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Buried objects detection in heterogeneous environment using UWB systems combined with curve fitting method

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Abstract

A new method is proposed to improve the accuracy of locating buried objects in heterogeneous environments using shifted time pulses with radio impulse ultra wide band (IR-UWB), time-hopping pulse position modulation (TH-BPSK UWB), binary phase shift keying (TH-BPSK UWB) systems combined with the least square curve fitting method (LSCFM). The analytical expression is validated by simulation and the locating errors used to assess the performance of systems. The numerical results indicate that the proposed method has higher accuracy than the conventional ones.

Keywords: IR-UWB; TH-BPSK UWB; TH-PPM UWB; Buried objects; Curve fitting method.

1. Introduction

Buried object locating systems in the underground or in non-destructive structures play an important role in modern life. Various detection techniques have been developed for locating buried pipelines such as ground penetrating radar-GPR [1], metal detection [2], acoustic transmission methods [3]. These methods can detect the position of metallic or non-metallic buried pipelines but greatly affected by environmental characteristics, noise and cannot determine the wave speed. Today, with the development of ultra wide band technology (UWB) due to high resolution, the UWB technique is one of the good candidates for positioning methods including locating buried objects in the non-destructive environments. The positioning based on the received signal strength index - RSSI proposed in [4], which can determine the environmental properties and shape of the object, but these parameters are determined with assumption that the propagation medium is homogeneous. Different from the RSSI method, the relative permittivity of the environment and the location of buried objects can be determined based on the propagation time calculated from the correlation function at the receiver. In order to increase accuracy in determining traveling time with heterogeneous environments, the paper proposes a method using UWB technology with shifted pulses by a certain time combined with LSCFM for locating many objects in heterogeneous environments. The rest of the paper is organized as follows: Section 2 describes the system model and its parameters; the proposed method is presented in Section 3; Section 4 presents the numerical results and Section 5 ends the paper.

2. System model

A positioning system in a non-destructive environment is illustrated in Fig. 1. The transmission medium has two layers with the relative permitivities ε_1 and ε_2, respectively. The transmitted signal is UWB pulse denoted as $s(t)$ and reflected from the first buried object which denoted as $r(t)$. $s(t)$ to the interface between two layers is partly reflected denoted as $A.r(t)$, the rest is through the interface and reflected from the second object denoted by $(1 - A)r(t)$. The location of each buried object is defined via horizontal parameter of Z_{ob} and the buried depth of d_{ob}. The IR-UWB, TH-BPSK and TH-PPM UWB signals are used as the transmitted signal. A IR-UWB

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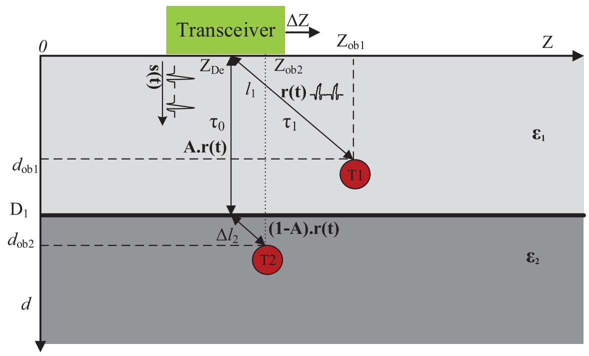

Fig. 1. System model.

signal takes the form [5]:

$$s_{IR}(t) = \sqrt{P}\sum_{i=0}^{N_p} g(t - iT_r), \quad (1)$$

a TH-BPSK and a TH-PPM UWB has the form [6]:

$$s_{BPSK}(t) = \sqrt{P}\sum_{i=0}^{N_p} d_i g(t - iT_r - c_i T_c), \quad (2)$$

$$s_{PPM}(t) = \sqrt{P}\sum_{i=0}^{N_p} g(t - iT_r - c_i T_c - d_i T_{PPM}), \quad (3)$$

where t is time, P is the transmit power, N_p is the number of transmitted pulses, $g(t)$ is the signal pulse with pulse width T_p; T_r is the repetitive period of the pulse; $d_i \in \{1, -1\}$ with TH-BPSK UWB signal and $d_i \in \{0, 1\}$ with TH-PPM UWB signal; T_c is TH chip width and T_{PPM} is the time shift associated with PPM signal. In this paper, the signal pulses used are derivatives of the basic Gaussian pulse named Gaussian monocycles with nth order is:

$$g_n(t) = B_{np}\frac{d^n}{dt^n}e^{-2\pi(\frac{t}{\alpha_p})^2}, \quad (4)$$

where α_p is a time normalization factor and B_{np} is normalized energy of $g_n(t)$. An example of the IR-UWB, TH-BPSK, TH-PPM UWB signals with second-order Gaussian monocycle are shown in Fig. 2 For the system model shown in Fig. 1, the received signal from the first buried object, the interface and the second buried object in Fig. 1 have the forms:

$$r_1(t) = A_1 s(t - \tau_1) + n_1(t), \quad (5)$$

$$r_{21}(t) = A_1 A_{21} s(t - \tau_{21}) + n_{21}(t) \quad (6)$$

$$r_{22}(t) = A_2(1 - A_{21}) s(t - \tau_{22}) + n_{22}(t); \quad (7)$$

where A_1, A_2 are the attenuation factors of the environment with layer 1 and 2 respectively; A_{21} is the reflection factor from the interface between two layers; and $n(t)$ is additive white Gaussian noise. The position of objects determined via traveling time is calculated using the correlation function:

$$R(x) = \int_{-\infty}^{\infty} r(t)\omega(t - x)dt. \quad (8)$$

$\omega(t)$ is the template signal at the receiver which is $g(t)$ with UWB-IR, TH-BPSK UWB [7]; and $g(t) - g(t - T_{PPM})$ with TH-PPM UWB [6]. The traveling time denoted by τ is calculated from the maximum value of $R(x)$:

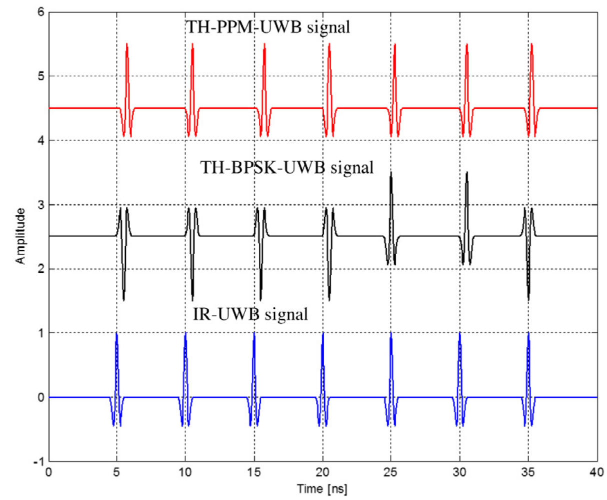

Fig. 2. The UWB signal shapes with $T_r = 5$ ns, $T_c = 0.9$ ns, $T_{PPM} = 0.15$ ns, $\alpha_p = 0.2877$ ns.

$$\tau = x_{val} = \text{Arg}\max_{x}\{R(x)\}. \quad (9)$$

The propagation velocity in the system is [8]

$$V_i = \frac{c}{\sqrt{\varepsilon_i}}, \quad (10)$$

where, ε_i is the relative permittivity of the ith layer, $c = 3.10^8$ m/s is the velocity of light in the vacuum environment. The distance from the device to the buried objects:

$$l_1 = \frac{1}{2}V_1\tau_1, \quad (11)$$

$$l_2 = \Delta l_2 + D_1 = \frac{1}{2}V_2\tau_2 + D_1. \quad (12)$$

3. Determining the traveling time and locating method

3.1. Determining the traveling time

The value of traveling time strongly affects the estimating of buried object's location. To increase the accuracy of estimated traveling time, in this paper, we propose a method of shifting transmitted pulses. Accordingly, let us consider a sequence of N_p transmitted pulses with a repetitive period of T_r, the nth pulse is shifted by a time constant $n\Delta T$ ($n = 1 : N_p$) with:

$$\Delta T = \frac{T_r}{N_p}, \quad (13)$$

hence, the transmitted signal in Eq. (1) has form:

$$s_{IRs}(t) = \sqrt{P}\sum_{i=0}^{N} g(t - iT_r - \frac{iT_r}{N_p}), \quad (14)$$

and similar forms of TH-BPSK, TH-PPM signals. The traveling time is determined according to the correlation values of

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N_p pulses as follows:

$$\tau = \frac{1}{N_p}\sum_{i=0}^{N_p}\tau_i = \frac{1}{N_p}\sum_{i=0}^{N_p}\operatorname*{Arg\,max}_{x}\int_{-\infty}^{\infty} r_i\left(t - \frac{iT_r}{N_p}\right)\omega(t-x)dt, \quad (15)$$

where $r_i(t)$ is the received signal of the ith pulse. With the estimated values of traveling time from the device to the buried object, the location of the object can be determined based on LSCFM.

3.2. Locating method

In Fig. 1, to locate the position of buried objects 'T1' and 'T2', the device is moved horizontally and emits a chain of shifted pulses after every movement step of ΔZ. The parameters ε_1, Z_{ob1}, d_{ob1}; D_1; ε_2, Z_{ob2}, d_{ob2} are estimated based on the traveling time values τ_1, τ_0, τ_2 and the position Z_{De} of the device. The relationship between the system parameters is expressed in the following equations

$$\tau_{1i} = 2\frac{\sqrt{\varepsilon_1\left(d_{ob1}^2 + (Z_{Dei} - Z_{ob1})^2\right)}}{c}, \quad (16)$$

$$\tau_0 = 2\frac{D_1\sqrt{\varepsilon_1}}{c}, \quad (17)$$

$$\tau_{2i} = \tau_0 + 2\frac{\sqrt{\varepsilon_2\left(d_{ob2}^2 + (Z_{Dei} - Z_{ob2})^2\right)}}{c}. \quad (18)$$

where $Z_{Dei} = i\Delta Z$ is the position of device at the ith moving times. The unknown parameters are calculated using LSCFM [9] which makes the deviation function in Eqs. (19) and (20) reach the minimum value.

$$E_1 = \sum_{i=1}^{M}[\tau_{1i} - f_1(Z_{Dei})]^2; \quad (19)$$

$$E_2 = \sum_{i=1}^{M}[\tau_{2i} - f_2(Z_{Dei})]^2; \quad (20)$$

where M is the number of movements of transceiver and $f_1(Z_{Dei})$, $f_2(Z_{Dei})$ are the right hand side of the Eqs. (16), (18). In Eqs. (19), (20), E_1 is a function of variables ε_1, Z_{ob1}, d_{ob1} and E_2 is a function of variables ε_2, Z_{ob2}, d_{ob2}; these variables are referred to as ε, Z_{ob}, d_{ob}. In addition, as seen in Fig. 3 and Eqs. (16), (17) the value of D_1 and therefor the value of τ_0 is constant when the device is moved, so with the estimated value of ε_1 and τ_0, D_1 is completely determined. The values of unknown vector $\mathbf{X} = (\varepsilon, \mathbf{Z_{ob}}, \mathbf{d_{ob}})$ determined by the following steps:

Step 1: Initialized with any value; check the constraint condition in Eqs. (19), (20), if it is false, perform step 2-updating the parameter, else, stop the algorithm.

Step 2: The parameter vector is replaced by the new one $(\mathbf{X}+\theta)$ with θ being an updated step vector, and calculate the deviation functions in Eqs. (19), (20). The deviation function has its minimum at zero gradient with respect to θ, hence θ can be determined satisfying:

$$[\mathbf{J^TJ} + \lambda \mathrm{diag}(\mathbf{J^TJ})]\theta = \mathbf{J^T}[\tau - \mathbf{f}(\mathbf{Z_{De}})]; \quad (21)$$

where $\mathbf{J}$ is the Jacobian matrix, whose ith row equals:

$$J_i = \frac{\partial f(Z_{Dei}, \mathbf{X})}{\partial \mathbf{X}}. \quad (22)$$

$\mathbf{Z_{De}}$ is a vector whose ith element is Z_{Dei}, the damping factor λ (non-negative) is adjusted at each iteration. If $\mathbf{E} = (E_1, E_2)$ is reduced rapidly, a smaller value of λ can be used, whereas λ can be increased.

Step 3: The updated step vector is computed as follows.

$$\theta = [\mathbf{J^TJ} + \lambda \mathrm{diag}(\mathbf{J^TJ})]^{-1}\mathbf{J^T}[\tau - \mathbf{f}(\mathbf{Z_{De}})]. \quad (23)$$

The algorithm repeats steps 2 and 3 until the constraint conditions in Eqs. (19), (20) are satisfied. And we have the estimated values of system parameters which are the best fitting curves.

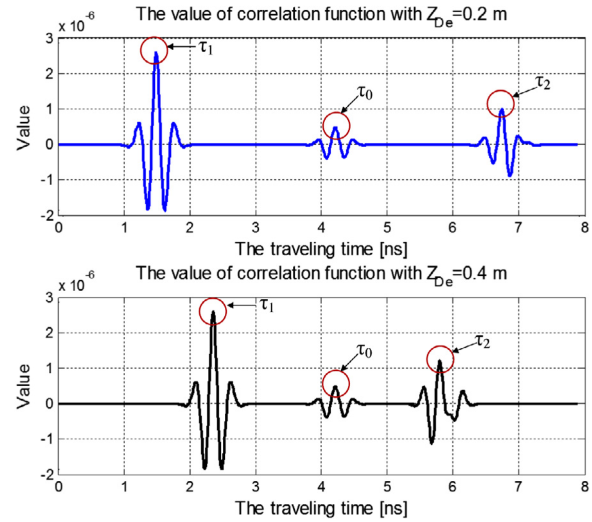

Fig. 3. The correlation shapes of received signal in IR-UWB system as shown in Fig. 1 with different position of the device.

Table 1
Simulation parameters.

Parameter	Notation	Value
Impulse width	PW	0.7 ns
Pulse repetition cycle	T_r	0.2 ns
Time normalization factor	T_p	0.2877 ns
Time shift of PPM	T_{PPM}	0.15 ns
Chip width	T_c	0.9 ns
Number of pulses	N_p	100
Movement step of the device	ΔZ	10 cm

4. Numerical results and comparisons

According to Section 3, we observe that the location of buried objects and the relative permittivity of the environment can be calculated based on traveling time using LSCFM. All the numerical results in this paper were computed using Matlab and the errors of estimated values in comparison with the true values were used to evaluate the proposed and

Table 2
Estimated results.

Parameter	True value	Estimated value by shifted TH-BPSK-UWB
ε_1, ε_2	2.5, 4.5	2.3415, 4.2387
D_1	0.4 m	0.4153 m

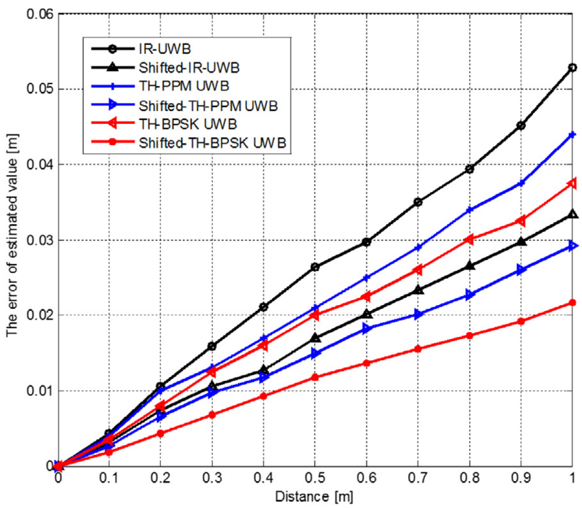

Fig. 4. The errors of estimated values of IR, TH-BPSK, TH-PPM UWB and proposed systems.

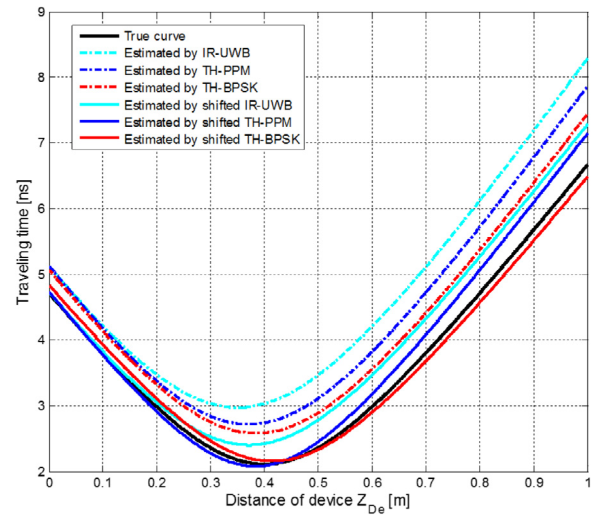

Fig. 5. The curves of traveling time according to the position of transceiver estimated by proposed method.

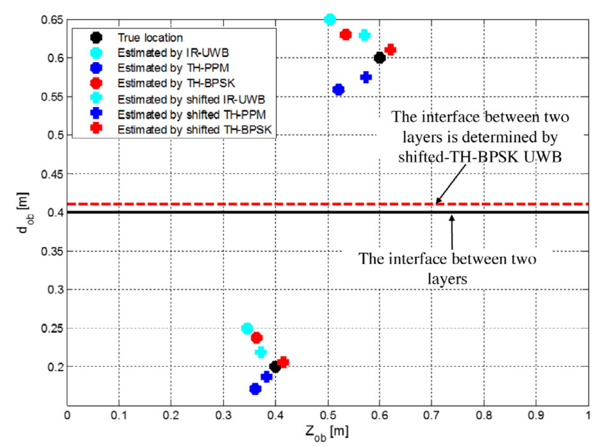

Fig. 6. The location of buried objects estimated by proposed method.

conventional methods. The parameters of an example UWB system are listed in Table 1 with using the second Gaussian monocycle. Simulation model is illustrated in Fig. 1. Firstly, UWB systems are compared based on determining the distance from device to a buried object in a homogeneous environment with the relative permittivity of $\varepsilon = 2.5$, the buried object moves within a distance of 0–1 m in the d direction. The performance of conventional IR, TH-BPSK, TH-PPM UWB and proposed systems are indicated in Fig. 4.

As seen, with the same system parameters, the TH-BPSK, PPM UWB give smaller errors than the IR-UWB system; the shifted-time systems outperform the conventional with average relative errors in comparison to the true values are about 1.9% with shifted-TH-BPSK, 2.6% with shifted-TH-PPM, and 3.2% with shifted-IR UWB meanwhile with conventional IR-UWB, TH-PPM UWB, TH-BPSK, the values of average relative errors are 4.8%, 4% and 3.5%, respectively. These results can be explained from Eqs. (1), (2), (3), (14), (15), when UWB pulses are modulated by time-hopping codes, the detection of received pulses according to TH codes is better than that of the IR system; BPSK antipodal modulated pulses also provide better detection of PPM. Besides, the transmitted pulses are shifted by a certain time of $(i.T_r/N_p)$ which makes the determination of traveling time more accurate because by moving the pulses, there exists a pulse in the received pulse sequence which has the traveling time closest to the true propagation time value. To determine the relative permittivity and location of the buried objects, the transceiver moved from position 0, in the Z axis direction (as illustrated in Fig. 1), at each movement step $\Delta Z = 10$ cm, emits a sequence of N_p pulses, receives the reflected signals, calculates the traveling time of signals from object 'T1', interface D_1 and object 'T2', and then, LSCFM is used as presented in Section 3.2. Table 2, Figs. 5 and 6 indicate the results for estimating the model parameters and Table 2 only presents estimated values that are not visually shown in Fig. 6. The parameters $\varepsilon_1, Z_{ob1}, d_{ob1}$ are computed at first, then D_1 is determined based on τ_0 and $\widehat{\varepsilon_1}$; then, with τ_0, τ_2, the parameters $\varepsilon_2, Z_{ob2}, d_{ob2}$ are also specified. Fig. 5 shows the curve of Eq. (16) for the first buried object ('T1'), Fig. 6 shows the locations estimated by the proposed method. Observe that similar to that shown in Fig. 4, the estimated results of shifted-TH-BPSK have the highest accuracy in the compared system.

5. Conclusions

In this paper, we propose a method to locate buried objects in the heterogeneous environments using shifted time pulses and LSCFM for UWB systems. Our analysis indicates that the accuracy of locating buried objects can be improved by proposed method with IR-UWB, TH-BPSK, and TH-PPM UWB systems. The performance of those system is assessed based on locating errors and TH-BPSK UWB system outperforms the others with the second-order Gaussian monocycle. The proposed method can be also applied to UWB systems with arbitrary order in positioning applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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