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Development of Time-Reversal Method for Detecting Multiple Moving Targets Behind the Wall

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Abstract

Through-the-wall Imaging (TWI) is crucial for various applications such as law enforcement, rescue missions and defense. TWI methods aim to provide detailed information of spaces that cannot be seen directly. Current state-of-the-art TWI systems utilise ultra-wideband (UWB) signals to simultaneously achieve wall penetration and high resolution. However, these systems are diffraction-limited and encounter problems due to multipath signals in the presence of multiple scatterers.

This poster introduces a novel time reversal (TR) based algorithm that uses the highly acclaimed MUltiple SIgnal Classification (MUSIC) method to image targets hidden behind an obstruction and achieve superresolution (resolution that beats the diffraction limit). The algorithm utilises spatiotemporal windows to divide the full Multistatic Data Matrix (MDM) into sub-MDMs. The summation of all images obtained from each sub-MDM give a clearer image of a scenario than we can obtain using the full-MDM.

1. Introduction

FREE-space imaging is typically employed in conventional radar [1] and synthetic aperture radar (SAR) techniques [2] since distortions in the atmosphere are often negligible. Figure 1 shows a block diagram illustrating the principle of radar imaging. The scene is illuminated with electromagnetic waves which reflect off any target in the medium and return to the receiving antenna giving information about the targets location. Conventional radar, sonar and optical image processes all utilize basic wave physics equations to provide focusing to individual points. Time reversal (TR) methods have become popular for remote sensing because they can take advantage of multipath signals to achieve super resolution (resolution that beats the diffraction limit).

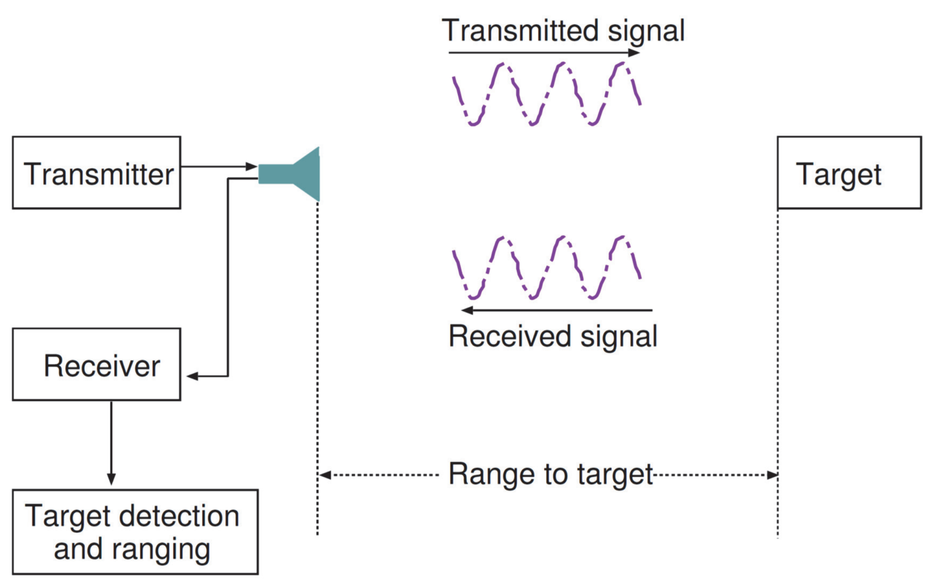


Figure 1: *Block Diagram illustrating the basic principle of imaging*

The Decomposition Of the Time-Reversal Operator (DORT in its French acronym) [3] and MUltiple SIgnal Classification (MUSIC) [4] methods are both TR techniques which involve taking the Singular Value Decomposition (SVD) of the Multistatic Data Matrix (MDM) which contains the signals received from the target(s) to be located. The MUSIC imaging method has generated a lot of interests due to its robustness and ability to locate multiple targets. However these TR-based methods encounter problems when the targets are behind an obstruction, particularly when the properties of the obstruction is unknown as is often the case in TWI applications.

2. Theory

The MUSIC method utilises the singular vectors of the MDM, whose elements $k_{s,r}(t)$, are obtained by transmitting a signal from N TRA antenna elements, one at a time, and recording the response signal in the medium at all antennas, where s is the transmitting antenna and r is the receiving antenna. The full-MDM, $K(t)$, which contains vital information about the targets in the medium, is represented by $K(\omega)$ in the frequency domain.

In TWI applications, the reflections from the wall dominate the MDM, $K(t)$, in power which is crucial for the application of the MUSIC methods. Hence, rather than the global information contained in the full-MDM, we obtain localized information from various parts of the scattering medium in the sub-MDMs, which reduces the number of targets to be detected at one time.

3. The spatio-temporal window algorithm

We select the Hanning window [6] as our time-window. By subsequent time-shifting, we obtain temporal-windows to completely cover the whole signal duration of interest. The mth time-window is obtained as

$$W_m(t) = 0.5\left(1-\cos\left(\frac{2\pi(t-\tau_m)}{P}\right)\right) \quad (1)$$

for $\frac{P(m-1)}{2} \le t \le P + \frac{P(m-1)}{2}$ and otherwise $W_m(t) = 0$, where τ_m is the time shift and P is the window interval. In order to avoid loss of data, the time-windows are shifted in time from one another to ensure that the addition of the time-windows gives a magnitude of 1. Hence, the time shift is defined as $\tau_m = \frac{P(m-1)}{2}$ $(1 \le m \le M)$ where $M = \left\lfloor \frac{T}{0.5P} - 1 \right\rfloor$ is the number of time-windows needed to cover the time simulated, T, for the scenario, and $\lfloor\,\rfloor$ represents a floor function that maps a real number to the largest previous integer.

By multiplying the Hanning windows $W_m(t)$ by the elements of the full-MDM $k_{s,r}(t)$, one at a time, we obtain M sub-MDMs as $K_m(t,P)$. We further segment $K_m(t,P)$ in space by selecting elements of $K_m(t,P)$ obtained from a set of N_s antennas where $1 \le N_s \le N$. Hence, for $K_m(t,P)$, we obtain the lth sub-MDM as

$$\boldsymbol{K}_{m,l}(t,P,N_s) = \begin{pmatrix} k_{l,l}(t)W_m(t) & . & . & k_{l,L}(t)W_m(t) \\ . & & . & . \\ k_{L,l}(t)W_m(t) & . & . & k_{L,L}(t)W_m(t) \end{pmatrix} \quad (2)$$

where $L = N_s - 1 + l$ and $1 \le l \le N + 1 - N_s$.

Assuming the excitation pulse width is Υ, the minimum size of the time-window is chosen to be Υ. Hence

$$P \ge \Upsilon. \quad (3)$$

This ensures that a single time-window covers the initial excitation signal transmitted from the TRA antennas. Furthermore, since the MUSIC methods utilise the singular vectors in the null subspace, the minimum value of N_s should be greater than the number of singular values in the signal subspace N_t of the full-MDM to ensure that we retain noise in the sub-MDMs. Therefore

$$N_s > N_t. \quad (4)$$

By performing the FFT on the elements of sub-MDM $K_{m,l}(t,P,N_s)$ we obtain $K_{m,l}(\omega,P,N_s)$. Furthermore the SVD on $K_{m,l}(\omega,P,N_s)$ gives

$$\boldsymbol{K}_{m,l}(\omega,P,N_s) = \boldsymbol{U}(\omega,m,l)\boldsymbol{A}(\omega,m,l)\boldsymbol{V}^{\dagger}(\omega,m,l) \quad (5)$$

where $\mathrm{A}(\omega,m,l)$ are $N_s \times N_s$ real diagonal matrices containing the singular values in descending order and, $\mathrm{U}(\omega,m,l)$ and $\mathrm{V}(\omega,m,l)$ are $N_s \times N_s$ unitary matrices containing the left and right singular vectors of $u_n(\omega,m,l)$ and $v_n(\omega,m,l)$ for $1 \le n \le N_s$, respectively.

We define the total sub-CF-MUSIC imaging functional as the summation of all sub-CF-MUSIC imaging functionals to obtain

$$\boldsymbol{M}_{\Gamma}(\bar{r},\omega_c,P,N_s) = \sum_{l=1}^{L}\sum_{m=1}^{M}\left[\sum_{n=N_t(\omega_c)+1}^{N_s} \boldsymbol{g}^{\dagger}(\bar{r},\omega_c)\cdot\boldsymbol{u}_n(\omega_c,m,l)\right]^{-1} \quad (6)$$

where ω_c is the centre frequency of interest. Similarly, the summation of the sub-UWB-MUSIC imaging functionals gives the total sub-UWB-MUSIC imaging functional as

$$\boldsymbol{M}_{\Gamma_{UWB}}(\bar{r},P,N_s) = \sum_{l=1}^{L}\sum_{m=1}^{M}\left[\int_{\Omega}\sum_{n=N_t(\omega)+1}^{N_s} \boldsymbol{g}^{\dagger}(\bar{r},\omega)\cdot\boldsymbol{u}_n(\omega,m,l)d\omega\right]^{-1} \quad (7)$$

where Ω is the frequency range of interest.

4. Numerical Simulations

Figure 2 shows the geometry of a scenario with one well-resolved PEC sphere, whose radius is 15mm and conductivity is 10^7 S/m, in a homogeneous medium (free-space) hidden behind a brick wall.

Figure 3 shows the total sub-CF-MUSIC and total sub-UWB-MUSIC (from 0.3 to 4.8 GHz) images when $N_s = 7$ and $P = 8\gamma$. The total sub-CF-MUSIC and total sub-UWBMUSIC imaging functional yield images that accurately locate the target.

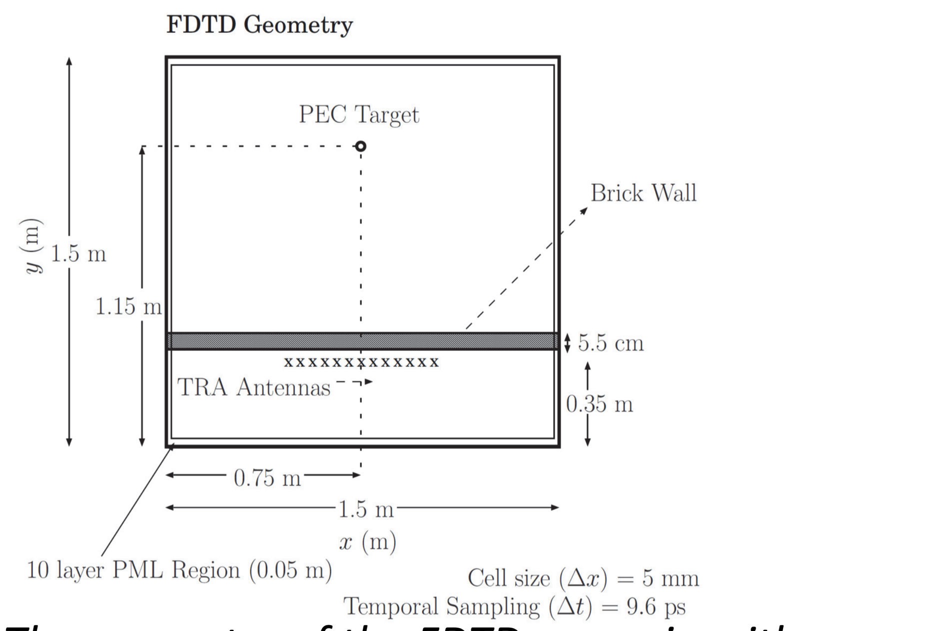
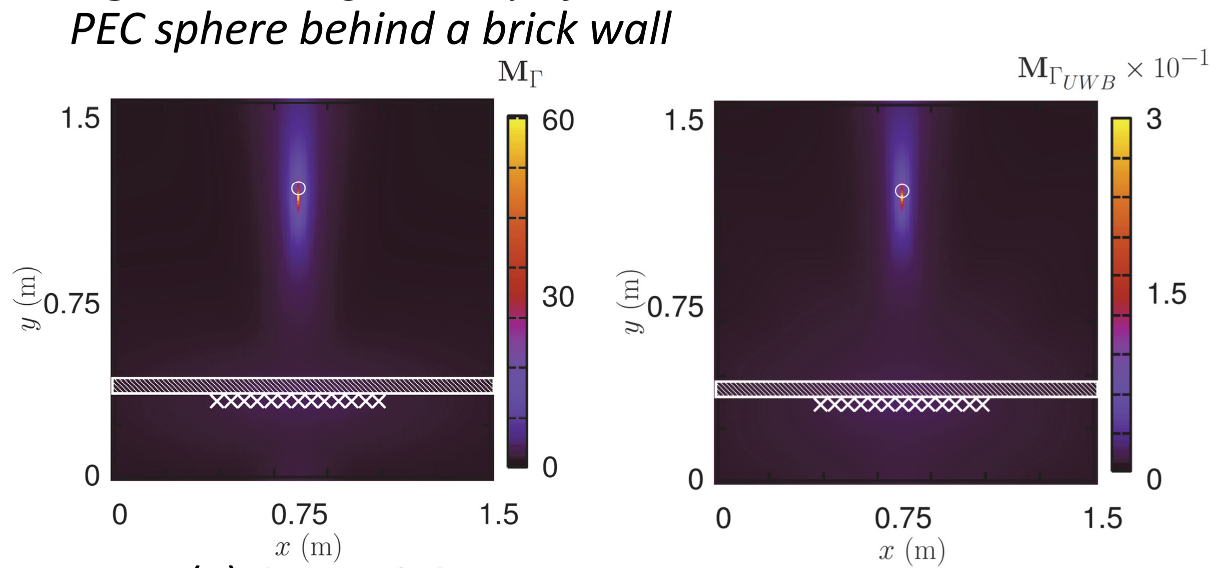


Figure 2: *The geometry of the FDTD scenario with one PEC sphere behind a brick wall*



(a) CF-MUSIC (b) UWB-MUSIC

Figure 3: *The total sub-CF-MUSIC and total sub-UWBMUSIC images produced when $P = 8\gamma$ and $N_s = 7$, where $\times$ represents the TRA antennas' locations and $\circ$ represents the target location*

5. Towards Multiple Moving Targets

The differential TR technique has been shown to be capable of locating and tracking well-resolved moving targets in the presence of stationary targets using the DORT method. We aim to merge the differential TR technique with the spatio-temporal window algorithm for the MUSIC method. The differential TR technique is based on obtaining the differential-MDM, which reject signals from stationary scatterers, to locate the moving targets. We probe the medium at t_1 and then at a later time t_2, where the targets has either moved or changed in size, to obtain the MDMs $K|_{t=t_1}$ and $K|_{t=t_2}$ respectively. We subtract $K|_{t=t_1}$ from $K|_{t=t_2}$ to obtain the full-differential MDM as

$$\boldsymbol{K_d} = \boldsymbol{K}|_{t=t_2} - \boldsymbol{K}|_{t=t_1}. \quad (8)$$

Applying the spatio-temporal window algorithm on the fulldifferential MDM allows us to obtain images that locate the moving targets in a TWI scenario.

Researching the TWI of multiple moving targets will require simulations on 3D scenarios much more complex than the 2D scenario depicted in Figure 2. Such scenarios will significant increase simulation run-time. Furthermore, the increased information obtained in the MDM from the a 3D scenario also increases the algorithm run-time. Reducing the algorithm run-time will enhance the suitability of the algorithm for applications such as law enforcement, rescue missions and defense which usually require high-speed imaging.

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