Squinted Array Beamforming for Wall Back Plate Detection

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***Abstract*— We consider the problem of detection of wall back plates, which intentionally or unintentionally block electromagnetic wave penetrations and prevent the waves from reaching the indoor scene. This renders the result of through-the-wall radar imaging incorrect and misleading. The proposed approach employs squint beamforming to avoid the strong direct returns from the front side of the exterior wall and allow the diffraction for the plate placed against or near to the back side of the wall to be detected. We aid squint beamforming with a wall removal technique based on eigenstructure of the data matrix. This technique is applied prior to imaging and mitigates sidelobe wall scattering residuals, which may still obscure the relative weak plate radar return.**

Keywords—Beamforming, through-the-wall radar, wall clutter mitigation.

I. INTRODUCTION

Through-the-wall radar imaging (TWRI) and urban sensing provide vision into optically obscured areas [1]-[3]. TWRI covers a broad range of applications in both civilian and military contexts, ranging from surveillance and reconnaissance to hostage rescue missions and searching for survivors in natural disasters. In TWRI, analysis of radar returns may not reveal any information about the indoor scene. This can be attributed to two possibilities, namely, the exterior wall is back plated such that electromagnetic (EM) waves cannot reach the scene or the scene is indeed empty.

In this paper, we introduce squint processing [4] combined with subspace wall mitigation techniques [5]-[7] to demonstrate the effectiveness of detecting and locating the wall back plate. The wall back plate refers to any blockage of EM waves due to large items placed from inside against the back end of the exterior wall. As such, it may represent a piece of furniture, such as a wall mirror or a filing cabinet. The proposed approach directs the beams away from the nominal angle perpendicular to the wall. By forming squint beams that look at both the walls and the scene with a squint angle, we attenuate the wall returns by forcing them along a spatial null or a small sidelobe. In essence, the specular nature of the front wall returns lends itself to low sensitivity towards strong wall reflections in squint beam configurations. The reflection from the back plate, on the other hand, will persist and would appear in the mainlobe due to its rather diffuse EM reflection.

The subspace wall mitigation technique aims at capturing the wall returns as dominant components in the eigenstructure of the raw data matrix. The latter has the data in space and frequency in its rows and columns, respectively. This is made possible via two fundamental properties of the exterior wall: 1) radar returns are strong, typically stronger than indoor targets and interior walls, and 2) Radar returns do not change much with antenna locations when the radar array aperture is assumed parallel to the wall. The eigenstructure technique has proven to be an effective approach for mitigating scatterings for different types of walls [5].

The remainder of the paper is organized as follows. In Section II, we describe the proposed squint beamforming based approach for wall back plate detection. Supporting results based on computational EM simulation data are provided in Section III. Section IV contains the concluding remarks.

II. PROPOSED APPROACH

A. Subspace Wall Mitigation

Consider a monostatic array aperture with N elements located at $\{\boldsymbol{x}_n, n = 0,1,\ldots,N-1\}$ parallel to an exterior wall. A stepped-frequency signal of M frequencies, which are equispaced over the desired bandwidth $\omega_{M-1} - \omega_0$, is used for interrogating the scene. The signals received by the N antennas at the M frequencies are arranged into an $M \times N$ matrix $\mathbf{B}$,

$$\mathbf{B} = [\mathbf{b}_0 \quad \mathbf{b}_1 \quad \cdots \quad \mathbf{b}_{N-1}] \tag{1}$$

where $\mathbf{b}_m$ is the $M \times 1$ column vector containing the stepped-frequency signal received by the nth antenna. The eigen-structure of the imaged scene is obtained by performing the SVD of $\mathbf{B}$ as

$$\mathbf{B} = \mathbf{UDV}^H \tag{2}$$

where **U** and **V** are unitary matrices containing the left and right singular vectors, respectively, and **D** is a diagonal matrix containing the singular values in decreasing order. The subspace wall removal technique assumes that the wall returns and target reflections lie in different subspaces. Therefore, the first K dominant singular vectors of the **B** matrix are used to construct the wall subspace,

$$\mathbf{S}_{wall} = \sum_{i=1}^{K} \mathbf{u}_i \mathbf{v}_i^H. \tag{3}$$

The subspace orthogonal to the wall subspace is,

$$\mathbf{S}_{wall}^{\perp} = \mathbf{I} - \mathbf{S}_{wall} \mathbf{S}_{wall}^H \tag{4}$$

where **I** is the identity matrix. To mitigate the wall returns, the data matrix **B** is projected on the orthogonal subspace

$$\tilde{\mathbf{B}} = \mathbf{S}_{wall}^{\perp} \mathbf{B}. \tag{5}$$

B. Squinted Beamforming

The preprocessed data is processed as follows. The region of interest is divided into a uniform grid of pixels. An appropriate sub-aperture of the N-element array with a desired squint angle is chosen. Let the subaperture consist of N_1 elements located at $\{\boldsymbol{x}_{n_0+i}, i = 0,1,\ldots,N_1-1\}$. An image is obtained using frequency-domain backprojection [8], [9] applied to the preprocessed data corresponding to the considered sub-aperture as

$$I(q) = \sum_{i=0}^{N_1-1} \sum_{m=0}^{M-1} \tilde{b}(m, n_0+i) \exp(j\omega_m \tau_{q,n_0+i}), \; q = 0,\ldots,Q-1 \tag{6}$$

where $I(q)$ is the complex amplitude of the qth image pixel, τ_{q,n_0+i} is the focusing delay corresponding to the qth pixel and the ith element of the sub-aperture, and $\tilde{b}(m, n_0+i)$ is the preprocessed measurement at the ith element corresponding to the mth frequency.

III. SIMULATION RESULTS

The simulation was performed using XFDTD software by REMCOM®. Fig. 1 provides a schematic of the scene layout for the computational EM simulation. A 0.2 m thick homogeneous wall has partial backing, which consists of a 0.5 m wide PEC plate. A monostatic array aperture of 2.025m extent, with an inter-element spacing of 0.0375 m, is placed at a standoff distance of 5 m from the wall. A stepped-frequency signal of 1 GHz bandwidth centered at 1.5 GHz is used for scene interrogation. The array aperture is divided into two sub-apertures of 1m extent each, which are labeled as "Array 1" and "Array 2" in Fig. 1. Note that the centers of both Array 1 and Array 2 are offset from the center of the PEC plate by 3.5125 m and 2.4625 m, respectively. Thus, both sub-apertures view the PEC plate from different squint angles, as illustrated in Fig. 1, with the squint angle provided by Array 1 greater than that by Array 2.

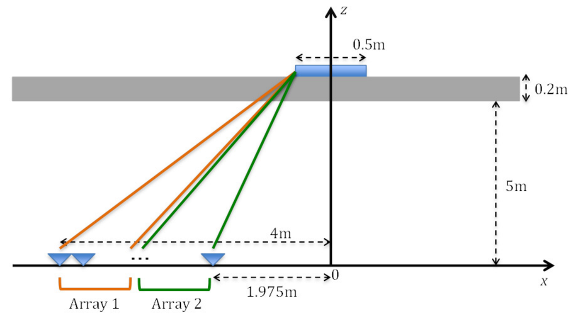
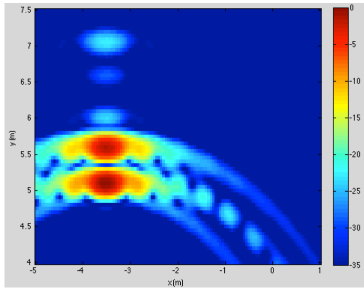


Fig. 1. Schematic of the EM simulation geometry.

The region, extending from -5 to 1 m along x-axis and from 4 to 7.5 m along y-axis, is divided into a number of pixels using a uniform square grid. Beamforming is applied to obtain images of this region corresponding to the two squinted apertures, which are shown in Figure 2. The image obtained with Array 1 is shown in Fig. 2(a), whereas Fig. 2(b) depicts the image resulting from processing of the measurements from Array 2. The wall response is visible in both images. However, we can clearly observe the edge diffraction pattern corresponding to the partial PEC backing in the image obtained with squinted geometry 2 only. Since the squint angle to the PEC backing provided by Array 2 is smaller, some of the strong sidelobes of the wall response from directly in front of the array is infringing on the region of the image being viewed with the squinted geometry. We, therefore, removed the wall response from the raw data corresponding to each sub-aperture by employing the subspace scheme. The returns from the homogeneous wall occupy a one-dimensional subspace, which is captured by the singular vectors associated with the dominant singular values of the corresponding raw data matrix (See Fig. 3). Figure 4 depicts the images corresponding to the two squinted geometries obtained by processing the wall-mitigated data. The return from the PEC backing stands out in the image (Fig. 4(b)) corresponding to Array 2. Note that there is a bias in the location where the edge diffraction pattern is captured in the image. This can be attributed to the fact that the wall effects on signal propagation were not accounted for in the imaging formation method.

IV. CONCLUSION

In this paper, we employ squint beamforming for detection of wall back plates, which prevent the EM waves from reaching the indoor scene. The proposed approach avoids the strong direct returns from the front side of the exterior wall, and allows the diffraction for the plate placed against or near to the back side of the wall to be detected. We further aid the squint beamforming with a subspace wall removal technique. Numerical EM simulation results have been provided, which validate the performance of the proposed approach.


(a)

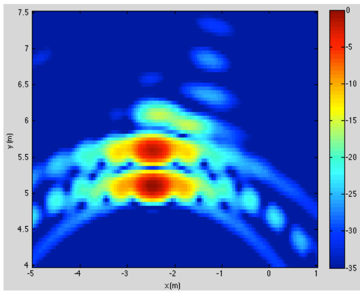
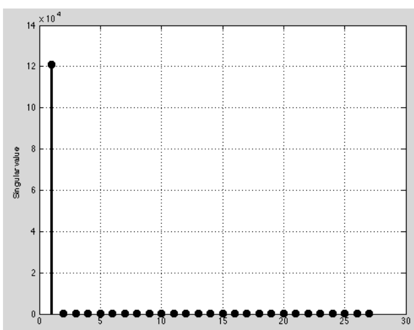

(b)

Fig. 2. Images using the squinted geometries of (a) Array 1, and (b) Array 2.


(a)

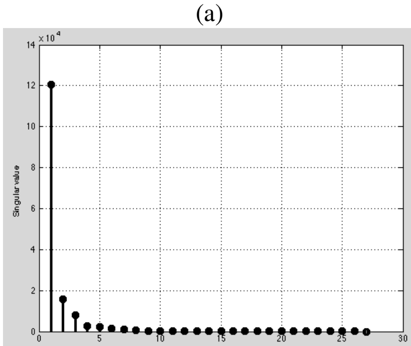
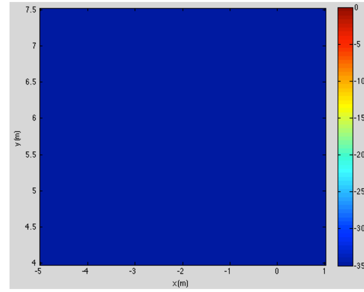

(b)

Fig. 3. Singular values of the data matrix corresponding to (a) Array 1, and (b) Array 2.


(a)

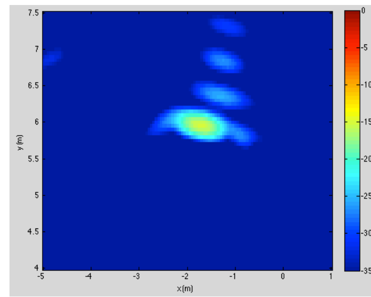

(b)

Fig. 4. Images using the wall-mitigated measurements for the squinted geometries of (a) Array 1, and (b) Array 2.

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REFERENCES

[1] M. G. Amin, *Through the Wall Radar Imaging*, CRC Press, FL, 2010.

[2] M. G. Amin and F. Ahmad, "Through-the-wall radar imaging: theory and applications," in R. Chellappa and S. Theodoridis (Eds.), *Academic Press Library in Signal Processing, Vol. 2: Communications and Radar Signal Processing*, Elsevier, 2013.

[3] H. Burchett, "Advances in Through Wall Radar for Search, Rescue and Security Applications," in *Proc. Inst. of Eng. and Tech. Conf. Crime and Security*, London, UK, June 2006, pp. 511–525.

[4] P. Sevigny and D. J. DiFilippo, "A multi-look fusion approach to through-the-wall radar imaging," in *Proc. IEEE Radar conference*, Ottawa, Canada, 2013.

[5] F. Tivive, A. Bouzerdoum, and M. Amin, "An SVD-based approach for mitigating wall reflections in through-the-wall radar imaging," in *Proc. IEEE Radar conference*, Kansas City, MO, 2011, pp. 519-524.

[6] R. Chandra, A. N. Gaikwad, D. Singh, and M. J. Nigam, "An approach to remove the clutter and detect the target for ultra-wideband through wall imaging," *J. Geophys. Engineer.* vol. 5, no. 4, pp. 412–419, 2008.

[7] F. Ahmad and M. G. Amin, "Wall clutter mitigation for MIMO radar configurations in urban sensing," in *Proc.11th Intl. Conf. Inf. Science, Signal Process., and their Applications*, Montreal, Canada, July 2012.

[8] F. Ahmad, G. J. Frazer, S. A. Kassam, and M. G. Amin, "Design and implementation of near-field, wideband synthetic aperture beamformers," *IEEE Trans. Aerosp. Electronic Syst.*, vol. 40, no. 1, pp. 206-220, Jan. 2004.

[9] F. Ahmad, M. G. Amin, and S. A. Kassam, "A beamforming approach to stepped-frequency synthetic aperture through-the-wall imaging," in *Proc. First IEEE Conf. on Computational Advances in Multi-Sensor Adaptive Processing*, Puerto Vallarta, Mexico, Dec. 2005.