Estimating Moving Targets Behind Reinforced Walls Using Radar

M. Nikolic(1), A. Nehorai (1), and A. Djordjevic(2)
(1) Washington University in St. Louis, St. Louis, MO 63130 USA
(2) University of Belgrade, 11120 Belgrade, Serbia
E-mail: nikolic2@ese.wusl.edu, nehorai@ese.wustl.edu, edjordja@etf.bg.ac.yu

Introduction

We consider the problem of estimating personnel hidden behind reinforced walls using exterior electromagnetic sensing. Several studies considered detection of targets behind a wall [1]-[2]. In [1] the wall is treated as a homogeneous dielectric slab of known thickness and electric permittivity. The case in which the wall parameters are unknown is studied in [2]. To the best of our knowledge, there are no studies on the estimation of targets located behind complex walls. Walls reinforced by steel parallel bars or square-grid meshes are frequently used in construction [3]. They cause attenuation and severe distortion of the incident signal, thus making the estimation more difficult than in the case of homogeneous walls. We treat the cases of known and unknown wall parameters separately. The algorithm is robust and does not require knowledge of bar diameter or separation. We also show that significant improvement is achieved when bar characteristics are available. This improvement is particularly pronounced when the signal-to-noise ratio is low.

Measurement model

Reinforced walls are generally one of two types, bars or mesh. When the incident electromagnetic field is parallel to the vertical bars, the horizontal bars have small influence on the transmission and reflection coefficient of the wall [3]. The same reasoning applies when the incident electric field is parallel to the horizontal bars. Therefore, without loss of generality we consider a wall reinforced with vertical bars. We assume the bars to be perfectly conducting and immersed in the homogeneous material with relative dielectric permittivity ε_r.

We consider 2D problem; however, the approach we propose is general and can be easily applied to 3D problems. We suppose a uniform linear array of M sensors placed in the front of the reinforced wall. The array takes measurements at N known positions, at L frequencies. For 2D modeling, instead of induced voltages, we use the induced electric field in the sensors. We determine the frequency response of the considered system using the method of moments [4]. The program uses the equivalence principle to divide the system under consideration into the following subsystems: sensors (filament conductors whose cross section is electrically small) and dielectric walls with metallic bars inside. The results of the calculations are the impedance parameters (z). The measured induced electric field in the i-th sensor reads

$$E_i(n,f_l)=\sum_{k=1}^{M}E_{ik}(n,f_l)+u=\sum_{k=1}^{M}z_{ik}(n,f_l)I_k(f_l)+u,\ \ i=1,\ldots,M\ ,\ \ n=1,\ldots,N\ ,\ \ l=1,\ldots,L\ ,\qquad(1)$$

where $E_{ik}(n,f_l)$ is the induced electric field in the i-th sensor when the k-th sensor is excited, $z_{ik}(k,f_l)$ is the mutual impedance coefficient between the i-th and k-th sensors, f_l is the operating frequency, n is the index of the measurement position, I_k is the feeding current of the k-th sensor, and u is the measurement noise and modeling error. We

978-1-4244-2042-1/08/$25.00 ©2008 IEEE

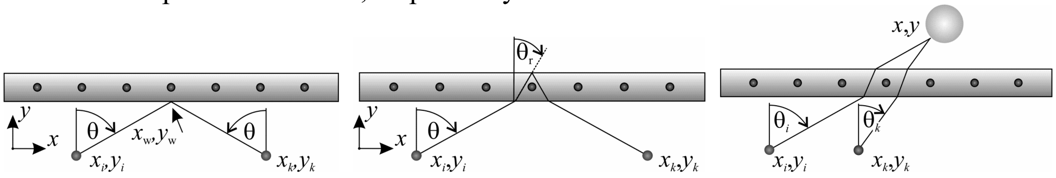
assume complex, zero-mean Gaussian noise with variance σ^2. The feeding current is the same for all sensors. We assume Gaussian current excitation.

Wall-permittivity and thickness estimation

Electromagnetic waves reflect from interfaces of media with different electromagnetic properties. The pulse reflected from the front side of the wall contains information on the dielectric permittivity. We add coherently the received signals with respect to the delay of those pulses. The time delay (τ_{ik}) between i-th and k-th sensor, according to Fig. 1a, is given by

$$\tau_{ik} = \sqrt{(x_i - x_{\mathrm{w}})^2 + (y_w - y_i)^2} + \sqrt{(x_k - x_{\mathrm{w}})^2 + (y_w - y_k)^2} / c_0 , \tag{2}$$

where (x_{i}, y_i), (x_{k}, y_k), and (x_{w}, y_{w}) are the coordinates of the i-th sensor, k-th sensor, and the reflection point on the wall, respectively.



(a) (b) (c)

Fig. 1. Scheme used for the estimation of (a) wall permittivity, (b) wall thickness, and (c) targets.

We compensate for different attenuations due to different distances between the transmitting and receiving sensors. The focused waveform reads

$$E_0(t) = \frac{1}{NM^2} \sum_{n=1}^{N} \sum_{i=1}^{M} \sum_{k=1}^{M} E_{ik}(n, t + \tau_{ik}) \sqrt{\tau_{ik}(n) c_0} . \tag{3}$$

We calculate the reflection coefficient and wall permittivity as

$$\hat{R} = \int_0^T E_0(t) h(t) dt \Big/ \left(\int_0^T h(t) dt \right)^2 , \quad \hat{\varepsilon}_{\mathrm{r}} = \left(\frac{1 - \hat{R}}{1 + \hat{R}} \right)^2 , \tag{4}$$

where $h(t - s / c_0)$ is the induced electric field in the sensor at a distance of s = 1 m from the transmitting sensor, and T is the pulse duration. We refer to $h(t)$ as a reference pulse.

We add coherently the pulses reflected from the back side of the wall to estimate the wall thickness. For the sensor pair from Fig. 1b, that delay reads

$$\tau(w) = \left((2y_w - y_i - y_k) / \cos\theta + 2w\varepsilon_{\mathrm{r}} \Big/ \sqrt{\varepsilon_{\mathrm{r}} - (\sin\theta)^2} \right) / c_0 . \tag{5}$$

We estimate the wall thickness from the correlation of the focused electric field with reference pulse $h(t)$:

$$I(w) = \sum_{n=1}^{N} \sum_{i=1}^{M} \sum_{k=1}^{M} \int_0^T E_{ik}(n, t + \tau_{ik}(w)) h(t) . \tag{6}$$

The correlation is calculated for different values for the wall thickness, w. The maximum of (6) defines the wall-thickness estimate. Because of the periodic nature of the reflected field, the correlation does not yield a unique solution. Nonetheless, practical limits on the wall thickness reduce the number of estimates to only a few.

Estimation of target positions

The presence of personnel inside a building is registered through changes in the measurements caused by their movements. We assume we have available measurements of the stationary scene behind the wall. We obtain the signals reflected from the targets by subtracting the measurements of the stationary background from the measurements perturbed by the appearance of the people. We apply beamforming [1] on the reflected signals to estimate the positions of humans. If the target is located at the point (x,y), the k-th sensor receives the signal transmitted from the i-th sensor delayed for $\tau_i + \tau_k$, where τ_i, (τ_k) is the signal propagation time from i-th (k-th) sensor to the target. According to Fig. 1c, this delay reads

$$\tau_{i,k}(x,y) = \left((y - y_{i,k} - w)/\cos\theta_{i,k} + w\varepsilon_{\mathrm{r}}/\sqrt{\varepsilon_{\mathrm{r}} - (\sin\theta_{i,k})^2} \right)/c_0 . \tag{7}$$

Hence, the pixel image at (x,y) is obtained as

$$\Delta E(t;x,y) = \sum_{n=1}^{N}\sum_{i=1}^{M}\sum_{k=1}^{M}\int_0^T \Delta E_{ik}\left(t + \tau_i(x,y) + \tau_k(x,y)\right)h(t), \quad \Delta E_{ik} = E_{ik} - E_{ik}^{\mathrm{stat}}, \tag{8}$$

where, E_{ik}^{stat} is the induced electric field in the case of the stationary scene, E_{ik} is the induced electric field due to the appearance of the moving objects.

In the case in which the bar parameters are known, instead of $h(t)$, in (8) we use new reference pulse that takes into account the influence of the bars on the signal shape

$$\widetilde{h}(t) = F^{-1}\{H(f)T(f,\theta_i)T(f,\theta_k)\} \approx F^{-1}\{H(f)(T(f,0°))^2 \exp(\mathrm{j}2\pi f\tau)\}, \tag{9}$$

where $T(f, \theta)$ is the transmission coefficient of the reinforced wall and τ_0 is the time delay that assures that the reference pulse is centered at $t = 0$.

Results

We consider the scenario in which, besides moving objects, there are static objects representing the furniture and interior walls. The number of the moving and static objects, as well as their properties, is unknown. The moving objects are modeled as perfectly conducting cylinders with radius $r = 0.2$ m, centered at $x = 1$ m, $y = 1.2$ m and $x = -1.5$ m, $y = 0.75$ m, respectively. Assumed wall thickness is $w = 0.2$ m and relative dielectric permittivity is $\varepsilon_{\mathrm{r}} = 3$. The wall is reinforced with metallic bars of diameter $D_{\mathrm{bar}} = 2$ cm and period $d_{\mathrm{bar}} = 15$ cm. The static objects are modeled as dielectric rectangles. The adopted relative permittivity for the static objects is the same as the wall permittivity. The measuring system consists of a uniform linear array of $M = 5$ sensors and the separation between adjacent sensors is 0.2 m. The array moves parallel to the wall at a distance of 0.75 m from the front side of the wall. The array takes measurements every 0.2 m. The frequency response is calculated from 5 MHz to 2 GHz in 5 MHz steps. The measurements are corrupted with white noise.

The estimated permittivity is $\hat{\varepsilon}_{\mathrm{r}} = 2.94$. The wall-thickness estimation, in the range of $0.1 \text{ m} < w < 0.4 \text{ m}$, yields maxima at: 0.2 m, 0.3 m, and 0.4 m. We used those estimates to compute scene images. The most focused image is obtained using the true wall thickness $\varepsilon_{\mathrm{r}} = 2.94$, $w = 0.2$ m. The result obtained for $SNR = 30$ dB is shown in Fig. 2.

The image quality (Fig. 3) is significantly improved when the corrected pulse shape $\widetilde{h}(t)$ is used compared with the case in which the distortion is not modeled (Fig. 2). This improvement is particularly pronounced when the signal-to-noise ratio is low. However, due to the lack of space we did not show those results.

Conclusion

We addressed the important problem in urban warfare of estimating moving targets such as personnel behind a reinforced wall using radar measurements. First, we considered the case in which the reinforced wall is completely unknown. We coherently added measured electric fields to estimate the wall thickness and concrete permittivity, independently. We applied beamforming to estimate the number and locations of the targets. The algorithm proved robust and performed satisfactorily in the case in which the bar parameters are unknown. We also analyzed the problem in which the characteristics of the metallic grid are known. We improved the estimation significantly by modeling the waveform distortion due to the bars. The resulting images are focused and represent the contours of the targets. In addition, the minimal necessary *SNR* is lower compared with the case in which the influence of the bars on the signal shape is ignored.

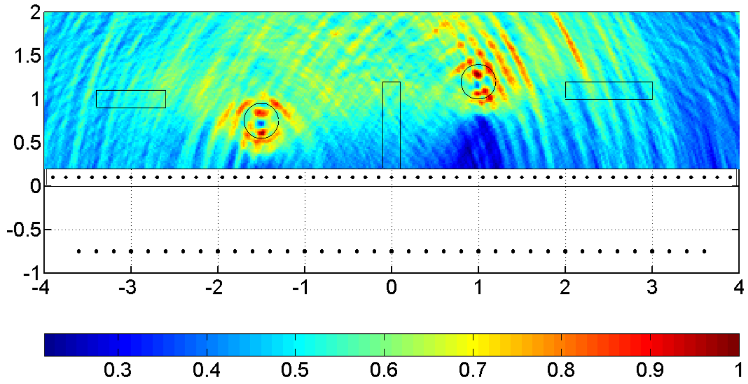


Fig. 2. Estimation of target position with unknown bar parameters (*SNR* = 30 dB).

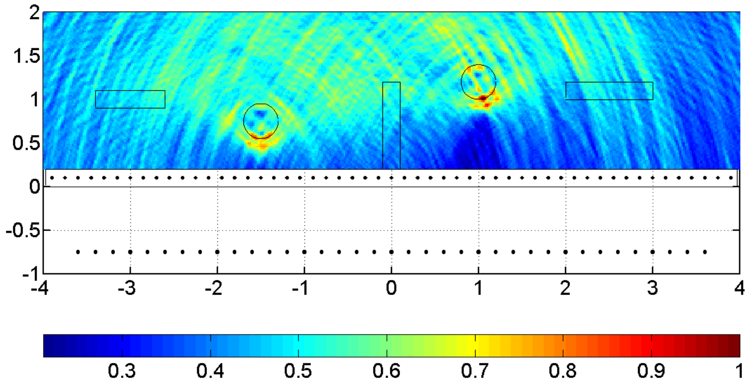


Fig. 3. Estimation of target positions with known bar parameters (*SNR* = 30 dB).

References

[1] F. Ahmad, M. G. Amin, and S. A. Kassam, “Synthetic aperture beamformer for imaging through a dielectric wall,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 41, no. 1, pp. 271–283, Jan. 2005.

[2] G. Wang and M. Amin, “Imaging through unknown walls using different standoff distances,” *IEEE Transactions on Signal Processing*, Vol. 54, No. 10, pp. 4015-4025, Oct. 2006.

[3] E. Richarlot, M. Bonilla, W. Wong, V. Fouad-Hanna, H. Baudrand, and J. Wiart, “Electromagnetic propagation into reinforced concrete walls,” *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 357–366, Mar. 2000.

[4] A.R. Djordjević, T.K. Sarkar, and S.M. Rao, “Analysis of finite conductivity cylindrical conductors excited by axially-independent TM electromagnetic field,” *IEEE Trans. Microwave Theory Techn.*, Vol. MTT-33, No. 10, pp. 960-966, Oct. 1985.