. Basic idea of the detection is to perform the range estimation algorithm (REA) by pulse echo method. From these, we can estimate the depth of the tunnel. The characteristics of the signal at the soil-tunnel (air) reflection interface are to be investigated.

Keywords Cross correlation · Peak detection · Pulse echo method · Range estimation · Ultrasonic frequency

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1   Introduction

Underground tunnels are used as both offensive and defensive aid. Cross-border tunnels are used for terrorist activities and purposes like smuggling illegal materials such as drugs, firearms, etc., with the intention of avoiding border security force. It is a serious offense especially in national border areas. Weapons, currency, drugs, and gold are also transported through these tunnels. The security of a nation can be completely threatened by these actions. It is important to locate such tunnels for enforcement of law and maintaining national security. In olden days, the underground tunnel and mine detection was done by echo mechanisms, like using hammers for hitting the ground and by measuring the echo that reflect back, the underground tunnels and mines could be identified. Pulsed electromagnetic search system (PEMSS), ground penetration radar (GPR), seismic sensor technology, brillouin optical time reflectometry (BOTR) [1], and GPDR (Ground Penetration Radar and RF microwave tomography) [2] are some of the methods that were used to detect the tunnels. Some of them are destructive methods and others are non-destructive methods. The tunnel is actually a hollow space compared to the other materials around it. One of the principles to find the hollow space is, by sending a narrow ultrasonic beam of suitable frequency to the ground and study the reflected beam from the tunnel or the hollow space. By analyzing the reflected signal characteristics, detection of a tunnel or a void is possible.

2   Related Work

Electromagnetic wave gradiometer [3]: Electromagnetic waves are transmitted to the ground and the conducting property of the tunnel or any other material inside the tunnel that enhances the conductivity and produce secondary electromagnetic fields around the conductor. These secondary fields will be received by the gradiometer. The gradiometer is synchronized in such a way that low signal strength secondary signal can be easily received. A low-frequency electromagnetic signal is generated (around 100 Hz) in order to illuminate the area where the tunnel probably resides. The tunnels have more conductivity as compared to the surrounding medium due to conducting elements present in the tunnels. The transmitted EM wave will induce a current flow in conductors associated with the tunnel and develop a secondary electromagnetic field (EMF). The secondary emf can be observable from the tunnel. Compared to the illuminating signal, the secondary emf is so small in magnitude. This system is efficient since it can suppress the primary signal by 70 dB and enhance the secondary signal by the use of a synchronized receiver (BW = 1 Hz).

Pulsed-electromagnetic search system (PEMSS) [4]: It is a cross-hole ground probing radar instrument. In intrusive and complex metamorphic terrain regions,

PEMSS is used as the primary instrument for the search system for clandestine tunnels. The operating frequency is from 20 kHz to 100 MHz. In this method, boreholes are used to locate the tunnels. If the transmitting signals are 30–40 MHz range, and the distance between the tunnel and the borehole is 20 m, then the received signal strength exhibit maximum power. Basically, PEMSS is a tool for rock mass characterization. PEMSS is a destructive detection method. With the help of the boreholes drilled in linear spacing, we can characterize the geology and lithological and structural rock mass discontinuities. The antenna array will be kept in these boreholes and are capable of transmitting signals of 20–100 MHz range. The received signals are processed for velocity (arrival time), attenuation, and dispersion using wiggle-trace, tomography, and signature analysis techniques [5]. As in gradiometer, this system has electromagnetic signal sensitivity to conductive mineral assemblages and to hydrogeological conditions. Characteristics of certain features can be recognized by detailed examination of travel time, attenuation, and a measure of dispersion. Discrete ground features, on the order of 2 meters can be detected if holes are no more than approximately 20 m apart. Probability of detection is high for planar structures at greater transmitter–receiver separations. Both theoretical considerations and empirical evidences suggest that signal propagation range is limited by structural, mineralogical, and hydrogeological conditions in the rock mass. The more acute the angle between a tunnel and a borehole pair straddling its axis, the greater the magnitude and the prominence of the PEMSS arrival-time anomaly. Detecting and imaging the underground tunnels using seismic waves [6]: Seismic reflections and synthetic aperture time delay from back projection algorithm can create the 3D images of the buried tunnel. Radon transform for the tool for detecting curves in the images. The previous work was designed and development of data collection system for electromagnetic waves with cross-hole tomography and seismic waves. Data acquisition and signal generation accomplished at 32,000 points per seconds with four second chirp excitation signal of 100 samples and 8 kHz signals. Low SNR tunnels can locate using 2D and 3D radon transform. This paper is an experimental study for underground tunnel detection and imaging using seismic waves. The seismic reflections are converted to 3D images using synthetic aperture time delay back projection algorithm. Radon transform is applied to these reflections to localize the linear features of the tunnel. They studied the performance of the radon transform in various noise levels. Radon transformed back projected images can show the lines which cannot visually seen in the reflected images. Probability of detection is higher for longer lines as compared to shorter lines. Simulation results compare with the experimental result in order to measure the performance accuracy of the Radon transform. The relation between the probability of detection and SNR as a function of the line length is analyzed in this work. Furthermore, the line detection in the presence of the white Gaussian noise with zero mean and variance is also analyzed. In this [7], authors considered uncorrelated signal and noise. Ground-penetrating radar (GPR) and seismic sensors are used in multimodal detection of subsurface targets. Seismic sensors were tested

in bistatic configuration and the GPR are expanded to multistatic configuration to provide improved performance. These two systems will measure entirely different properties that are GPR electrical property and seismic system mechanical properties.

3 System Architecture

The architecture for the underground tunnel detection using nondestructive method includes the ultrasonic transceivers and range estimation algorithm (REA). The proposed architecture of the underground tunnel detection system consists of one transmitter for transmitting the ultrasonic frequency pulse and one receiver for receiving the reflected signal from the target. The system mainly uses the two ultrasonic sensors which can produce a frequency from 1 to 60 kHz. The system architecture, Fig. 1, shows the placement of transmitter and receiver to estimate the velocity of ultrasonic signal and calculate the depth of the tunnel.
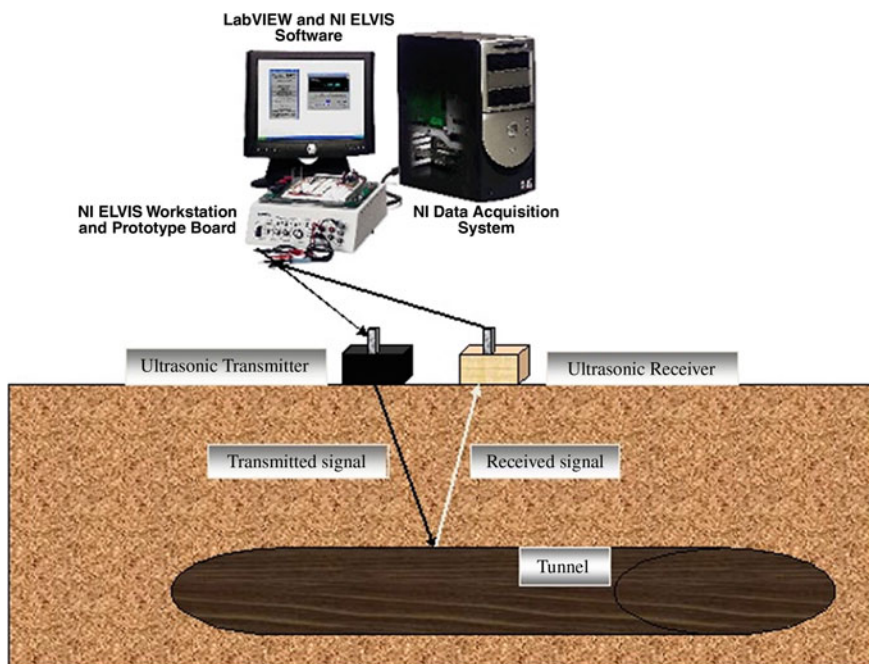

Fig. 1 System architecture

3.1 Ultrasonic Sensors

Ultrasonic sensors are mainly used for generating and receiving sound waves. They are either made of piezoelectric material or magnetostrictive material. Piezoelectric materials have the property of generating and gathering voltage output according to the variations in the input pressure. Transmitter will convert the electrical signal to an ultrasonic sound signal and the receiver will convert the ultrasonic signal to an electrical signal. Parameters for the sensor selection are linear frequency range, sensitivity, directivity, and change in the sensitivity with the temperature, etc. The frequency range shows the range in which the sensors work. The directivity implies whether the sensor is omnidirectional or not. Cost and ease of use are the other parameters for sensor selection criteria [8].

3.2 Principle of Operation

In ultrasonic testing (UT), high-frequency ultrasound energy will be used for detection. Typical pulse/echo principle will use for general inspection purposes. An ultrasonic testing and inspection system consists of different functional units, such as the transmitter/receiver, display devices, and processor. The transducer generates high-frequency ultrasonic energy which propagates through the materials in the form of waves and their wave motion is due to compression and rarefaction. When there is a void (discontinuity) in the wave path, part of the energy will get reflected back from the void surface. The receiving transducer will convert received reflected signal into an electrical signal. From the travelling time of the signal, the distance traveled by the signal can be estimated. From the analysis of received signal, information about the reflector location, size of the reflector, orientation, and other features can easily be achieved [9]. Figure 2 Block diagram describes the steps of the tunnel detection process.

$$D = v_s * t/2 \qquad\qquad (1)$$

D: Distance from the ground to tunnel
v_s: Velocity of the ultrasonic sound in the soil
t: Round trip time.

4 LabVIEW Implementation

The system mainly consists of three sections, i.e., signal generation section, signal acquisition section, range estimation algorithm (Time delay estimation) section. The first section includes creating the input signals with the accurate frequency
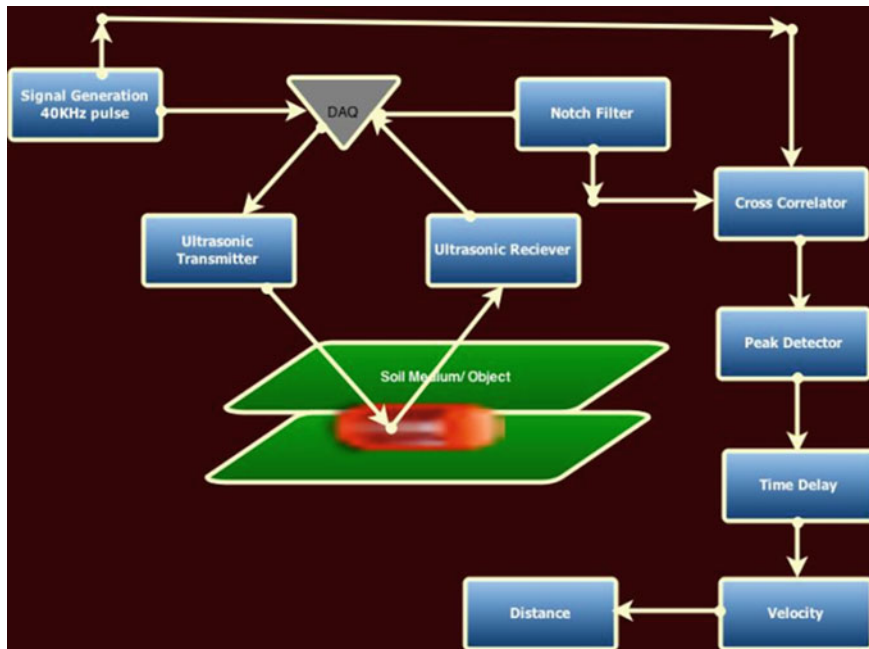
Fig. 2 Block diagram

(40 kHz) amplitude and pulse width. This signal should be capable of penetrating through the soil up to 20 m. The second section involves the acquisition of the ultrasonic signals received by the reflection from the object (tunnel). The third section involves the cross-correlation of the input and output signal of the ultrasonic transmitter and receiver. Cross-correlation is used to estimate the time delay between the signals.

LabVIEW signal express was used for data collection and recording. It is an interactive logging, software for acquiring, analyzing, and presenting data from various acquisition devices.

4.1 Frequency Selection

First step is to identify the optimum frequency. Ultrasonic frequency range is between 20 kHz and 200 MHz. As the frequency increases, the resolution increases but penetration power decreases. At low frequencies, the resolution decreases but penetration power increases. So low frequencies can cover large distances than high frequencies. Frequency selection is medium dependent, here medium is homogeneous soil.

4.2 System Overview Software

LabVIEW is using the programming language *G* which is a data flow programming language. LabVIEW signal express was used for data collection and recording. It is an interactive logging, software for acquiring, analyzing, and presenting data from various acquisition devices. It is virtual instrumentation application software. It can create user-defined system software instrumentation systems [10]. NI ELVIS uses LabVIEW and NI data acquisition hardware creates a virtual instrumentation system.

4.3 Signal Generation Block

Signal generation part consists of DAQ Assistant Express VI which creates edits and runs tasks using NI-DAQmx. Data contains the samples to write the task, number of samples specifies the number of samples to generate for the finite task. We have to generate a 40 kHz pulse in order to drive the ultrasonic sensor. In order to create this, pulse signal is multiplied by the sine wave. Here normalization of the signal obtained. This 40 kHz 50,000 sample sine pulses will be fed to the ultrasonic transmitter through the NI Elvis DAQ block. Figure 3 shows the input generations
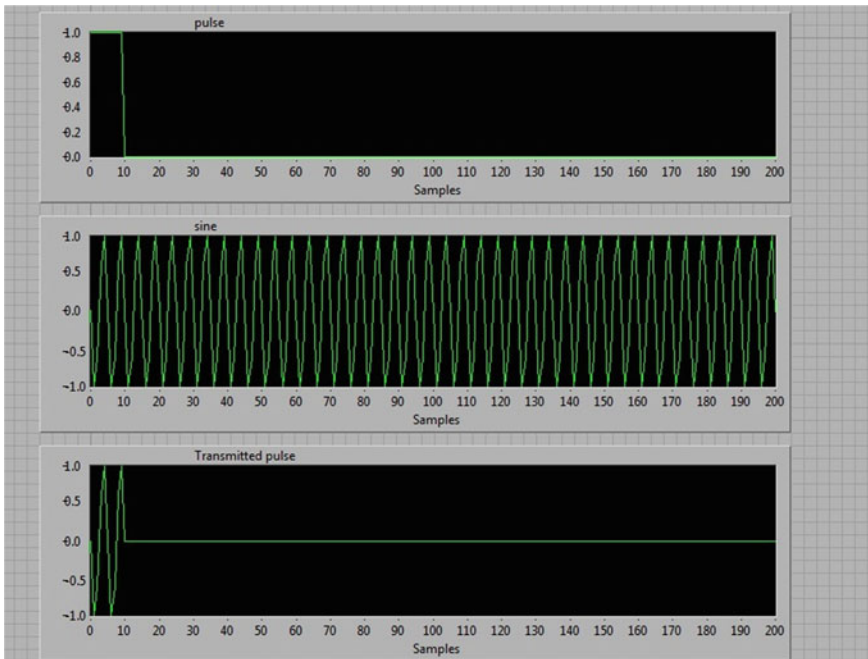

Fig. 3 Generated input

block output which consists of a signal pulse which acts as a window for the continuous sine waves.

The signal generation is an important part of UT or any other measurement system. When the real-world signals are not available to simulate the test algorithm, two applications examples are used. For example, DAQ device is unavailable for obtaining real-world signals or when it is not possible to access to real-world signals then generate signals to apply to a digital-to-analog (D/A) converter.

Frequency Normalization: In the analog systems, the unit of signal frequency is hertz (Hz), or cycles per second. A digital system uses digital frequency and is the ratio of the modulating frequency and the sampling frequency. It is also known as the normalized frequency and its unit in cycles per sample. The normalized frequency ranges from zero to one which equivalent to analog frequency range of zero to the sampling frequency f_s.

4.4 Signal Acquisition Block

The ultrasonic receiver receives the reflected signal and applied it to the LabVIEW system. The reflected signal is the delayed version of the transmitted signal. It also has the attenuation in its amplitude. There will be multiple echoes means signals with time delay and amplitude reductions are also present. The signal path contains the other noise signals too. In all these noise, the DC content or power-line interference is the predominant one. So in order to avoid the noise, we will use the notch filter with cutoff frequencies 40 and 60 Hz. Figure 4 shows the received signal and the filtered signal.

Notch filters are band stop filters and the main function of the notch filter is to eliminate the power line interferences and noise signals. Digital notch filters can be designed in both infinite impulse response (IIR) and finite impulse response (FIR) structures. As compared to the FIR filters, IIR filters have the advantage that for a given set of specifications, at lower order itself it gets an efficient approximation. The disadvantages of the IIR filters are they potentially unstable and do not provide linear phase characteristics. But FIR filters are unconditionally stable and can be designed for linear phase characteristics.

4.5 Time Delay Estimation

For time delay estimation [11] the range estimation algorithm is used. TDE has significant practical importance in many fields like radar, sonar, seismology, ultrasonic, etc. It is the first stage for identifying, localizing, and tracking radiating sources or reflecting targets.

Cross-correlation: The transmitted signal and the received signal output from the sensor are correlated with each other. After correlating the two signals, the

Fig. 4 Received output

correlation peak is detected using the peak detector. The time axis of the peak in correlation corresponds to the time delay. In this case, 500,000 samples are taken at a time to correlate.

So the correlation output has 1,000,000 values. If any delay is present between the correlated signals, then the peak will deviate from the 49,999th position by the value equivalent to that delay.

Cross-correlation is the tool for determining the time delay between two signals. The signals are correlated positively then the maximum value will obtain or if correlated negatively then correlated then will get the minimum values. The significance of the cross-correlation is that it gives point of time at signals aligned perfectly. Argument of maximum of the cross-correlation will give the time delay between two signals.

$$TimeDelay = argmax((f * g(t)))$$ (2)

The correlation technique presented offers a good possibility for measuring the distance between the ground and the tunnel by the time delay between two signals. Cross-correlation gives equivalent of power spectral density. Hence cross-correlation a well-suited tool for analyzing time invariant systems, where spurious signals or noise interfere with the output measured signal.

R_t: Transmitted signal = $A(t)$
R_x: Received signal = $B(t + \tau)$
$R_{tx}(\tau)$: Cross-correlated signal

$$R_{tx}(\tau) = \int\limits_{\infty}^{\infty} A(t)B(t+\tau) \tag{3}$$

5 Testing and Analysis

Compare the results from simulated scenario to the DAQ acquisition method. Ultrasonic velocity in soil is varying according to the frequency. An ultrasonic wave has lowest speed in gaseous medium, moderate speed in liquid medium, and highest in solid medium. Hence in soil medium, it has high frequency. Table 1 shows the experimental results of velocity of ultrasonic sound in air and wood. The velocity of ultrasonic signal in one medium depends on the density of the material. The main soil parameters affecting the speed of propagation is the density, impedance, water content, transducer impedance matching, etc. Transmission of waves in a material is models with two parameters: velocity and attenuation. Ultrasonic velocity can be correlated to mechanical properties of a material, whereas ultrasonic attenuation can be correlated to microstructural properties of a material. Here we avoid all these parameters and considered soil as homogeneous and even medium. The reflected signal should be amplitude attenuated and delayed in time. This model will give the real-world values of the distance compared to the ideal values from the unattenuated signal. Table 2 shows the time delay and the velocity at different noise power levels at a constant distance of 0.01 m. Table 3 shows the distance of the object at various depths and the time delay with the average velocity

Table 1 Experimental results velocity for different depths

Medium	Distance (cm)	Velocity (m s^{-1})
Air	1	332.163
Air	5	339.358
Wood	6	3800
Wood	9	3500

Table 2 Time delay and velocity at different noise levels

Noise level (dB)	Time delay (ms)	Distance (m)	Velocity (m s^{-1})
0.0	0.021075	0.01	948.99
0.20	0.017031	0.01	1176.25
0.40	0.022439	0.01	891.29
0.60	0.001679	0.01	1195
0.80	0.00987	0.01	2025
1	0.0212854	0.01	939.6

Table 3 Distance and time delay with constant velocity 1000 m/s

Time delay (μs)	Distance (m)
20	0.01
100	0.05
200	0.1
300	0.15
400	0.2
500	0.25

1000 m/s from Table 2. We can obtain the values which similar to the real lossy environment. Cross-correlation is a powerful tool it will automatically nullify the environmental noise content from the result.

6   Conclusion

Cross-border underground tunnels are threat to our homeland security. These tunnels are the main migration path for the terrorists. So the detection of such tunnels is necessary for our security. The pulse echo technique with round trip time is a better method for the distance estimation and hence we can find the depth of such clandestine tunnels.

By range estimation algorithm, we calculated the velocity for the soil sample and then estimate the unknown depth at which the tunnel resides. With this experimental result (velocity), the depth of the tunnel easily discovered. Due to the noise present in the transmission and reception process, we get velocity values slightly different from the actual results which cause deviation in estimated value of depth. Penetration capability of the signal or the maximum distance estimation is limited by the power of the signal.

7   Future Works

The aim of the project was to estimate the depth of the tunnel. Using the frequency estimation and the range estimation algorithm, we calculate the depth of the tunnel from the ground. The power of the generated signal is too low to penetrate up to the required distance. So amplification using a high-power amplifier and robust algorithm for the localization of the tunnel are considered as future work. The system with a single transmitter and receiver can extended to an array of transmitters and receivers with mobility for surveillance of user area.

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