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ULTRA-WIDE BAND SIGNAL PROCESSING METHODS FOR POSITIONING BURIED OBJECTS

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PUBLICATIONS

J1. **N. T. Huyen**, P.T.Hiep, V.V.Son, D.D.Ha, "A variable impulse width method for improving the ranging accuracy of IR-UWB penetrating systems," *Journal of Science and Technology*, No.196, pp.103-114, Feb., 2019.

J2. P.T.Hiep,**N.T.Huyen**, "Locating the buried object in the non-destructive structures using TH-BPSK UWB system," *Journal of Science and Technology*, No.198, pp.87-97, May., 2019.

J3. **N.T.Huyen**, D.D.Ha, and P.T.Hiep, "Buried Objects Detection in Heterogeneous Environment using UWB Systems Combined with Curve Fitting Method," *ICT Express Journal, (SCIE, Q1, IF=4.317)*, Vol. 6, Issue 4, Dec. 2020, pp. 348-352, doi:https://doi.org/10.1016/j.icte.2020.06.006.

J4. **N.T.Huyen**, N.L.Cuong, P.T.Hiep, "Proposal of UWB-PPM with Additional Time Shift for Positioning Technique in Non-destructive Environments," *Applied Sciences Journal (ISSN 2076-3417), (SCI, Q1, IF= 2.679)*, vol. 10, Issue 17, 6011, 9/2020, doi: https://doi.org/10.3390/app10176011.

J5. **N.T.Huyen**, D.D.Ha, P.T.Hiep, "Positioning the Adjacent Buried Objects Using UWB Technology Combine with Levenberg-Marquardt Algorithm," *Advances in Electrical and Electronic Engineering Journal, (Scopus, Q3, IF= 0.93, SJR=0.23)*, vol. , no. , pp., 20xx.(Under Review).

C1. **N.T.Huyen**, Pham Thanh Hiep, "Application of RSSI to ground penetrating radar using ultra wideband technology," *International Conference on Advanced Technologies for Communications (ATC) 2018*, pp.137-141, Oct., 2018 (Scopus).

C2. **N.T.Huyen**, Pham Thanh Hiep, "Proposing adaptive PN sequence length scheme for testing non-destructive structure using DS-UWB," *The 3rd International Conference on Recent Advances in Signal Processing, Telecommunications & Computing (SigTelCom) 2019*, pp.10-14, Mar., 2019.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDIES

The thesis presented the essential contents of UWB technology used in measuring distance and positioning buried objects using non-destructive techniques. Based on the analysis of the potential applications of the UWB systems, the dissertation has the following main contributions.

- Distance measuring techniques in free space such as RSSI, TOA, and the method of changing the impulse width, and the length of PN sequence are proposed for determining the penetration depth of penetrating UWB systems [C1], [J1]. These researches are applied to the homogeneous environment.
- A novel CFST combined with LFM algorithm method for locating nearby buried objects in the homogeneous medium is proposed to improve the accuracy and resolution in determining distances and locating buried objects [J5].
- The UWB-PPM-ATS [J4] and UWB-PST [J3] are introduced for locating the multi-buried objects in the heterogeneous medium. By those methods, the positioning accuracy is significantly improved.

The simulation results show that with the proposed UWB signal processing methods, the accuracy and resolution of the UWB systems are significantly improved. However, the dissertation still exists some limitations like: the investigated environments are dry, the range is short, and the computational complexity is higher when the positioning accuracy is increased.

There are several possible open problems which require further investigations in order to have a full understanding about their applicability as follows.

- Developing identification algorithms used for buried object based on UWB technology

- Building algorithm of positioning simultaneously many buried objects in heterogeneous environments.

- Locating the moving objects using penetration UWB systems by generating an adaptive reference waveform at the receiver side.

INTRODUCTION

In recent years, studying on non-destructive evaluation have been a burning issue of many research groups. The purpose of the non-destructive testing like soils, concretes, and other materials is to detect and locate the fault structures, buried objects in the evaluated environment. The discovery of the buried objects including cracks by non-destructive evaluation has several benefits in life as used in solving the consequences of war, rescuing trapped victims, and overcoming construction problems. Among the non-destructive techniques, the ground penetrating radar (GPR) system is widely used because it can locate both non-metallic and metallic objects without prior knowledge.

In the GPR systems, the penetration and resolution of the system depend mainly on the signal bandwidth. Traditional systems use a narrow signal frequency band to modulate a sinusoidal carrier signal. The narrow bandwidth makes the information capacity of the radio system limited. This information capacity is especially essential for radiolocation systems in which the lifetime of the targets is limited. Therefore, narrowband radio systems have practically exhausted the information opportunities in range resolution and target characteristics. To solve this problem, a new radar system was developed to transmit signals with ultra-wide bandwidth (UWB).

To increase the accuracy in determining the relative permittivity and locating the buried objects, several signal processing methods applied to transmitted and received UWB signals were proposed in the thesis. The investigated distance and buried object position were determined by analyzing the reflected signal combined with the Gauss-Newton and Lavenberg-Martquardt estimation algorithms.

The dissertation is organised into three chapters except for introduction, conclusion, future work, bibliography and appendix. Chapter 1 gives the backgrounds related to this research. Chapter 2 presents the proposed methods of locating a single buried object in a homogeneous environment, and Chapter 3 introduces the proposed methods of locating the multiple buried objects in a heterogeneous environment.

Chapter 1

OVERVIEW OF UWB TECHNOLOGY

1.1 Introduction to UWB technology

Ultra-wide band (UWB) is a new technology with outstanding features in many applications such as communications, position, medical, and so on. Before 2001, the applications of UWB are limited to military only; since 2002, the Federal Communications Commission (FCC) has gradually allowed commercialization of the UWB frequency bands, making it possible for anyone to use its properties. The UWB signal is characterized by a very wide bandwidth when compared to conventional, narrow band (NB) signals.

In recent years, the rapid development of UWB signaling technologies has been tested on commercial applications from wireless to remote sensing networks, tracking devices, and penetrating radars. In particular, the UWB technology makes major improvements in three wireless applications such as communications, radar, and measurement positioning. A system using UWB tech-

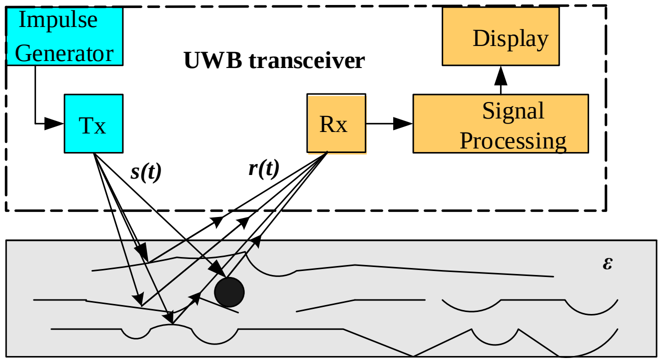
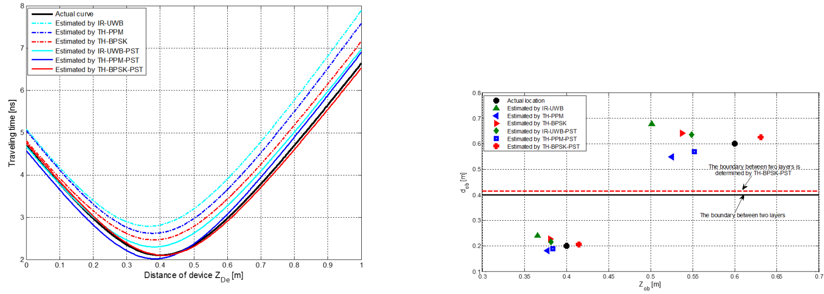


Figure 1.1: The principle of measuring and positioning buried objects with the UWB system.

nology for measuring the distance and positioning buried object is illustrated in Fig. 1.1, where ε is the relative permittivity (dielectric constant) of environ-



(a) (b)

Figure 3.8: The curves of traveling time according to the position of transceiver (a); The location of buried objects estimated by UWB-PST (b).

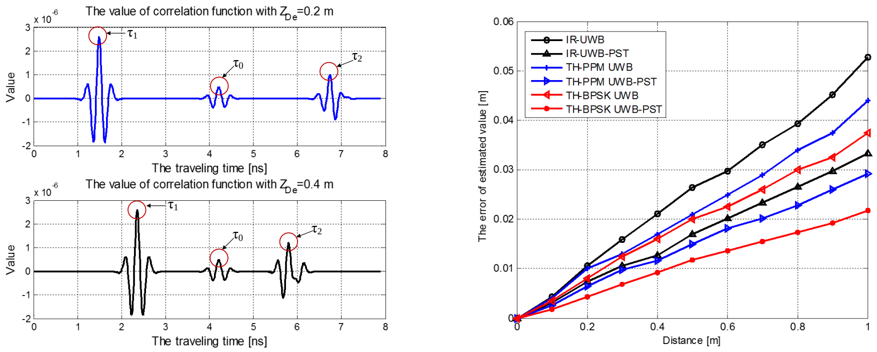
methods indicated in Table 3.2. Observing that the distance error of the UWB-PST TH-BPSK is smaller than the others. This reason can be explained that the conventional methods based on processing GPR images have problems with nearby and tangent hyperbolas (when buried objects are close) and with background noise. Therefore, the distance error of the proposed methods is smaller than in the conventional methods.

Table 3.2: The comparison of results.

Method used in GPR system	Distance Error [cm]
The Multiresolution Monogenic Signal Analysis [93]	5.8
Wideband chaotic [59]	10
The power spectral density [82]	2.03
UWB-PPM-ATS	2.86
UWB-CFST	3.52
UWB-PST TH-BPSK	1.85

3.4 Summary

In this chapter, the methods used to locate the closely buried objects, called CFST and UWB-PST for UWB systems are proposed. The CFST method may be applied to locate the multi-buried objects are close to each other. The UWB-PST can be used for improving the accuracy of locating multi-buried objects in the heterogeneous medium.



(a) (b)

Figure 3.7: The correlation shapes of received signals in the IR-UWB system (a); The errors of estimated values of IR, TH-BPSK, TH-PPM UWB and proposed systems (b).

The TH-BPSK and PPM UWB give smaller errors than the IR-UWB system. The UWB-PST outperforms the conventional with the mean relative error about 1.9 % with shifted-TH-BPSK, 2.6 % with shifted-TH-PPM, and 3.2 % with shifted-IR UWB. The estimated results are indicated in Table 3.1, Fig. 3.8. Fig. 3.8 shows the results estimated by the UWB-PST. It is similar to those

Table 3.1: Estimated results.

Parameter	Actual value	By IR-UWB	By TH-PPM	By TH-BPSK	By UWB-PST IR-UWB	By UWB-PST TH-PPM	By UWB-PST TH-BPSK
ε_1	2.5	3.0132	2.8687	2.6462	2.631	2.6201	2.3415
Z_{ob1} [m]	0.4	0.3658	0.3795	0.3806	0.3818	0.3838	0.4146
d_{ob1} [m]	0.2	0.2395	0.1813	0.2270	0.2160	0.1883	0.2058
D_1 [m]	0.4	0.4282	0.4273	0.4231	0.3805	0.4187	0.4153
ε_2	4.5	4.2316	4.2852	4.3214	4.3106	4.3683	4.4125
Z_{ob2} [m]	0.6	0.5013	0.5248	0.5373	0.5487	0.5521	0.6307
d_{ob2} [m]	0.6	0.6787	0.5483	0.6418	0.6358	0.5695	0.6263

shown in Fig. 3.7, the estimated results of UWB-PST-TH-BPSK have the highest accuracy among the compared systems. For comparison, the evaluation is based on the mean absolute error of the estimated distance between different

ment. $s(t)$ denotes the transmitted pulse signal, and $r(t)$ is the received signal:

$$r(t) = \sum_i r_i(t) + \sum_k r_{kob}(t) + n(t), \tag{1.1}$$

$$r_i(t) = A_i A(d_i) s(t - \tau_i), \tag{1.2}$$

$$r_{kob}(t) = A_{kob} A(d_k) s(t - \tau_{kob}), \tag{1.3}$$

where A_i represents the product of the reflection coefficient from the surface between the layers and transmission coefficients through the i^{th} layer in propagation environment; $A(d_i)$ is the attenuation of amplitude respect to the penetrated distance d_i; τ_i is the delay time of UWB pulse, also called as the propagation or traveling time. A_{kob} and τ_{kob} are the reflection coefficient at the surface and the traveling time of the reflected signal from the k^{th}- buried object, respectively. $n(t)$ represents the additive white Gaussian noise (AWGN).

In the UWB system, $s(t)$ is generated based on Gaussian [30] and their derivatives. The Gaussian type is mathematically described by Eq. (**??**) [32] and shown in Fig. 1.2.

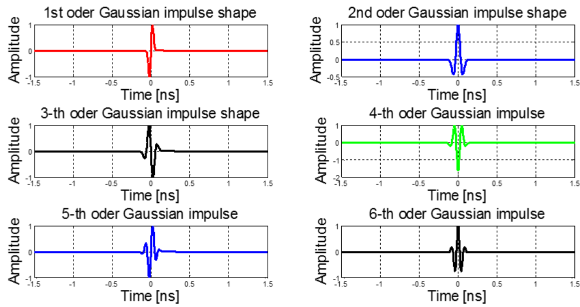
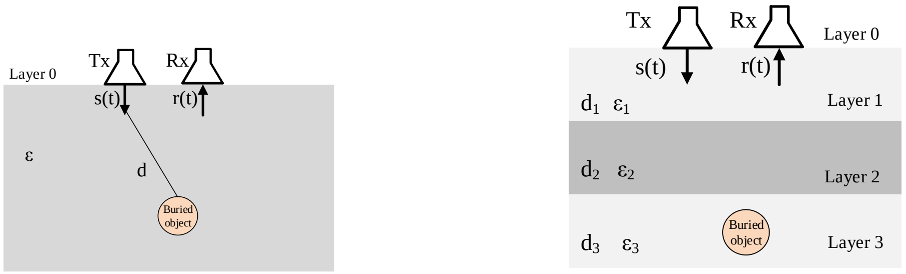


Figure 1.2: The Gaussian pulse shapes.

A sequence of UWB signal pulses can be generated by Gaussian pulses (commonly referred to as IR-UWB single pulse) or modulated according to different modulation types. General modulation techniques used for UWB signals include pulse amplitude modulations (PAMs), On-Off Keying (OOK), and pulse position modulation (PPM) [34]. In addition, using time hopping sequence (TH) to create TH-PPM, TH-BPSK signal types; direct sequence UWB (DS-UWB)[35] or designing a generator circuit which generates the 4-th and 5-th order derivatives of Gaussian pulses in TH-QPSK system [36] are also used. Each modulation technique has a different application range, the choice of suitable modulation configuration not only increases the efficiency of the system implementation, maximizes the benefits of ultra-wide bandwidth, but also reduces the complexity of the system.

In the distance measurement systems using UWB technology, for improving the processing time and reducing the mean distance measuring error, the UWB modulated signals are used. To detect buried objects in environments such as underground, brick, concrete, etc., penetrating radar systems are used very commonly. The investigated environments are classified into homogeneous and heterogeneous environments. A homogeneous medium is understood here as a single-layer with the constant relative permittivity, or in other words, the wave-propagation velocity in this medium is constant. A heterogeneous medium is one with many layers of different dielectric constants and wave propagation velocities. An illustrative example of a homogeneous and heterogeneous medium is shown in Fig 1.3. Consider a UWB system model with a homogeneous envi-



(a) (b)

Figure 1.3: The homogeneous (a) and the heterogeneous (b) mediums

ronment as illustrated in Fig. 1.4.

The transmitted signal $s(t)$ goes through an environment with the relative permittivity of ε. The reflected (scattered) signals from the buried object are captured by the receiving antenna. Both the Tx and Rx antennas are directional to maintain an illumination area that is smaller than the transverse area of the buried object. The distance can be estimated by the delay (traveling) time

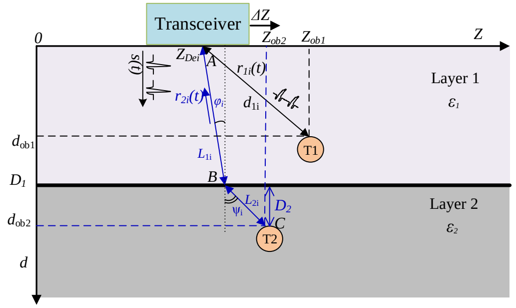


Figure 3.6: System model for positioning multi-buried objects in the heterogeneous environment.

The traveling time is determined according to the correlation values of N_p pulses as follows.

$$\tau = \frac{1}{N_p}\sum_{i=0}^{N_p}\tau_i = \frac{1}{N_p}\sum_{i=0}^{N_p} Arg\max_x \int_{-\infty}^{\infty} r_i\left(t - \frac{iT_r}{N_p}\right)\omega(t-x)dt, \tag{3.11}$$

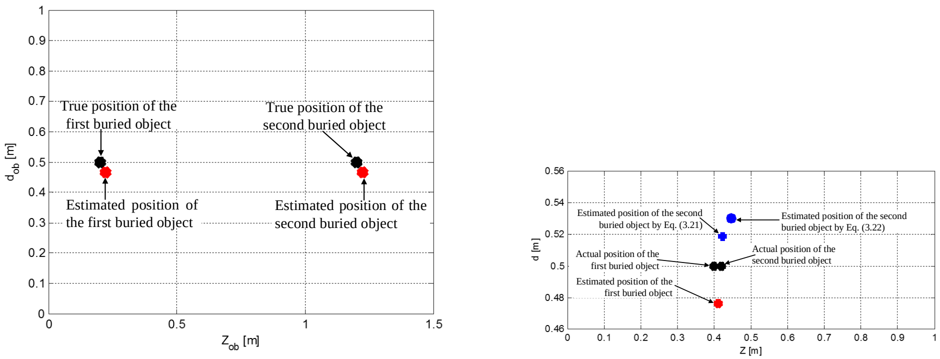
The relationship between the system parameters are expressed in the following equations.

$$\tau_{1i} = 2\frac{\sqrt{\varepsilon_1\left(d_{ob1}^2 + (Z_{Dei} - Z_{ob1})^2\right)}}{c}; \tau_0 = 2\frac{D_1\sqrt{\varepsilon_1}}{c}; \tau_{2i} = 2\left(\frac{L_{1i}}{V_1} + \frac{L_{2i}}{V_2}\right). \tag{3.12}$$

According to the LMF estimation method, the parameters of the model are calculated such that the deviation function reaches the minimum value.

$$E_1 = \sum_{i=1}^{M}[\tau_{1i} - f_1(Z_{Dei})]^2; E_2 = \sum_{i=1}^{M}[\tau_{2i} - f_2(Z_{Dei})]^2, \tag{3.13}$$

As seen in Fig. 3.7 (a), the values of D_1 and τ_0 are constant when the device is moved, so with the estimated values of ε_1 and τ_0, D_1 is completely determined. The UWB-PST is evaluated in terms of the positioning errors in a well-known homogeneous medium (see Fig. 3.7 (b)) and in a unknown heterogeneous medium (see Fig. 3.8).



(a) (b)

Figure 3.5: Two buried objects are far from each other (a); two buried objects are close to each other (b).

LMF algorithm in which τ is replaced by τ_2. The results of locating two objects are illustrated in Fig. 3.5. As seen in Fig. 3.5, the estimated error by Eq. (3.8) is smaller than by Eq. (3.9). The results can be explained by comparing Eqs. (3.8) and (3.9), the amplitude of the reflected signal from the second object reduces by the amplitude of the received signal from the first object with (3.9). Hence, the value of the correlation function by Eq. (3.9) also reduces, causing higher errors.

3.3 A proposed method of positioning multi-buried objects in the heterogeneous environments

A positioning system in a heterogeneous environment is illustrated in Fig. 3.6. The detection and separation of the reflected signals in heterogeneous environments are very complicated. Therefore to increase the accuracy of detecting of the reflected signals, a method of shifting transmitted pulses with UWB signal named UWB-PST (UWB Pulse Shifting Technique) is proposed to locate multi-buried objects in heterogeneous environments. The UWB transmitted signal in the UWB-PST as follows.

$$s_{IRs}(t) = \sqrt{P}\sum_{i=0}^{N_p} g(t - iT_r - \frac{iT_r}{N_p}), \tag{3.10}$$

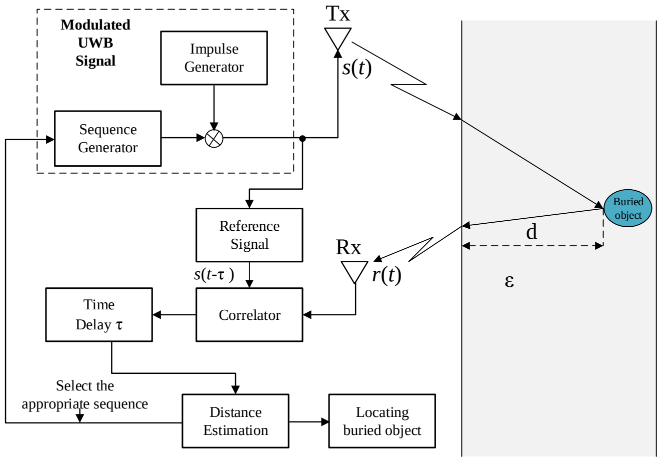


Figure 1.4: The block diagram of the distance estimation configuration using UWB technology.

denoted by τ and calculated from the maximum value of $R(x)$:

$$R(x) = \int_{-\infty}^{\infty} r(t)\omega(t - x)dt. \tag{1.4}$$

$\omega(t)$ is the reference signal at the receiver which is $g(t)$ with UWB-IR and TH-BPSK UWB [42], $g(t) - g(t - T_{PPM})$ with PPM and TH-PPM UWB [43]. So the traveling time is:

$$\tau = x_{val} = \mathrm{Arg}\max_{\mathrm{x}}\{\mathrm{R(x)}\}. \tag{1.5}$$

Because the traveling time of signal is twice propagation time from the transceiver antenna to the buried object, hence the depth d is given by [44]:

$$d = \frac{c\tau}{2\sqrt{\varepsilon}}. \tag{1.6}$$

For each distance value of d, PN sequence has an optimal length denoted as N_{opt}. The optimum criterion here is the minimum length of the PN (TH) sequence while ensuring that the error of estimated distance is within allowed ranges. The method of determining N_{opt} is proposed in research [C2] and is

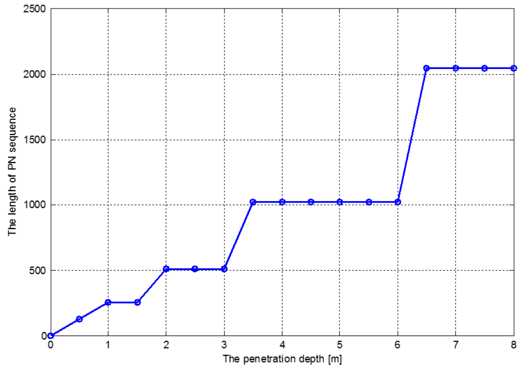


Figure 1.5: The spreading sequence length according to the penetration depth in the sand dry environment.

named the adaptive length of the ranging distance, or called the linear searching method. The results of the calculation of the PN sequence length according to the penetration depth of the UWB signal with the investigated medium as sand dry are shown in the Fig. 1.5. In addition, to increase the accuracy of distance estimation in a homogeneous environment, a variable impulse width method for the IR-UWB penetrating system is proposed in [J1] and the results are illustrated in Fig. 1.6.

1.2 The related works

With the high spatial resolution ranging, the UWB-based penetration system is one of the potential candidates for the non-destructive testing (NDT). There are many systems of locating and detecting buried objects, in which the most popular one could be penetrating radar systems; for example, the ground penetrating radar (GPR) [10], [11]. The resolution and detection distance of the non-destructive techniques which are used in the penetrating systems strongly depend on the signal shapes, the system bandwidth, and the material of the buried objects (plastic or metal) as well as information of environmental properties (relative permittivity). The performance of UWB GPR system depends mainly on the method of the received signal processing. They can provide a high image resolution and efficient data processing when using reverse domain

equation of correlation function is rewritten as follows.

$$R_{\Sigma}(\delta) = \int_{-\infty}^{\infty} r_{\Sigma}(t)p(t-\delta)dt = \int_{-\infty}^{\infty} [r_1(t) + r_2(t)]p(t-\delta)dt = R_1(\delta) + R_2(\delta), \tag{3.6}$$

and the traveling time can be calculated as:

$$\tau_{\Sigma} = \text{Arg}\max_{\delta}\{\mathrm{R}_{\Sigma}(\delta)\}. \tag{3.7}$$

According to the received signal $r_{\Sigma}(t)$, the traveling time from the second object to the device is denote by τ_2, and can be computed as

$$\tau_2 = \delta_{op} = \left[\text{Agr}\max_{\delta}\{\mathrm{R}_{\Sigma}(\delta) - \mathrm{R}_1(\delta)\}\right], \tag{3.8}$$

or

$$\tau_2 = \delta_{op} = \left[\text{Agr}\max_{\delta}\left\{\frac{\mathrm{R}_{\Sigma}(\delta)}{\mathrm{R}_1(\delta)}\right\}\right]. \tag{3.9}$$

The determination of the traveling time τ_2 using Eqs. (3.8) and (3.9) is named the correlation function separation technique (CFST). Fig. 3.4 illus-

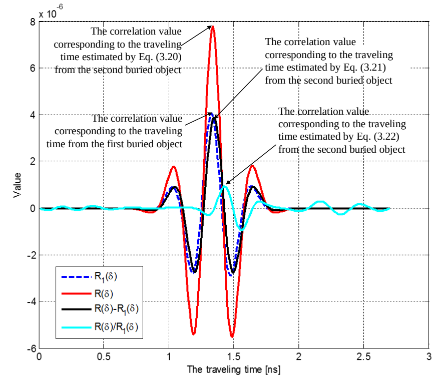
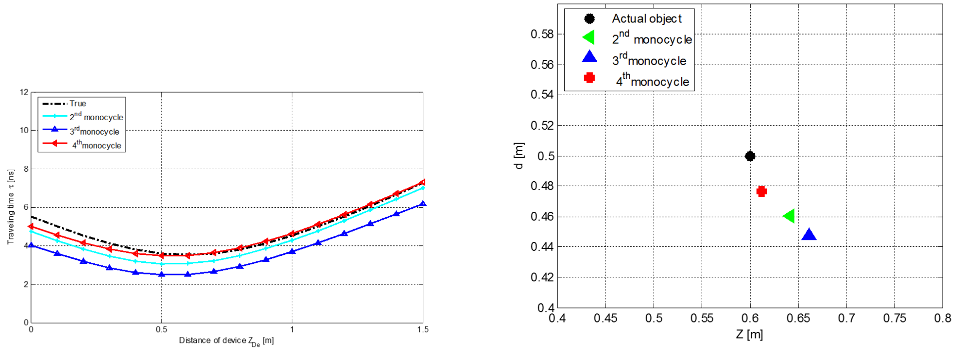


Figure 3.4: The correlation function shapes with the first buried object at $(Z_{ob1}, d_{ob1}) = (0.3, 0.2)$m; $Z_{mov} = 0.04$m; the transceiver at $Z_{Dei} = 0.3$ m.

trates examples of the correlation function shapes when there are two closely buried objects in the homogeneous environment. The position of the second object can be located in the same way as presented in the Section 3.1 by using the



(a) (b)

Figure 3.2: The actual and estimated locations by different types of Gaussian monocycles in the case of a single buried object; the traveling time changes according to the position of device (a) and the estimated positions of the buried object (b).

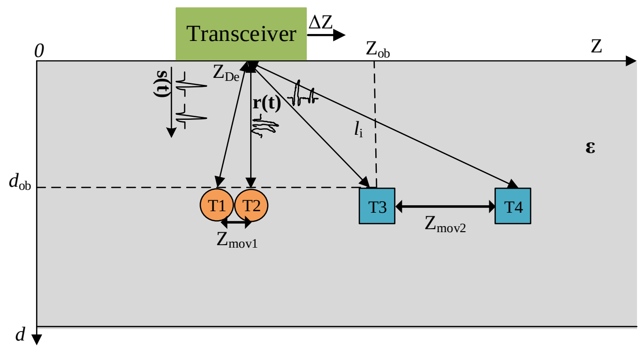
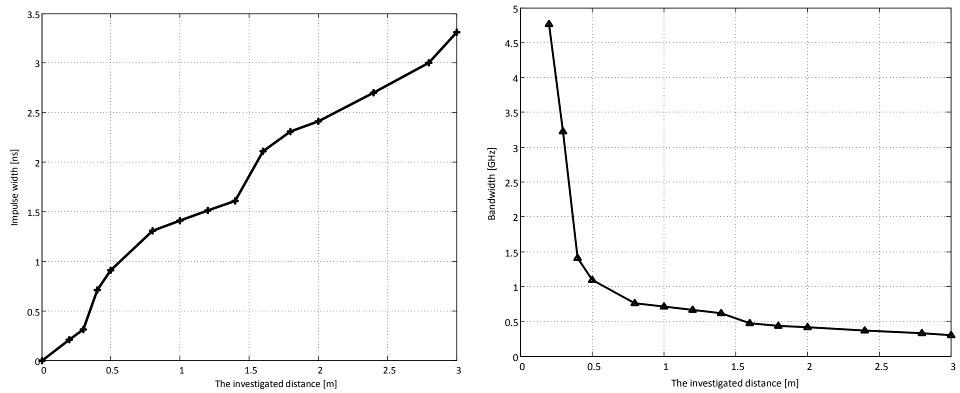


Figure 3.3: System model for positioning multi-buried objects in a homogeneous environment.

using the correlation function values and the position of the first object. The



(a) (b)

Figure 1.6: The width of impulse (a) and the bandwidth (b) according to the investigated distance

conversion techniques [58], or using wide band chaotic signals based on time domain correlation and back-projection algorithm [59].

For locating purposes, UWB indoor positioning systems were presented in [28], [41], [75] to exploit two-way flight time for the distance determination. In the range-based localization systems, the position of a sensor node can be estimated by using lateration, or trilateration, or multilateration technique [78], [79]; however, these techniques are not applicable to locate buried objects in penetrating systems. In underground environment, to locate personnel in coal mines, the time difference of arrival (TDOA) algorithm was proposed for the UWB wireless sensor network in [80], and this system can achieve high-precision positioning in real-time. The existence of the buried object can be detected using the GPR scan [11], [81] or combined with the spectral analysis of the radar data [82]. In [18] buried object characteristics (the depth, thickness, and frequency-dependent permittivity) were determined by measuring the reflection coefficient with the buried object using the mean square error (MSE) method.

When using UWB technology for measuring distance, non-destructive testing, positioning buried objects, it is the most important to develope a suitable signal processing method for the improvement of system performance.

The thesis focuses on the methods of processing UWB signals for measuring distances and locating buried objects. Distance measuring techniques in free space such as RSSI and TOA were proposed for measuring the penetration depth with penetrating UWB systems in [C1], [J1]. In [J1], the solution of changing the impulse width of the UWB signal adaptively with the investigated depth was proposed. In addition, to increase the accuracy of penetration distance measurements, the system using DS-UWB signal with a variable PN sequence length was proposed in [C2]. These researches were applied for the homogeneous investigated environments. With the heterogeneous environments, in order to increase the ability of accurate detection of the reflected UWB signal and thereby increase the accuracy of distance estimation, a UWB PPM technique with an optimal additional time shift, called UWB-PPM-ATS was proposed in [J4].

In summary, the thesis proposed novel UWB signal processing methods applied for IR-UWB and modulated UWB signals to increase the accuracy of measuring penetration distance and locating buried objects. The proposed methods were used in positioning a single and multiple buried objects in the homogeneous, and heterogeneous environments. The results of the proposed methods were performed by mathematical analysis and simulation using Matlab software. The performance of proposed systems are evaluated by the positioning errors in comparison with the actual values and with conventional systems. Furthermore, these methods can be used for non-destructive testing to determine the quality, integrity of materials, probing a wall with different layers of construction materials, and locating buried objects such as detecting the locations of underground cables, water pipes, etc.

1.3 Summary

This chapter presents background knowledge of UWB technology, methods of generating UWB signals, advantages and disadvantages of UWB technology, and the model of a penetrating UWB system used for measuring the distance. In particular, it presents a comprehensive review of recent researches on UWB and buried object positioning methods, and outlines some challenging issues that promote the contributions of this work in the subsequent chapters. The research objectives and methods in the thesis are also presented in this chapter.

mum value.

$$E(\widehat{\mathbf{X}}) = \sum_{i=1}^{M}[\tau_i - f(Z_{Dei}, \widehat{\mathbf{X}})]^2, \tag{3.2}$$

where M is the number of movements of the transceiver, and

$$f(Z_{Dei}, \widehat{\mathbf{X}}) = 2\frac{\sqrt{\widehat{\varepsilon}\Big(\widehat{d}_{ob}^2 + (Z_{Dei} - \widehat{Z}_{ob})^2\Big)}}{c}. \tag{3.3}$$

The necessary conditions for E to be minimum are:

$$\frac{\partial E}{\partial \varepsilon} = 0, \frac{\partial E}{\partial Z_{ob}} = 0, \frac{\partial E}{\partial d_{ob}} = 0. \tag{3.4}$$

Vector $\widehat{\mathbf{X}}$ is determined by the following steps.

Step 1: Assign any arbitrary initialization values to $\mathbf{X}$ (usually zero values), denoted by $\mathbf{X}_{int}$.

Step 2: Replace the value of $\mathbf{X}$ with new ones $(\mathbf{X} + \delta)$.

Step 3: δ can be determined satisfying:

$$[\mathbf{J}^T\mathbf{J} + \lambda \mathrm{diag}(\mathbf{J}^T\mathbf{J})]\delta = \mathbf{J}^T[\tau - f(\mathbf{X})], \tag{3.5}$$

where the factor λ (non-negative) is adjusted at each iteration.

The algorithm repeats Steps 2 and 3 until the constraint condition in Eq. (3.4) is satisfied. The output of LMF algorithm are the final estimated values. The calculation results by Matlab software are shown in Figs. 3.2.

The estimated results of the parameters of the IR-UWB systems for using different Gaussian monocycles are shown in Fig. 3.2.

3.2 Positioning multi-buried objects in a homogeneous environment

Consider a positioning system model with multiple buried objects in a homogeneous environment as illustrated in Fig. 3.3.

The reflected signals from 'T3' and 'T4' are $r_1(t)$ and $r_2(t)$ do not overlap, consequently the procedure of locating a single object have been applied as presented in Section 3.1. However, in case 'T1' and 'T2', $r_1(t)$ and $r_2(t)$ overlap. In this case, the thesis proposes a method to determine the second object by

Chapter 3

CORRELATION FUNCTION SEPARATION AND SHIFTED PULSE-BASED BURIED OBJECTS POSITIONING METHODS

3.1 A proposed method of positioning a single buried object

The nonlinear algorithm estimation called Levenberg - Marquardt Fletcher (LMF) [91] was applied into calculations of distances, the relative permittivity and the position of buried object in the case of unknown propagation environment. In the simplest case, there is a buried object in a homogeneous environment with a single layer as shown in Fig. 3.1. Here, the position of the object is considered in the two-dimensional space (2-D), and is regarded as a reflection point of propagation.

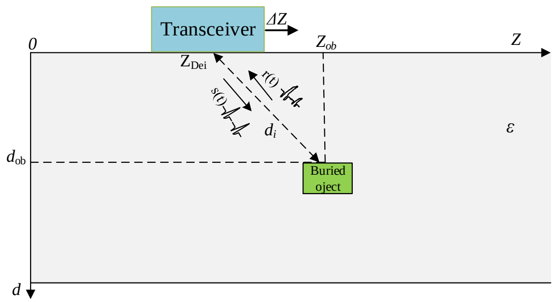


Figure 3.1: System model for positioning a single buried object in the homogeneous environment.

The unknown parameter vectors of the system are denoted by

$$\mathbf{X} = (\varepsilon, d_{ob}, Z_{ob}). \tag{3.1}$$

$\mathbf{X}$ is determined so that the deviation function in Eq. (3.2) reaches the mini-

Chapter 2

DETERMINATION OF THE PROPAGATION DISTANCE USING UWB PENETRATING SYSTEM

2.1 Analysis of a UWB penetrating system

Consider a detection and localization system using UWB technology illustrated in Fig. 2.1. The investigated medium is heterogeneous with three layers, whose thickness and relative permittivities are d_1, d_2, d_3 and ε_1, ε_2, ε_2, respectively.

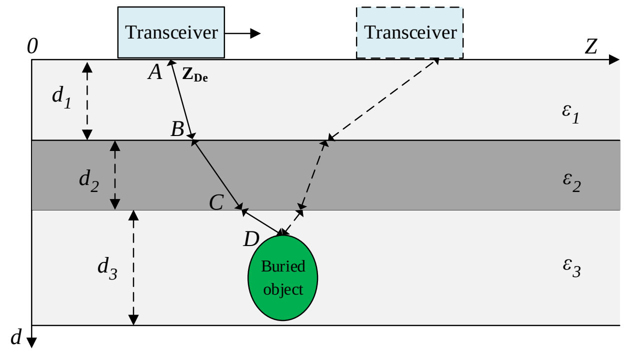


Figure 2.1: The penetrating UWB system.

The transmitted signal is a sequence of UWB pulses, which are IR-UWB pulses $s(t)$, takes the form:

$$s(t) = \sqrt{P} \sum_{i=0}^{N-1} g(t - iT_r), \tag{2.1}$$

The propagation distance can be determined based on the value of traveling time or RSSI as indicated in Fig. 2.2. In the procedure of distance estimation, if the traveling time is used, the received signal is fed to the *Correlator* to calculate

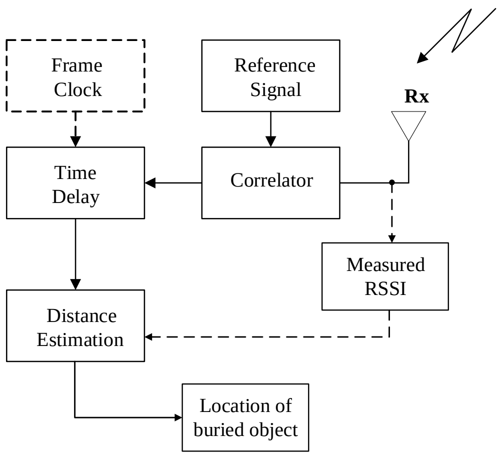


Figure 2.2: Block diagram of distance estimation procedure in the UWB system.

the time delay and estimate the distance; and if RSSI is used, the received signal is fed to the *Measured RSSI* and the distance is estimated.

2.2 Determination of the propagation distance based on RSSI

In the penetrating system, the propagation distance is the distance from the transceiver to the buried object with the homogeneous medium, and is the sum of propagation distances through the layers with the heterogeneous medium (see Fig. 2.1). Those distance are estimated by RSSI as follows.

$$d = \frac{1}{2} \times 10^{\left(\frac{P_{Tx} - RSSI}{10\eta}\right)} [m]. \tag{2.2}$$

The propagation distance and the path loss exponent η of the transmission medium are estimated by the Gauss-Newton algorithm. The Gauss-Newton method is used to estimate the path loss exponent and the location of the buried object in a homogeneous environment by using RSSI. The position of buried object is defined by coordinates of (Z_{ob}, d_1), and (Z_{ob}, d_2) in the 2-D space, Z_{ob} is the coordinate at the center of the object, and the radius is $R = (d_2 - d_1)/2$. The transceiver antennas is set at position of $(Z_{De}, 0)$. To determine the path

UWB-PPM is about 11%, while those of UWB-PPM-ATS with $\zeta = -0.08$, and -0.16 ns are about 7%, and 13%, respectively. Therefore, the UWB-PPM- ATS with $\zeta = -0.08$ ns performs better for all distance values. The results in Fig. 2.5 indicate that the time shift ζ directly affects the performance of UWB-PPM systems. The value of $(T_{PPM} + \zeta)$ with suitable value of ζ, the accuracy of the UWB system was improved (such as $\zeta = -0.08$ ns in this case). Otherwise, with other values of ζ, it is possible to make the error of distance estimation of the UWB-PPM system higher than that of the conventional UWB-PPM.

2.3.1 *Comparison of the computational complexity*

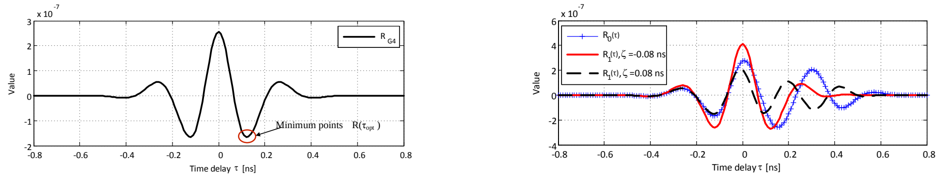
The complexity of the UWB-PPM-ATS technique is investigated by the number of floating point operations (FLOPS) performed for the correlation function in the receiver side. Assume that a FLOP stands for a real multiplication, a real summation, or a real subtraction. Ignoring the operations of generating UWB signals, the computational complexity is evaluated based on the number of FLOPS illustrated in Table 2.2. It can be seen that the proposed UWB-PPM-ATS system has higher computational complexity than that of the conventional UWB-PPM system. This is also a limitation of our proposal.

Table 2.2: The computational complexity.

Modulation Technique	Number of FLOPS for the N^{th} pulse	Specific values of FLOPS
UWB-OOK	$60 \times N \times T_r/\mu_p$	105×10^4
UWB-PPM	$60 \times N \times T_r/T_{PPM}$	150×10^4
UWB-PPM-ATS with $\zeta = -0.08$ ns	$60 \times N \times T_r/(\zeta)$	375×10^4
UWB-PPM-ATS with $\zeta = -0.16$ ns	$60 \times N \times T_r/(\zeta)$	187.5×10^4

2.4 Summary

In this chapter, the method of applying RSSI combined with Gauss-Newton algorithm for IR-UWB system to determine the propagation distance and the position of a buried object is proposed. However, due to the rapid attenuation of the signal, this method is only applicable for short-range detection and homogeneous medium. In the heterogeneous medium, to increase the ability of correct detection of the received UWB signal, the UWB PPM ATS method is proposed. The position of UWB pulse is modulated by PN sequence with an optimal additional time shift. This makes the error of distance estimation significantly reduced.



(a) (b)

Figure 2.4: Correlation functions of the conventional UWB-PPM (a) and UWB-PPT-ATS schemes with different time shifts (b).

including UWB-OOK and conventional UWB-PPM according to the accuracy of distance estimation in heterogeneous medium. Our trials indicated that the UWB-PPM pulses shifted by a certain time constant can be used to improve the accuracy of estimating the distance. The errors of estimated values are illustrated in Fig. 2.5 for OOK, PPM and ATS systems with $\zeta = -0.08$ ns and $\zeta = -0.16$ ns.

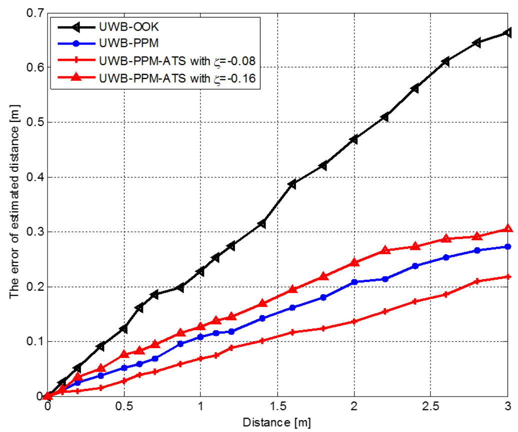


Figure 2.5: Comparison of distance estimation errors between OOK, PPM and the proposed UWB-PPM-ATS modulation techniques.

Observe that the relative error of the UWB-OOK system is about 24%, of

loss exponent and the location of buried object, the UWB transceiver transmits and receives UWB signals while moving along the Z-direction, and measures the RSSI in each movement step.

The parameters Z_{ob}, d_1, d_2 and η of the system are assigned as elements of the vector $\mathbf{r} = (Z_{ob}, d_1, d_2, \eta)$, and estimated so that the deviation function reaches the minimum value:

$$E(\widehat{\mathbf{r}}) = \sum_{i=1}^{N} \left\{ \frac{1}{2} \times 10^{\frac{P_{Tx} - RSSI(Z_{Dei})}{10\widehat{\eta}}} - \frac{\widehat{d}_1}{\widehat{d}_2} \sqrt{\widehat{d}_2^{\,2} + \left(\widehat{Z}_{ob} - Z_{Dei} \right)^2} \right\}^2, \tag{2.3}$$

where N is the number of movements of the device. The Gauss-Newton method is done by steps as follows.

Step 1: *Initialize parameters*
The elements of vector $\mathbf{r}$ are assigned to any non-negative value (usually zero values).

Step 2: *Update the parameter values*
In each iteration, the value of vector $\mathbf{r}$ is updated as:

$$\widehat{\mathbf{r}}^{k+1} = \widehat{\mathbf{r}}^{(k)} + \Delta^{(k)}, \tag{2.4}$$

where:

$$\Delta^{(k)} = \left(\mathbf{J^T J} \right)^{-1} \mathbf{J^T E}(\widehat{\mathbf{r}}^{(\mathbf{k})}), \tag{2.5}$$

$\mathbf{J}$ is the Jacobian matrix:

$$\mathbf{J} = \left[\frac{\partial E\left(\widehat{\mathbf{r}}^{(k)}\right)}{\partial \widehat{d}_1}, \frac{\partial E\left(\widehat{\mathbf{r}}^{(k)}\right)}{\partial \widehat{d}_2}, \frac{\partial E\left(\widehat{\mathbf{r}}^{(k)}\right)}{\partial \widehat{Z}_{ob}}, \frac{\partial E\left(\widehat{\mathbf{r}}^{(k)}\right)}{\partial \widehat{\eta}} \right]. \tag{2.6}$$

Step 3: *Check the stop condition* If the cost function has the minimum value, the algorithm stops and produces the estimated results. Otherwise, the algorithm repeats from Step 2. The simulation results are obtained after 50 iterations, and shown in Table 2.1 and Fig. 2.3.

According to Table 2.1 and Fig. 2.3, it can be seen that by using the Gauss-Newton nonlinear estimation method for the RSSI and TOA of the penetration UWB system, the path loss exponent of propagation medium and the location of the buried object can be determined. In addition, due to low cost, low power consumption and simple hardware, the development of RSSI method is simpler

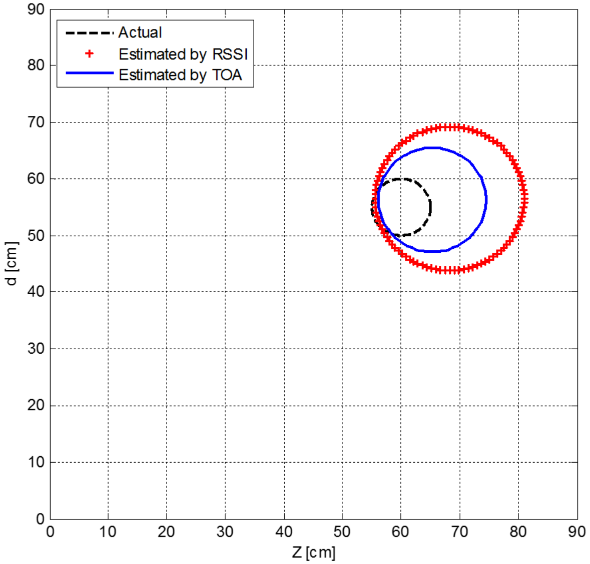


Figure 2.3: The estimated values by RSSI and TOA.

Table 2.1: Comparing the estimated results of penetrating UWB system using RSSI and TOA method.

Parameter	Actual value	RSSI-based method	TOA- based method	Error of RSSI method	Error of TOA method
η	3	3.3568	2.9959	0.3568 (11.9%)	0.0041 (0.2%)
d_1 [m]	0.5	0.4384	0.4713	0.0616 (12.3%)	0.0287 (5.7%)
d_2[m]	0.6	0.6923	0.6551	0.0923 (15.4%)	0.0551 (9.1%)
R[m]	0.05	0.1270	0.0919	0.077 (152%)	0.0419 (8.4%)
Z_{ob} [m]	0.6	0.6830	0.6532	0.083 (13.8%)	0.0532 (8.9%)

and unnecessary to strictly synchronize as for TOA method. However, RSSI should be applied to short distance, and the dry and homogeneous investigated environment because the UWB signal attenuates rapidly.

The distance estimation based on RSSI and TOA methods is applied to the homogeneous medium. However, with the heterogeneous medium, the reflected

UWB signal's shapes are significantly changed compared with the transmitted signals. Therefore, to increase the ability of the correct detection of the reflected UWB signal, modulation techniques for the UWB signal are applied, including the pulse position modulation UWB-PPM. The accuracy of UWB-PPM positioning system depends significantly on the system parameters. Hences, to improve the accuracy of UWB-PPM system, the pulse position modulation technique with an optimal pulse shift is proposed.

2.3 Proposal of UWB-PPM with an additional time shift

The conventional UWB-PPM signal is given as in Eq. (2.7) with p_i being the i^{th} component of a PN sequence, and $p_i \in \{0, 1\}$.

$$s(t) = \sum_{i=1}^{N} g(t - iT_r - p_i T_{PPM}), \tag{2.7}$$

The time shift T_{PPM} directly affects the quality of UWB-PPM systems. To make the UWB-PPM systems more flexible, the time shift T_{PPM} is adjusted with a certain time constant to achieve its optimal value. The pulse position is changed with a time constant denoted by ζ. The signal of UWB-PPM-ATS is given as:

$$s(t) = \sum_{i=1}^{N} g(t - iT_r - p_i(T_{PPM} + \zeta)), \tag{2.8}$$

The sign '+' in Eq. (2.8) means the algebraic additions so ζ can take either positive or negative values.

The depth of a buried object is estimated based on the correlation function according to Eq. (1.4). With the conventional UWB-PPM scheme, the template waveform at the receiver is $g_4(t) - g_4(t - T_{\text{PPM}})$, and in the UWB-PPM-ATS scheme, the template waveform is $g_4(t) - g_4(t - T_{\text{PPM}} - \zeta)$. The correlation of those scheme is:

$$R_0(\tau) = \int_{-\infty}^{\infty} r(t) \Big[g_4(t) - g_4(t - T_{\text{PPM}}) \Big] dt, \tag{2.9}$$

$$R_1(\tau) = \int_{-\infty}^{\infty} r(t)[g_4(t) - g_4(t - T_{\text{PPM}} - \zeta)]dt. \tag{2.10}$$

The shapes of $R_{G4}(\tau)$,$R_0(\tau)$ and $R_1(\tau)$ are shown in Fig. 2.4. The performance of UWB-PPM-ATS technique is compared with other modulation techniques