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Life detection and location methods using UWB impulse radar in a coal mine

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ABSTRACT

An ultra-wideband impulse radar was studied for the detection of buried life in coal mines. An improved Empirical Mode Decomposition (EMD) method based on a cross-correlation filter was proposed for reduction of multipath and noise interference. Multipath interference was first removed by cross-correlation filtering. Then the delays of each pulse in every echo were summed. An EMD algorithm was used for noise reduction for the total delay of each echo. The corresponding EMD results of every echo were then summed and averaged. Finally, evidence for the existence of buried life and their position were obtained from amplitude–frequency curves of the averaged EMD results. Detailed simulation experiments are presented to validate the effectiveness of this proposed method. The experimental results show that this method can efficiently eliminate multipath interference and reduce noise interference in echoes, which makes detection and location of buried life in coal mines more accurate.

1. Introduction

Mine safety is the key problem restricting the development of the coal industry. Rescue in the coal mine presently depends mainly on people and rescue dogs. However, the limitations of these methods constrict coal mine disaster rescue efforts [1]. Life detection radar uses radar principles to achieve non-contact life detection, location, and identification [2,3]. In recent years, single frequency continuous wave and Ultra-Wideband (UWB) life detection radar systems have been studied [3]. UWB life detection radar is being paid more and more attention because of its high range resolution and strong penetration performance [4–8].

Roadway spaces in a mine are small and the humidity is high. Under these conditions electromagnetic wave transmission exhibits strong multi-path effects [9–11]. However, the frequency of the electromagnetic waves used is unrestricted underground. UWB impulse life detection radar systems have high resolution, a simple realization, require small transmitter power, have powerful anti-multipath capability, and have great penetration ability. These systems are more suitable for the underground environment and can provide the amount of information from rescue goals [12,13]. Therefore, in this paper, a UWB impulse life detection radar technology was studied for life detection in coal mines.

A transmitted signal and echo model are established. The total delay of every echo pulse train is decomposed and averaged by an improved Empirical Mode Decomposition (EMD) method based on cross-correlation calculations. The existence and position of life are obtained from subsequent amplitude and frequency analysis. The effectiveness of the proposed method is demonstrated by sample calculations and simulation.

2. Echo model of UWB impulse life detection radar

2.1. Transmitted signal model

A Gaussian monocycle pulse is selected as the UWB monopulse signal. It is described by:

$$f(t) = 4 * \pi \frac{t}{\tau^2} \exp\left(-2 * \pi \frac{(t - T_c)^2}{\tau^2}\right) \tag{1}$$

where τ is the pulse width parameter and T_c a pulse shift parameter.

Gaussian monocycle pulses are encoded into transmitted signals by a pseudo random code [7]. This may be described as:

$$\begin{aligned} s(t) &= \sum_{n=0}^{N-1} c_n f(t - nT) \\ &= \sum_{n=0}^{N-1} 4c_n * \pi \frac{t - nT}{\tau^2} \exp\left(-2 * \pi \frac{(t - nT)^2}{\tau^2}\right) \end{aligned} \tag{2}$$

where the c_n $\{n = 0, 1, \ldots, N\}$ are elements of the pseudo random code sequence; N the length of the pseudo random code sequence; and T the period of a pulse.

2.2. Echo model

The transmitting and receiving antennas are supposed to converge on the same position on the obstacle surface located d_0 me-

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ters from the human body. The distance between the body and the radar is then defined as:

$$d(t) = d_0 + \Delta d(t) \tag{3}$$

where $\Delta d(t)$ is any micro-motion of the human body caused by breathing and heartbeat. This may be considered equivalent to a simple harmonic vibration:

$$\Delta d(t) = a_h \sin(\omega_h t + \phi_h) + a_b \sin(\omega_b t + \phi_b) \tag{4}$$

where a_h, ω_h, and ϕ_h are respectively the amplitude, circular frequency, and constant phase angle of the heartbeat signal. Likewise, a_b, ω_b, and ϕ_b are respectively the amplitude, circular frequency, and constant phase angle of the breathing signal.

Eq. (2) now gives the echo as:

$$\begin{aligned} r(t) &= s\left(t - \frac{2d(t)}{\upsilon}\right) \\ &= s\left(t - \frac{2d_0 + 2a_h \sin(\omega_h t + \phi_h) + 2a_b \sin(\omega_b t)}{\upsilon}\right) \\ &= \sum_{n=0}^{N-1} 4c_n * \pi \frac{t - nT - \frac{2d(t)}{\upsilon}}{\tau} \exp\left(-2 * \pi \frac{(t - nT - \frac{2d(t)}{\upsilon})^2}{\tau^2}\right) \end{aligned} \tag{5}$$

where υ is the transmission speed of the signal through the obstacles.

Eq. (5) shows that if there is a living organism the echo delay consists of two parts: a fixed delay caused by the position of the living object and a time-varying Doppler delay caused by a signal arising from any life motion. If breathing, heartbeat, or other vital signs are taken as harmonic vibrations then the echo delay has periodic variations. Therefore, all pulse delays in an echo are summed and decomposed to judge if life exists and to calculate the position of the living object if one exists.

3. Empirical mode decomposition principle

In 1998 Huang proposed an analysis method called Empirical Mode Decomposition (EMD) appropriate for non-stationary and nonlinear signals [14]. It differs from both the short time Fourier transform and the wavelet transform because EMD does not require a prior set of basis functions. This gives it a certain adaptability. It adaptively decomposes peaks in the time-domain waveform. Then the signal is expressed by a set of different Intrinsic Mode Functions (IMF) having different characteristics. Each IMF must satisfy certain conditions [15–17]. These are that the numbers of poles and cross-zero points be equal, or the difference is at most one, and that the sequence be symmetric along the time axis.

The decomposition of function $x(t)$ proceeds as:

(1) Find all maximum or minimum points of $x(t)$. Use a cubic spline function to interpolate the original data sequence into an upper and lower envelope respectively.

(2) Calculate the average envelope, m_1, of the upper and lower envelopes.

(3) Subtract the average envelope from $x(t)$ to obtain $h_1 = x(t) - m_1$.

(4) Generally, h_1 does not satisfy the IMF conditions. Now consider h_1 as a new signal and repeat steps (1), (2), and (3) to obtain h_{1k} until the values of the criterion $SD = \sum_{t=0}^{T}\left[\frac{|h_{1(k-1)}(t) - h_{1k}(t)|^2}{h_{1(k-1)}^2(t)}\right]$ fall between 0.2 and 0.3. At this point an IMF has been obtained, which is expressed as $c_1 = h_{1k}$.

(5) Calculate $r_1 = x(t) - c_1$. Now consider r_1 to be a new sequence. Repeat the above four steps until the last r_n is a monotonic function. In this way n IMFs and one residual r_n are obtained.

4. Target detection and location algorithms and simulation

The signal from a living object is a low-frequency signal. The normal heart rate is usually 70–100 times per minute. The heart contraction caused by each heartbeat is roughly a few millimeters. The normal respiration rate is usually 15–30 times per minute. Amplitude fluctuations in the chest caused by each breath are about a few centimeters. Thus, the periodic Doppler delay caused by the life signal is expected to be very weak.

Multiple reflections and refractions of the transmission signal in the roadway might cause multipath signals to reach the receiver during echo sampling. This produces multipath interference. In addition, system noise might affect the results of signal extraction. Therefore, an improved EMD algorithm based on cross-correlation calculations is proposed to eliminate multipath interference and to reduce noise interference. This makes the detection results more accurate.

4.1. Echo pre-processing

The transmitted signal consists of a series of Gaussian monocycle pulses coded by a pseudo random code that has good autocorrelation characteristics. For example, the correlation function of a Barker code has an N:1 main lobe to side-lobe peak amplitude ratio. Using this property the interval of the transmitted pulse train may be set as an integer times the pulse width and the cross-correlation operation is done on two echo signals. That is so say, if the transmitted pulse train interval is assumed as 0 we may write:

$$\begin{aligned} R_{12}(t) &= \frac{1}{NT}\int r_1(t) * r_2(t + NT)dt \\ &= \frac{1}{NT}\int s\left(t - \frac{2d_1(t)}{\upsilon}\right) * s\left(t - \frac{2d_2(t)}{\upsilon}\right)dt \end{aligned} \tag{6}$$

where $r_1(t)$ and $r_2(t)$ are respectively echoes of two adjacent transmitted signals, NT is the cycle of the transmitted pulse train, and $d_1(t)$ and $d_2(t)$ are two echo delays relative to the transmitted signals.

Compared to the transmitter pulse width or the transmitted signal interval the Doppler delay changes very slowly. So the delays caused by any life signal present in two adjacent echoes may be considered equal. When the two received signals are echoes reflected by a target then $d_1(t) \approx d_2(t)$. The cross-correlation function of two echo signals is then equal to the autocorrelation function. Hence:

$$R_{12}(t) = \frac{1}{NT}\int s\left(t - \frac{2d_1(t)}{\upsilon}\right) * s\left(t - \frac{2d_1(t)}{\upsilon}\right)dt = R_{11}(t) \tag{7}$$

If Eq. (2) is the transmitted pulse train then Fig. 1 shows the autocorrelation curve of this pulse train.

The phase of any multipath signals and the target echo signal are typically not phase aligned. That is to say when one of two adjacent echoes is a multipath signal the cross-correlation function will be very small. Therefore, the cross-correlation filter operates between two adjacent echoes to eliminate multipath signals from the various echoes.

4.2. An improved EMD target extraction algorithm

The first pulse in a transmitted pulse train is considered to be the reference waveform of a matched filter after passing through the cross-correlation filter. Each pulse is cross-correlated with the reference waveform one by one in every echo, which provides every pulse delay. If each transmitted pulse train has N pulses, N-delay data can be obtained from each echo. Then the N-values