LOCATING THE BURIED OBJECT IN THE NON-DESTRUCTIVE STRUCTURES USING TH-BPSK UWB SYSTEM

Thanh Hiep Pham¹, Thi Huyen Nguyen¹,*

¹Le Quy Don Technical University

Abstract

The ultra-wideband (UWB) communication system utilizing impulse signals is an attractive technique which can achieve low power consumption, high data rate, and high accuracy in location estimation. One of the applications of UWB is ground penetrating radar (GPR) which has been using to investigate non-destructive structures. In this paper, we proposed a method of locating a buried object in non-destructive structures (concrete, dry soil) using time hopping BPSK UWB (TH-BPSK UWB) modulation system with a certain pulse shape combined with Gauss-Newton nonlinear estimation algorithm. The results of the proposed method were evaluated using computer simulation in terms of the errors of estimated position and spatial resolution.

Keywords: Ultra-wideband; TH-BPSK UWB; ground penetrating radar; Gauss-Newton method.

1. Introduction

In the radio communication systems, UWB is known as an emerging technology with some unique attractive features such as it can offer a wealth of advantages for both high rate communications and high resolution ranging [1]. It comes from the fact that it uses impulse radio with very short pulses. These are typically on the order of 1 ns, opening up for high spatial resolution. This characteristic makes UWB very suitable for localization purposes. It has successfully been applied to a wide variety of localization applications, such as industrial [2], health care [3], [4], motion capture [5] and GPR. UWB positioning accuracy is reported to be on the order of decimeters [2], [3].

Several modulation techniques have been proposed for UWB signals, such as pulse position modulation (PPM) and a variety of pulse amplitude modulations (PAMs), including binary phase-shift keying (BPSK) and on-off keying (OOK) [6]. TH combined with PPM was originally proposed for UWB systems [7]. Currently, TH-PPM and TH-BPSK UWB systems are often considered as alternatives for a given application, although the differences between the two systems lead to different performance characteristics. The performances of TH-PPM and TH-BPSK UWB systems were compared in [8], [9], based on a Gaussian approximation (GA).
A comparison of different UWB modulation schemes in the multiple-access system was also presented recently in [10] in terms of bit-error rate (BER).

In this paper, we present a non-destructive environment positioning approach using the TH-BPSK UWB technique and time-of-arrival (TOA) measurements and then explain the non-linear least square (NLLS) algorithm. A simulation for a simple case of a buried object is represented to evaluate the proposed method. The rest of the paper is organized as follows: Section 2 represents the system model, the distance estimation method and the identification of a buried object with the NLLS algorithm is explained in Section 3, and Section 4 concludes the paper.

2. System model

2.1. Analysis of TH-BPSK system

The penetrating system model is illustrated in Fig. 1 below and the parameters in the model are explained in detail later in the paper.

Fig. 1. The penetrating TH-BPSK system

A typical TH-BPSK UWB signal with antipodal data modulation takes the form [11]:

$$s_{BPSK}(t) = \sqrt{E_b} \sum_{i=0}^{N_s-1} d_i p(t - iT_r - c_i T_c)$$  \hspace{1cm} (1)

The parameters employed in these model are described as follows:

- $t$ is time, $E_b$ is the bit energy common to all signals.
• $N_s$ is the length of the repetition code [11].
• $d_i \in \{\pm 1\}$ represents modulated data symbols.
• $p(t)$ is the signal pulse with pulse width $T_p$, repetition period $T_r$ and normalized so that $\int_{-\infty}^{+\infty} p^2(t) dt = 1$.
• $c_i$ represents the TH code, it is pseudo-random sequence taking integer values in the range $[0, 1]$ and $T_c$ is TH chip width satisfied: $T_c \leq T_r$.

The reflected signal $r(t)$ can provide significant information such as the shape and materials of the reflecting object and is the result of the following operation [12]:

$$r(t) = \eta s_{BPSK}(t - \tau) + n(t)$$

(2)

where $n(t)$ is the AWGN with two-sided power spectral density $N_0/2$, $\tau$, $\eta$ is the time delay between transmitter and receiver clocks, and the channel attenuation respectively. To detect the received signal, $r(t)$ is generally correlated with the reference signal $s_{ref}(t - \tau)$ that matches the transmitted pulse waveform. The output of the correlation block is determined as below:

$$R(\tau) = \int_{-T/2}^{T/2} r(t) s_{ref}(t) dt$$

(3)

where $T$ is impulse width.

The distance from the buried object to the TH-BPSK UWB device is determined from the delay time value $\hat{\tau}$ - calculated according to the maximum value of $R(\tau)$ as

$$d = \frac{c \hat{\tau}}{2\sqrt{\varepsilon}}, \text{ and } \hat{\tau} = \arg \left( \max_{\tau} \left( R(\tau) \right) \right)$$

(4)

where $c$, $\varepsilon$, $\hat{\tau}$ are the velocity of light in free space, the dielectric constant of the wave propagation environment and the estimation of $\tau$, respectively. A factor of $1/2$ is that the transmit and receive antenna at the same location, so the radio wave propagation distance is twice the distance from the buried object to the penetration system. The waveform and cepstrum (results from taking the inverse Fourier transform (IFT) of the logarithm of the estimated spectrum of a signal) of the received signal can be shown as in Fig. 2.
Based on the distances calculated from the received signals, some simple object shapes can be estimated using the NLLS algorithm.

It can be seen that there is a variety of pulse shapes that have been proposed for UWB impulse radio systems such as the Gaussian pulse, Manchester monocycle, Gaussian monocycles, and Hermite pulse. The different shapes of Gaussian pulse have been studied and evaluated in [11]. The Gaussian monocycles have the form:

$$g_0(t) = e^{-2\pi \left( \frac{t}{\tau_p} \right)^2}$$

The $n$-th derivative of the Gaussian monocycles is:

$$g_n(t) = E_n \frac{d^n}{dt^n} e^{-2\pi \left( \frac{t}{\tau_p} \right)^2}$$

where $E_n$ is the normalized energy of the pulses, $\tau_p$ represents a time normalization factor related to pulse width (PW) such as: $\tau_p = \frac{pw}{4 \times 5}$ for the first derivative and $\tau_p = \frac{pw}{2 \times 3}$ for the second derivative of Gaussian,... In this paper, we restrict our performance analysis of TH-BPSK UWB systems to those employing the 2\textsuperscript{nd} order Gaussian monocycle [13].

2.2. The distance measuring method

The distance from the object to the device is estimated based on the wave propagation time. This time is determined using the correlation output via the matched filter. In the estimation method, the calculation of this time is done by $M$ times $\hat{\tau}_m$ based on $M$ maximum values of the correlation output $\max_{\tau} \{ R_m(\tau) \}_{m=1}^M$ for each $N_s$,
then calculate $M$ values of estimated distance $\{d_m\}^M_{m=1}$ and take the average value $\bar{D}$ as a reference value. The standard deviation between the estimated distances $\hat{d}_m$ and $\bar{D}$ is calculated according to Eq. (9) as below and used as a criterion for evaluating the convergence of the estimation algorithm. The estimation of distance is successful when the standard deviation does not exceed a threshold value and the estimated distance value is obtained by $\bar{D}$. Otherwise, $M$ is increased and the estimation algorithm will be repeated. The estimation algorithm is illustrated in three steps as follows.

**Step 1:** Calculating the delay time:

$$\{\hat{\tau}_m\}^M_{m=1} = \arg \max_{\tau} \{R_m(\tau)\}^M_{m=1}$$

(7)

**Step 2:** Calculating the estimated distance:

$$\hat{d}_m = \frac{c\hat{\tau}_m}{2\sqrt{\varepsilon}}$$

(8)

**Step 3:** Calculating the average of estimated distance and standard deviation:

$$\bar{D} = \frac{1}{M} \sum_{m=1}^{M} \hat{d}_m, \text{ and } \sigma_{\hat{d}} = \sqrt{\frac{1}{M} \sum_{m=1}^{M} (\hat{d}_m - \bar{D})^2}$$

(9)

If $\sigma_{\hat{d}} \leq \sigma_{th}$, the estimated distance is $\bar{D}$, otherwise, the procedure will be repeated from step 1 with another $M$. The mean error threshold $\sigma_{th}$ is chosen by 2% of the maximum detectable distance 5m [14] of the penetrating systems. Based on calculated distances, we can identify the shape of some simple buried objects. The algorithm of estimating the shape of a buried object is presented in Section 3.

### 3. The estimation of the system parameters

#### 3.1. Proposed estimation algorithm

The buried object that should be estimated is assumed to be a pipeline, such as water pipe, gas pipe and so on. Therefore, the NLLS algorithm should find out the started position, length and diameter of this pipe based on the estimated distances from the surface of the pipe to the device. In order to reduce the complexity, we assume that the non-destructive environment is homogeneous and has a dielectric constant is $\varepsilon_1$, the parameters are estimated using the reflected signals from the upper surface of the pipeline and those signals are reflected completely, the distance parameters have the unit of meters. The model is shown in Fig. 3.
As shown in Fig. 3, there is a buried pipe in the concrete environment which has the started position at the coordinates \((x_1, d_1)\), the length is \((x_2 - x_1)\), and the radius is \(R = (d_2 - d_1)/2\), transceiver antennas is set at the position \((x_a, 0)\). The distance between the buried object to the device is half the real propagation distance of electromagnetic wave and is denoted as \(d(x_a)\):

\[
d(x_a) = \left\{ \frac{d_1}{d_2} \sqrt{d_2^2 + (x_a - x_i)^2} \right\}
\]  

\(d(x_a)\) is determined based on the calculation of the average value \((\bar{D} \text{ in Eq. (9)})\) and denoted as \(\hat{d}(x_a)\). From the estimated value \(\hat{d}(x_a)\) of \(d(x_a)\), we can calculate the unknown parameter vector \(\hat{r} = (\hat{x}_1, \hat{d}_1, \hat{d}_2)\) where \(\hat{x}_1, \hat{d}_1, \hat{d}_2\) are estimated parameters of the position of the pipeline and can be determined by using the NLLS algorithm as follows [15].

\[
\hat{r}^* = \arg \min_{\hat{r}} (W(d - \hat{d}(\hat{r}))^2)
\]

where \(d\) and \(\hat{d}(\hat{r})\) are the column vector of \(d(x_a)\) and \(\hat{d}(x_a, \hat{r})\); \(W\) is the diagonal weight matrix. \(\hat{d}(x_a, \hat{r})\) is given by:

\[
\hat{d}(x_a, \hat{r}) = \left\{ \frac{\hat{d}_1}{\hat{d}_2} \sqrt{\hat{d}_2^2 + (x_a - \hat{x}_i)^2} \right\}
\]

and then the optimal \(\hat{r}^*\) can be calculated by the Gauss-Newton method:

\[
\hat{r}^{(k+1)} = \hat{r}^{(k)} + \Delta^{(k)}
\]

where

\[
\Delta^{(k)} = (J^T J)^{-1} J^T e(\hat{r}^{(k)})
\]

and

\[
e(\hat{r}^{(k)}) = W(d - \hat{d}(\hat{r}^{(k)}))^2
\]

\(J\) is the Jacobian matrix:

\[
J = \begin{bmatrix}
\frac{\partial e(\hat{r}^{(k)})}{\partial d_1}, & \frac{\partial e(\hat{r}^{(k)})}{\partial d_2}, & \frac{\partial e(\hat{r}^{(k)})}{\partial x_1}
\end{bmatrix}
\]
The estimation of \( x_1 \) and \( x_2 \) values is equivalent, so in the above algorithm, we only focus on estimating of \( x_1 \), and the radius of the object \( \hat{R} \) is determined:

\[
\hat{R} = \frac{\hat{d}_2 - \hat{d}_1}{2}
\]  

(16)

3.2. The estimation of the parameters

a) Simulation parameters

In order to estimate the above parameters, at first, we perform the estimation of the dielectric constant of the wave propagation environment and then estimating the remaining parameters. To estimate the dielectric constant, we assume that the distance is known with a value equal to \( d_0 \) [m]. Deriving from the propagation time which is calculated according to the correlation output, the estimated value of \( d_0 \) can be obtained as \( \hat{d}_0 \). So the estimated value of \( \varepsilon_1 \) is the value making Eq. (17) reaches to the smallest value.

\[
|d_0 - \hat{d}_0| = \left| d_0 - \frac{\hat{\tau}_0 c}{2\sqrt{\varepsilon_1}} \right|
\]  

(17)

where \( \hat{\tau}_0 \) is the estimated propagation time from the correlation value, hence the estimation of \( \varepsilon_1 \) is determined as bellows.

\[
\hat{\varepsilon}_1 = \arg \min_{\varepsilon_1} \left| d_0 - \frac{\hat{\tau}_0 c}{2\sqrt{\varepsilon_1}} \right|
\]  

(18)

with \( \hat{\varepsilon}_1 \), the other parameters of the system are calculated based on the NLLS algorithm and the distance data presented in Sections 3.1 and 2.2 as above. The simulation parameters are described in Tab. 1 as below.

Tab. 1. Simulation Parameters [8]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time normalization factor</td>
<td>( \tau_p )</td>
<td>0.2877 ns (2\textsuperscript{nd} order monocycle)</td>
</tr>
<tr>
<td>Center frequency and bandwidth</td>
<td>( f_c, \Delta F )</td>
<td>5 GHz, 2 GHz (UWB); 1 GHz, 100 MHz (NB)</td>
</tr>
<tr>
<td>Repetition correlation number</td>
<td>( M )</td>
<td>50</td>
</tr>
<tr>
<td>Mean error threshold</td>
<td>( \sigma_{th} )</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Test distance</td>
<td>( d_0 )</td>
<td>1 m</td>
</tr>
<tr>
<td>Chip width</td>
<td>( T_c )</td>
<td>0.9 ns</td>
</tr>
</tbody>
</table>
b) Numerical results and comparisons

The accuracy between the TH-BPSK UWB system, the IR-UWB conventional and the NB one in estimating $d_0$ are compared in Fig. 4, the results are illustrated by circles with a radius equal to the estimated values of $d_0$, respectively. We can see that the TH-BPSK UWB system provides a higher accuracy than the other because, in the TH-BPSK UWB system, the transmitted impulse is multiplied by the time-hopping sequence, so in comparison to the IR UWB system, the ability to detect the received signal is better and therefore the spatial resolution is clearly higher.

![Graph showing accuracy comparison between TH-BPSK UWB, IR-UWB, and NB systems](image)

*Fig. 4. A comparison of the accuracy between the TH-BPSK UWB, IR-UWB, NB systems*

With the estimated distance values as shown in Fig. 4, according to the Eq. (18), we have the estimated value of the dielectric constant of the environment with those systems as shown in Tab. 2. The other parameters in Fig. 3 are estimated according to the equations from Eq. (9) to Eq. (16) and the estimated results are presented in Tab. 2 and Fig. 5 as below.

*Tab. 2. The estimated parameters*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>The actually values</th>
<th>NB</th>
<th>IR-UWB</th>
<th>TH-BPSK-UWB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>2.5</td>
<td>5.062</td>
<td>3.306</td>
<td>2.304</td>
</tr>
<tr>
<td>$d_1$ [cm]</td>
<td>60</td>
<td>72.212</td>
<td>63.915</td>
<td>57.537</td>
</tr>
<tr>
<td>$d_2$ [cm]</td>
<td>80</td>
<td>129.908</td>
<td>88.911</td>
<td>83.305</td>
</tr>
<tr>
<td>$R$ [cm]</td>
<td>10</td>
<td>28.848</td>
<td>12.498</td>
<td>12.884</td>
</tr>
<tr>
<td>$x_1$ [cm]</td>
<td>100</td>
<td>150.524</td>
<td>102.077</td>
<td>99.502</td>
</tr>
</tbody>
</table>
The actually values versus the estimated values

**Fig. 5. The estimated values by the TH-BPSK UWB, IR UWB, and NB systems**

Tab. 2 and Figs. 4, 5 show the performance of the TH-BPSK UWB system with the 2nd order Gaussian monocycle assuming the environment is homogeneous. We observe that the TH-BPSK UWB system outperforms the other systems in measuring distance and identification buried objects in nondestructive structures; so TH-BPSK UWB is one of the suitable modulation configurations in the design of UWB systems for positioning buried object.

4. **Conclusion**

In this paper, we have derived accurate, analytical expressions for the measuring distance and identification of the buried object in non-destructive structures of the TH-BPSK UWB system. The performance of this system is evaluated based on the error of location estimation. The measuring distances are based on calculating the average values of the correlation in a matched filter and with those obtained distances, some simple objects can be estimated by using the NLLS algorithm. The evaluation of the obtained results in this paper provides reliable information for selecting suitable modulation schemes in the design of UWB systems with distance measurement applications. The issue of assessing the impact of different shapes of impulses, the nature of the environment (heterogeneous, moist soil) on the performance of the UWB systems will be analyzed in our future plans.

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References


ĐỊNH VỊ VẬT THỂ TRONG CÁC CẤU TRÚC KHÔNG PHÁ HỦY SỬ DỤNG HỆ THỐNG TH-BPSK UWB

**Tóm tắt:** Hệ thống truyền thông băng thông siêu rộng (UWB) sử dụng tín hiệu xung là một trong những kỹ thuật hấp dẫn có thể đạt được mức tiêu thụ công suất thấp, tốc độ dữ liệu cao và độ chính xác cao trong ước lượng vị trí. Một trong những ứng dụng của UWB là đa đa xuyên thấu mặt đất (GPR) đã được sử dụng để khảo sát các cấu trúc không phá hủy. Trong bài báo này, một phương pháp định vị vật thể bị chôn vùi trong các cấu trúc không phá hủy (bê tông, đất khô) được đề xuất bằng cách sử dụng hệ thống điều chế TH-BPSK UWB nhảy thời gian (TH-BPSK UWB) với một dạng xung xác định kết hợp với thuật toán ước lượng phi tuyến Gauss-Newton. Các kết quả của phương pháp đề xuất đã được đánh giá bằng cách sử dụng mô phỏng máy tính dựa trên sai số về vị trí ước lượng và độ phân giải không gian của hệ thống.

**Từ khóa:** Băng thông siêu rộng; TH-BPSK UWB; đa đa xuyên thấu; phương pháp Gauss-Newton.