FDTD-Based Time Reversal Detection for Multiple Targets or Moving Object

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Abstract **─** Based on the Finite-Difference Time-Domain (FDTD) method, this paper presents a novel Time Reversal (TR) algorithm for multiple targets or moving object detection. Two numerical experiments are carried out by the Finite-Difference Time-Domain (FDTD) programs. The results confirm that the proposed TR algorithm could detect multiple targets effectively and track the moving object accurately. The re-focusing waves are very similar with the excitation signal, which can be applied in communications.

Index Terms **─** FDTD, moving object, multiple targets, time reversal detection.

I. INTRODUCTION

The time-reversal technique was introduced to acoustics by Fink in 1992, which has been applied successfully for target imaging, underwater communication and nondestructive testing [1]. Then TR technique was transposed to electromagnetism [2,3]. Due to its spatial-temporal focusing, TR technique is believed to improve the performance of current microwave systems [4]. Time-Reversal Mirror (TRM) is the key component in a TR system, which is used to reverse electromagnetic wave in time domain [5]. TRM usually consists of a transmitter-receiver array and a time reversal device.

In recent years, microwave detection has been exhaustively analyzed and experimentally researched, which may be widely applied in tomography [6], cancer treatment [7,8] and ultra-wideband radar technique [9,10]. Microwave detection can be achieved by a variety of methods, such as FDTD method [11], the Iterative Time Reversal Mirror (ITRM) [12], the Decomposition of the Time Reversal Operator (DORT, the French abbreviation of 'Décomposition de l' opérateur de retournement temporal') [13], and the Time Reversal Multiple Signal Classification (MUSIC) [14]. TR algorithms based on the Transmission-Line Method (TLM) have also been proposed [2,15]. Among these methods, FDTD is the most accurate and simplest one. Therefore, FDTD method is adopted in this paper.

In existing investigations, most TR FDTD algorithms for detection have only considered one target [7-9,16]. This paper investigates the TR FDTD algorithm for multiple targets and also uses it to track a moving object. This algorithm can precisely detect and localize the targets. Additionally, this paper has qualitatively analyzed the factors which may influence the spatial-temporal focusing.

II. TIME REVERSAL TECHNIQUES

The time-symmetry of wave propagation is the basis of TR technique [17]. In a linear, homogeneous, isotropic, and time-invariant medium without a source, the electric-field intensity E(r, t) can be described by the following vector wave equation:

$$\nabla^2 \boldsymbol{E}(\boldsymbol{r},t) - \mu\varepsilon \frac{\partial^2 \boldsymbol{E}(\boldsymbol{r},t)}{\partial t^2} = 0 . \qquad (1)$$

Equation (1) does not contain any time-varying coefficient nor the odd derivation of time, which is so-called time-symmetry of wave equation. In other words, if E(r, t) is a solution of the vector wave equation, its time reversed mode E(r, -t) is also a solution of equation (1). Furthermore, E(r, T-t) is also a solution of the wave equation.

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A typical schematic of TR process is shown in Fig. 1. Firstly, a source emits a wave front which propagates through a complex medium and is received by the TRM [5,16]. Then, the received signal is time-reversed and retransmitted by the TRM. The time-reversed electromagnetic field back-propagates, and a spatial-temporal focusing can be observed at the initial position exactly. So TR is an adaptive waveform transmission scheme that utilizes the rich scattering medium to best match to the target response.

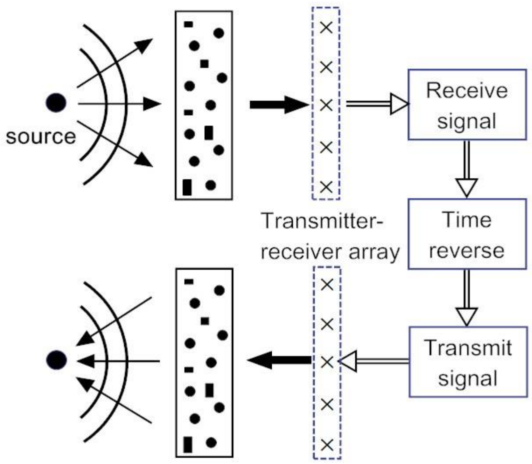

Fig. 1. Typical process of TR.

III. FDTD SIMULATION MODEL

A simplified Two-Dimension (2D) lossless indoor space model is used to carry out FDTD simulations (see Fig. 2). The propagation in this model is described by TMz mode consisting of Hx, Hy and Ez, which means the magnetic fields (Hx and Hy) are orthogonal to the normal to the plane of propagation.

The simulation model is a 3 m * 3 m indoor space, which is surrounded by three concrete walls (10-cm-thick, permittivity εr=6.4), a Perfect Electric Conductor (PEC) door and a glass window (permittivity εr=3.7). There are three PEC boxes, one PEC round table, one glass box and one wood desk (permittivity εr=7.6) in the room. The circles on the left are three targets, and the five diamonds on the right represent the TRM of five transmitter-receivers with space of 0.5 m. To verify the accuracy of the TR FDTD algorithm, the positions of targets and TRM are fixed before the simulation.

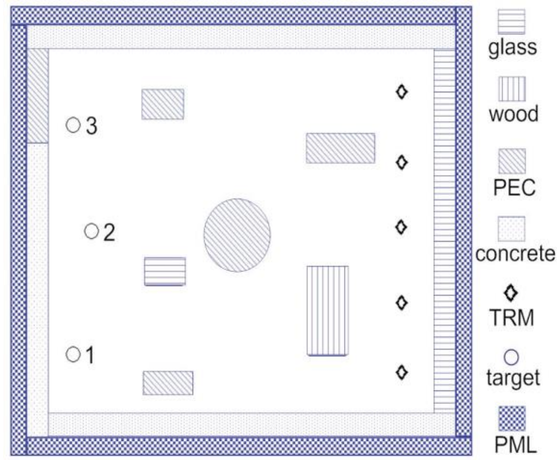

Fig. 2. Simplified 2D lossless indoor space model.

The size of FDTD grid cell is 12.5 mm * 12.5 mm. A split-field Perfectly Matched Layer (PML) is set outside the walls and window to absorb outgoing waves [18]. The PML has a thickness of 8 cells. The order of the PML parameter npml is 2, and the theoretical reflection coefficient R(0) is 10-5. The excitation signal is a second-order Gaussian pulse with a center frequency of 2.4 GHz, and a bandwidth of 1 GHz (see Fig. 3). The problem is run for 1,200 time steps.

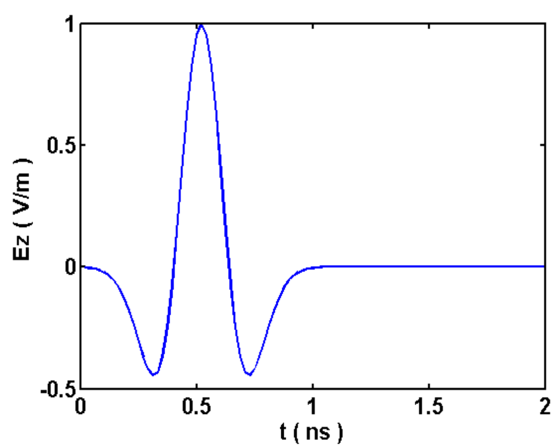

Fig. 3. The second-order Gaussian pulse.

For simplicity, the media are lossless, and specific antenna elements are not modeled. Therefore, a target is an ideal isotropic point source assigned an electric field Ez, and an observation point represents a receiving antenna of TRM.

As FDTD is performed directly in time domain, in order to get the best TR image, it is very important to determine the optimal time instant when the TR electromagnetic wave focuses back to the targets. Due to the spatial focusing property of TR, the best image of targets is expected to have some sharp peaks at the target locations and small value elsewhere. That is, the best image has minimum entropy. Therefore, a minimum entropy criterion is adopted to choose the optimal time instant. As the inverse varimax norm is known to be an easily computable and accurate approximation to entropy [19], we use the inverse varimax norm S instead of entropy, which can be calculated by:

$$S(E_z^n) = \frac{\left\{\sum_i \sum_j \left[E_z^n(i,j)\right]^2\right\}^2}{\sum_i \sum_j \left[E_z^n(i,j)\right]^4}, \qquad (2)$$

where (i, j) are the grid cell coordinates, n is the time step of FDTD, and summation is over all the grids of room. We can calculate the inverse varimax norm at every time step and find out the minimal one. Then we get the best TR image of targets and its corresponding time instant.

IV. RESULTS AND DISSCUSSSION

In this section, two numerical examples are provided to demonstrate the performance of TR FDTD algorithm under various conditions. The FDTD codes written by ourselves are calculated in MATLAB.

A. Detection and localization for multiple targets

To simulate this situation, three targets at different locations are excited by the identical second-order Gaussian pulse (see Fig. 3) at the same time. The waves travel through the multi-path environment and arrive at the TRM. Then the signals received by the TRM are normalized, time reversed and transmitted (see Fig. 4).

According to the minimum entropy criterion mentioned in Section III, the best image of targets is obtained at time step of 976 (t=20.33 ns), which is shown as Fig. 5. We can observe three targets clearly in the image. These three targets locate exactly at the same position respectively as shown in Fig. 2, which means that with TR FDTD algorithm we can precisely detect and localize multiple targets.

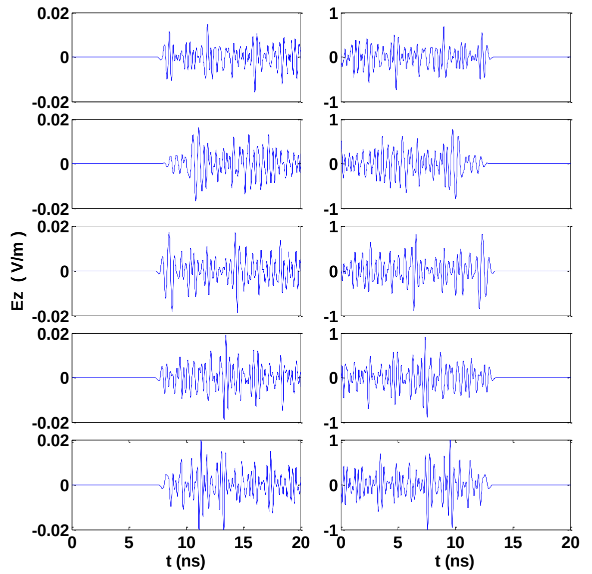

Fig. 4. Received and transmitted signals of TRM: (a) five signals received by TRM, and (b) normalized time reversed signals.

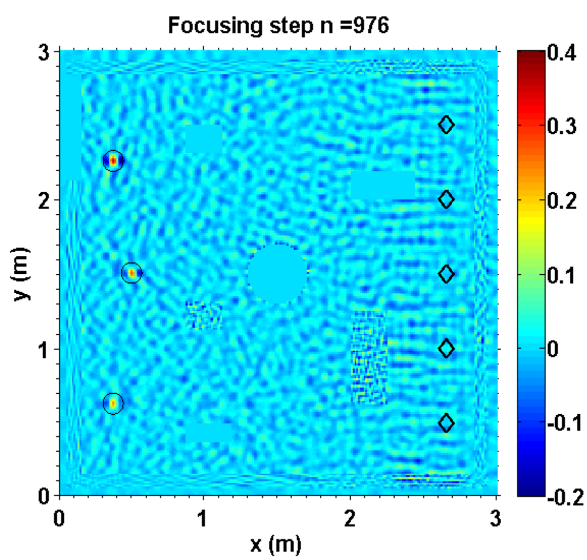

Fig. 5. Locations of three targets.

Figure 6 illustrates the time domain waveforms of the re-focused wave at three target locations. Although three targets emit the excitation pulse with the same amplitude, the amplitudes of re-focused waves are different, because TRM receives different amounts of energy from different targets. Generally, the more energy TRM received, the higher amplitude of the re-focused wave is obtained at the corresponding target location.

Three re-focused waveforms are very similar with the excitation signal. Theoretically, the re-focused waveform is the time reversed second-order Gaussian pulse. However, the second-order Gaussian pulse is center symmetric about the peak in time domain. Therefore, the time reversed second-order Gaussian pulse is the same with the original one.

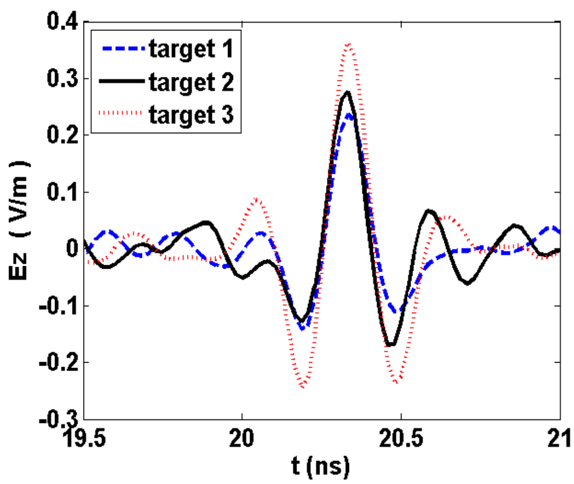

Fig. 6. The re-focused waveforms in time domain at three target locations.

B. Detection and localization for moving object

To imitate the movement of one target, target is excited from location 1 to location 3 with excitation 1 to 3 correspondingly. The excitation signals are second-order Gaussian pulses with different time delays (see Fig. 7).

Three re-focusing time steps need to be determined in this application, which means to find each minimum inverse varimax norm of three re-focused waves. However, for each re-focused waveform, the inverse varimax norm at re-focusing time step is only a little smaller than those around the re-focusing time steps. Therefore, a time gating with 0.5 ns width is adopted to avoid choosing two or more time steps from the same re-focused waveform.

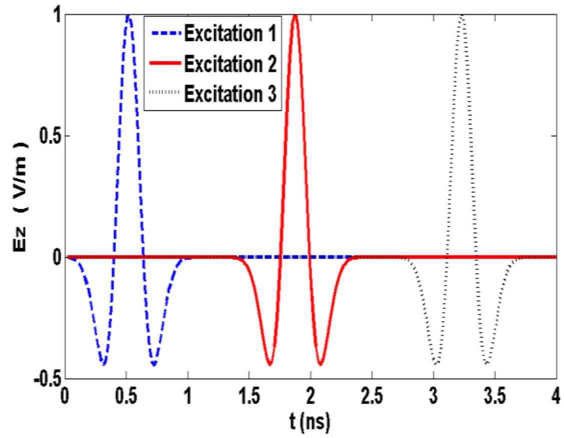

Fig. 7. Second-order Gaussian pulses with different time delays.

Figure 8 illustrates the received and transmitted signals of TRM.

The track of a moving object in TR FDTD algorithm is shown as Fig. 9. Three time instants when the TR electromagnetic wave focuses back to the target locations are time step of 846, 911 and 976, whose corresponding time is 17.63 ns, 18.98 ns and 20.33 ns.

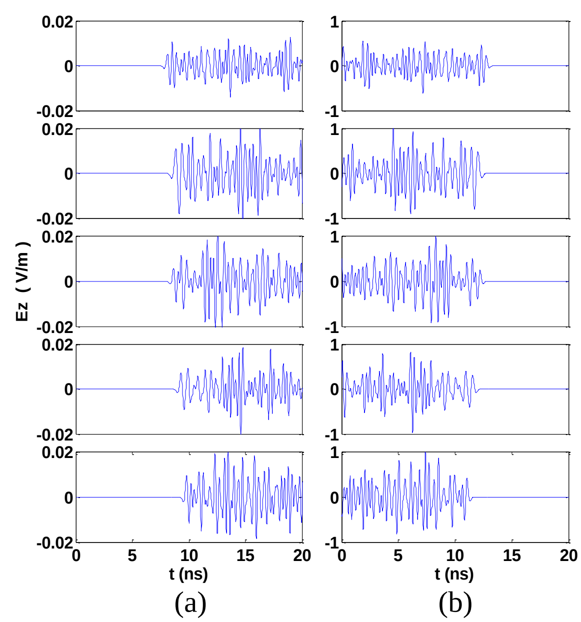

Fig. 8. Received and transmitted signals of TRM: (a) five signals received by TRM, and (b) normalized time reversed signals.

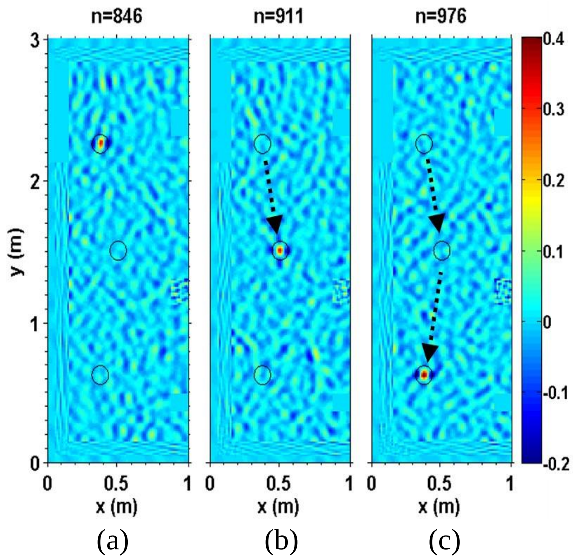

Fig. 9. Track of the moving object in TR FDTD algorithm: (a) first re-focusing image at time step of 846, (b) second re-focusing image at time step of 911, and (c) third re-focusing image at time step of 976.

Figure 10 illustrates the re-focused waves at three locations, which is very similar to the excitation signals in Fig. 7. From location 3 to location 1, the TR wave focuses sequentially at 17.63 ns, 18.98 ns and 20.33 ns respectively, which agree well with Fig. 9. Besides, the amplitude of re-focused wave at location 1 is largest, because target is first excited at location 1 with excitation 1. Compared with other excitations, the reflected and scattered waves of excitation 1 could travel more times to and from the TRM, which means the TRM receives maximum amount of energy from location 1.

It is important to notice that the focusing time sequence of TR wave is just in reverse order of exciting time sequence. That is, the TR wave would focus last at the location excited first. Therefore, to describe the movement accurately in the time domain, the image of TR FDTD algorithm should be time reversed again. So based on the Fig. 9, we can finally obtain both the real track of the moving object and the time differences between adjacent locations, which is shown as Fig. 11.

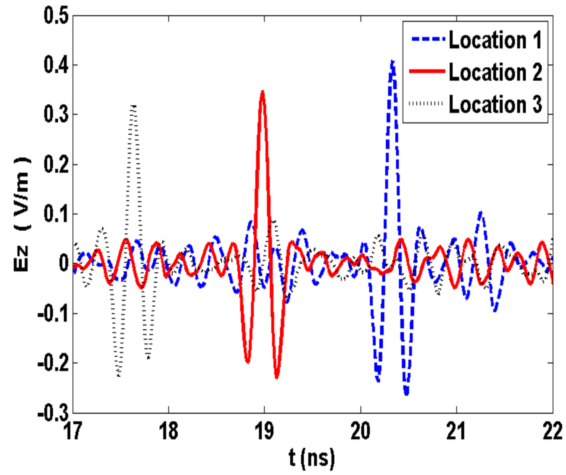

Fig. 10. The re-focused waveforms in time domain at three locations.

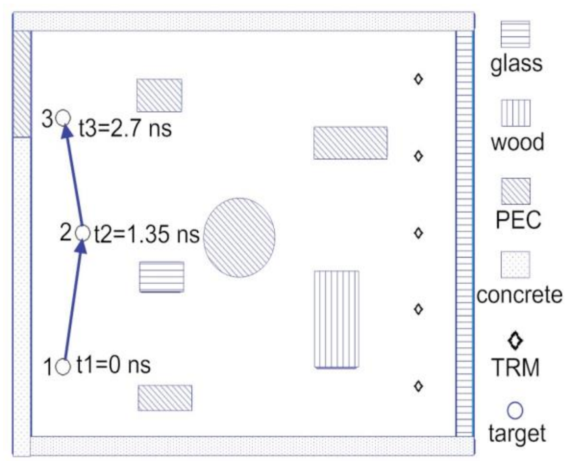

Fig. 11. Real track of the moving object.

V. CONCLUSION

Based on a simplified lossless indoor space model, this paper has presented a TR FDTD algorithm to detect and localize for multiple targets or moving object. The imaging results demonstrate the effectiveness of the proposed TR FDTD algorithm in the complex environment. As the TR technique is based on time-symmetry, the proposed algorithm is also available for lossy medium or reciprocal environment. However, because of big FDTD calculation amount or the failure of minimum entropy criterion, it is not the best choice for some scenarios, such as very large detecting space, non-reciprocal or high target density environment. Therefore, the TR FDTD algorithm proposed in this paper can be widely applied in indoor location and tracking, short range communications in complex scattering environment and self-adaptive Wireless Power Transmission (WPT) system.

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