A Beamforming Approach to Imaging of Stationary Indoor Scenes under Known Building Layout

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Abstract— **In this paper, we exploit a priori knowledge of building layout for imaging of stationary scenes associated with through-the-wall radar imaging and urban sensing. More specifically, the support of the part of the image corresponding to the exterior and interior walls is assumed known. This information may be available either through building blueprints or from prior surveillance operations. The contributions of the exterior and interior walls are removed from the data through use of projection matrices, which are determined from wall specific dictionaries. The wall-free data is then processed by delay-and-sum beamforming to obtain the image of the stationary indoor scene. Numerical electromagnetic data is used to demonstrate the effectiveness of the proposed approach.**

I. INTRODUCTION

Through-the-wall radar imaging (TWRI) technology aims at achieving actionable intelligence in a reliable manner for a variety of applications in both civil and military paradigms [1]-[3]. This goal is faced with various challenges, the predominant one stemming from the presence of one or more walls between the radar and the targets. The backscatter from the first wall, which is the exterior wall of the building being imaged, is much stronger than the returns from the interior of the building. This is because the signal undergoes attenuation in the wall materials and the more walls the signal has to go through to reach the indoor targets, the weaker are the returns. Further, the reverberations in the front wall can significantly contaminate the radar data, especially in case of nonhomogeneous walls. All of these factors hinder the main intent of providing enhanced system capabilities for imaging of building interiors and detection and localization of stationary indoor targets. Moving targets are a lesser challenge and are outside the scope of this paper [4].

Several approaches have been proposed for dealing with front wall returns in imaging of stationary scenes [5]-[8]. Among these approaches is the subspace decomposition method [7], [8]. It utilizes the approximately identical wall scattering characteristics across the array elements and also the higher strength of the front wall reflections compared to that of the target reflections. When singular value decomposition (SVD) is applied to the measured data matrix, the wall subspace can be captured by the singular vectors associated with the dominant singular values. As a result, the front wall contributions can be removed by projecting the data measurement vector at each antenna on the wall orthogonal subspace. It is noted that as the round-trip signal traveling times from the antennas to each interior wall, which is parallel to the front wall, are constant across the array aperture, the subspace decomposition method will also mitigate returns from interior parallel walls as long as they are not shadowed by other contents of the building [9].

In this paper, we propose an alternative scheme for imaging of stationary indoor scenes. We assume prior knowledge of the building layout. That is, the support of the part of the image corresponding to the exterior and interior walls is assumed known. This knowledge may be available either through building blueprints or from prior surveillance operations. The radar returns are cast as the sum of reflections from wall and non-wall objects. Focusing on stepped-frequency synthetic aperture radar (SAR) operation, we employ projection matrices that are determined from wall specific scattering responses, which are specular in nature, to remove the exterior and interior wall contributions from the measurements. Then, we proceed to apply delay-and-sum (DS) beamforming to obtain an image of the part of the scene containing the stationary indoor targets. Using numerical electromagnetic (EM) data, we demonstrate the effectiveness of the proposed approach for accurate reconstruction of stationary through-the-wall scenes.

The remainder of this paper is organized as follows. Section II presents the signal model under the assumption of known support of the exterior and interior walls. The wall contribution removal technique and scene reconstruction are discussed in Section III. Section IV evaluates the performance of the proposed approach for through-the-wall scene reconstruction using numerical EM data of a single story building. Conclusions are drawn in Section V.

II. SIGNAL MODEL

Consider a monostatic SAR with N antenna positions located along the x-axis parallel to a homogenous front wall. The transmit waveform is assumed to be a stepped-frequency signal of M frequencies, which are equispaced over the desired bandwidth $\omega_{M-1} - \omega_0$,

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$$\omega_m = \omega_0 + m\Delta\omega, \quad m = 0,1,\cdots,M-1 \tag{1}$$

where ω_0 is the lowest frequency in the desired frequency band and $\Delta\omega$ is the frequency step size. The scene behind the front wall is assumed to be composed of P point targets and L-1 interior walls, which are parallel to the front wall and to the radar scan direction. Due to the specular nature of the wall reflections, a SAR system located parallel to the front wall will only be able to receive backscattered signals from interior walls, which are parallel to the front wall. The contribution of walls perpendicular to the front wall will be captured primarily through the backscattered signals from the corners [10]. Although not part of this work, the corner reflections can be readily incorporated into the signal model and the proposed scene reconstruction approach.

The received signal corresponding to the mth frequency at the nth antenna position, with phase center at $\mathbf{x}_{tn} = (x_{tn}, 0)$, is given by

$$z(m,n) = \sum_{p=0}^{P-1} \sigma_p e^{-j\omega_m \tau_{p,n}} + \sum_{l=0}^{L-1} \sigma_{w,l} e^{-j\omega_m \tau_{w,l}} \tag{2}$$

where σ_p and $\sigma_{w,l}$ are the complex amplitudes associated with the pth target return and the lth wall return, respectively, and $\tau_{p,n}$ and $\tau_{w,l}$ are the respective two-way traveling times between the nth antenna and the pth target and the nth antenna and the lth wall. Note that since the scan direction is parallel to the walls, the delay $\tau_{w,l}$ does not depend on the variable n and is a function only of the downrange distance between the lth wall and the antenna baseline.

Assume that the scene being imaged is divided into a finite number of pixels, say Q, in crossrange and downrange. Let $\mathbf{z}_n$ represent the received signal vector corresponding to the M frequencies and the nth antenna location, and $\mathbf{s}$ be the concatenated scene reflectivity vector of length Q corresponding to the spatial sampling grid. Under the assumption that the building layout is known a priori, $\mathbf{s}$ can be expressed as $\mathbf{s} = [\ \mathbf{s}_1^T \quad \mathbf{s}_2^T\ ]^T$, where $\boldsymbol{s}_1 \in \mathbb{C}^{Q_1}$ is the part corresponding to the walls parallel to the antenna baseline whose support is known, and $\boldsymbol{s}_2 \in \mathbb{C}^{Q_2}$, $Q_2 = Q - Q_1$, is the remaining part of the image containing the stationary indoor targets. Using (2), we can express the nth received signal in matrix-vector form as

$$\mathbf{z}_n = \boldsymbol{A}_n \boldsymbol{s}_1 + \boldsymbol{C}_n \boldsymbol{s}_2 \tag{3}$$

where $\boldsymbol{A}_n$ and $\boldsymbol{C}_n$ are the dictionaries corresponding to the wall and point target, respectively. The $(m,\ q_2)$th element of the $M \times Q_2$ matrix $\boldsymbol{C}_n$ is given by

$$[\boldsymbol{C}_n]_{m,q_2} = \exp\left(-j\omega_m \tau_{q_2,n}\right) \tag{4}$$

where $\tau_{q_2,n}$ is the two-way traveling time between the nth antenna and the q_2th pixel of the image part containing the stationary targets. The wall dictionary $\boldsymbol{A}_n$ is an $M \times Q_1$ matrix, whose (m, q_1)th element takes the form [11]

$$[\boldsymbol{A}_n]_{m,q_1} = \exp\left(-j\omega_m 2y_{q_1}/c\right)\Im_{q_1,n} \tag{5}$$

where y_{q_1} is the downrange coordinate of the q_1th pixel in the image part with known support, and $\Im_{q_1,n}$ is an indicator function, which assumes a unit value only when the q_1th pixel lies in front of the nth antenna. That is, if x_{q_1} represents the crossrange coordinate of the q_1th pixel and δx represents the crossrange sampling step, then $\Im_{q_1,n} = 1$ provided that $x_{q_1} - \frac{\delta x}{2} \le x_{tn} \le x_{q_1} + \frac{\delta x}{2}$.

Equation (3) considers the contribution of only one antenna location. Stacking the measurement vectors corresponding to all N antennas to form a tall vector

$$\mathbf{z} = [\boldsymbol{z}_1^T \quad \boldsymbol{z}_2^T \quad \cdots \quad \boldsymbol{z}_{N-1}^T]^T, \tag{6}$$

we obtain the following representation of the measurement vector:

$$\mathbf{z} = \boldsymbol{A}\boldsymbol{s}_1 + \boldsymbol{C}\boldsymbol{s}_2 \tag{7}$$

where

$$\boldsymbol{A} = [\boldsymbol{A}_0^T \quad \boldsymbol{A}_1^T \quad \cdots \quad \boldsymbol{A}_{N-1}^T]^T, \quad \boldsymbol{C} = [\boldsymbol{C}_0^T \quad \boldsymbol{C}_1^T \quad \cdots \quad \boldsymbol{C}_{N-1}^T]^T. \tag{8}$$

III. Exterior and Interior Wall Contributions Removal and Scene Reconstruction

Given the measurement vector $\mathbf{z}$ and knowledge of the support of the walls, the goal is to reconstruct the part of the image where the stationary indoor targets are located. As such, we first need to remove the contributions of the interior and exterior walls in the scene from $\mathbf{z}$. Let $\boldsymbol{P}_A$ be the matrix of the orthogonal projection from $\mathbb{C}^Q$ onto the orthogonal complement of the range space of the matrix $\boldsymbol{A}$. If $\boldsymbol{A}$ is a full rank matrix, then $\boldsymbol{P}_A$ can be expressed as [12]

$$\boldsymbol{P}_A = \boldsymbol{I}_{MN} - \boldsymbol{A}\boldsymbol{A}^\dagger \tag{9}$$

where $\boldsymbol{I}_{MN}$ is an identity matrix of dimensions $MN \times MN$, and $\boldsymbol{A}^\dagger$ denotes the pseudoinverse of $\boldsymbol{A}$. On the other hand, if $\boldsymbol{A}$ has a reduced rank, then we have to resort to the SVD of $\boldsymbol{A}$ to obtain the matrix $\boldsymbol{P}_A$ as

$$\boldsymbol{P}_A = \boldsymbol{U}_A \boldsymbol{U}_A^H \tag{10}$$

where $\boldsymbol{U}_A$ is the matrix consisting of the left singular vectors corresponding to the zero singular values and the superscript 'H' denotes the Hermitian operation. Applying the projection matrix $\boldsymbol{P}_A$ to the observation vector $\mathbf{z}$, we obtain

$$\mathbf{z}_A \equiv \boldsymbol{P}_A\mathbf{z} = \boldsymbol{P}_A(\boldsymbol{A}\boldsymbol{s}_1 + \boldsymbol{C}\boldsymbol{s}_2) \approx \boldsymbol{P}_A\boldsymbol{C}\boldsymbol{s}_2 \tag{11}$$

Thus, the measurement vector $\mathbf{z}_A$ contains contributions from only the image part, $\boldsymbol{s}_2$, which can then be reconstructed by using delay-and-sum (DS) beamforming [13].

IV. Simulation Results

In this section, we present scene reconstruction results for the proposed technique using numerical EM data and provide performance comparison with the subspace decomposition based wall-mitigation approach [8].

The simulation is based on the Xpatch® EM Simulator. We modeled a single story building, with overall dimensions of 7m×10m×2.2 m, containing four humans (labeled 1 through 4) and several furniture items, as shown in Fig. 1. The exterior

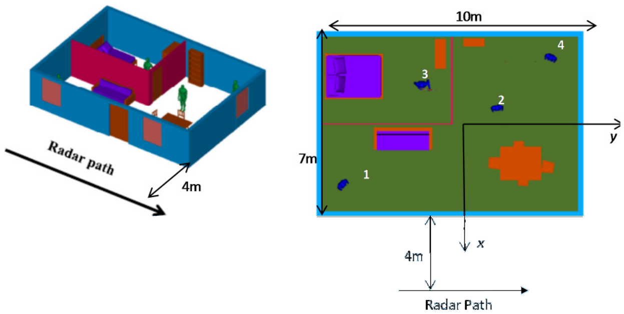


Fig. 1. Building Layout and Contents.

TABLE I
MATERIAL PROPERTIES

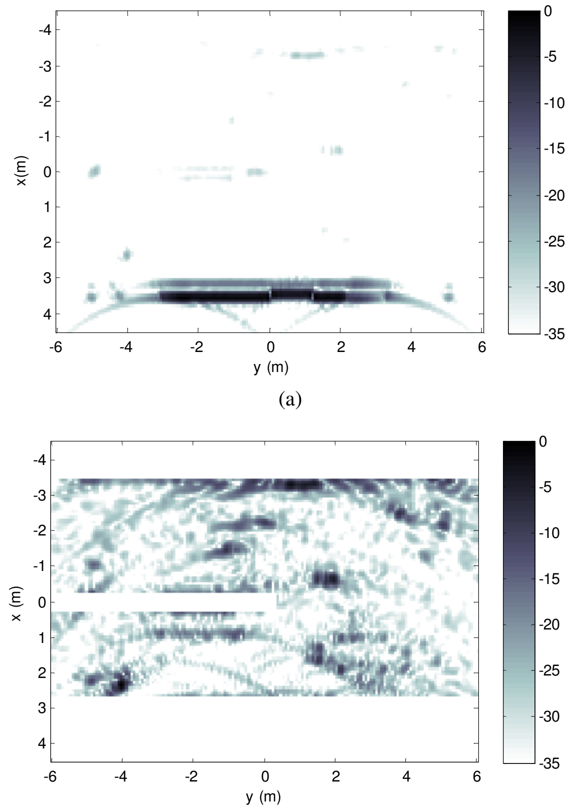
Material	ε'	ε''
Brick	3.8	0.24
Concrete	6.8	1.2
Glass	6.4	0
Wood	2.5	0.05
Sheetrock	2.0	0
Foam Cushion and Fabric	1.4	0
Ground	10	0.6
Human	50	12

walls were made of 0.2 m thick bricks and had glass windows and a wooden door. The interior walls were made of 5 cm thick sheetrock and had a wooden door. The ceiling/roof is flat, made of a 7.5 cm thick concrete slab. The entire building is placed on top of a dielectric ground plane. The furniture items, namely, a bed, a couch, a bookshelf, a dresser, and a table with four chairs, were made of wood, while the mattress and cushions were made of generic foam/fabric material. Humans 1 through 4 were positioned at various locations in the interior of the building with different azimuthal orientation angles. Human 3, positioned inside the interior room, was carrying an AK-47 rifle. The human model was made of a uniform dielectric material with properties close to those of skin [14]. The AK-47 model is made of metal and wood [15], [16]. The dielectric properties of the various materials employed are listed in Table 1.

A 6m long synthetic aperture line array, with an inter-element spacing of 2.54 cm and located parallel to the front of the building at a standoff distance of 4 m, was used for data collection. Monostatic operation was assumed. The antenna was positioned 0.5m above the ground plane and its boresight was aimed perpendicular to the exterior wall. A stepped-frequency signal covering the 0.7 to 2 GHz frequency band with a step size of 8.79 MHz was employed.

The region to be imaged was chosen to be 9 m x 12 m centered at the origin and divided into 121 x 161 pixels, respectively. Fig. 2(a) shows the image obtained with DS beamforming using the raw data. In this figure and all subsequent figures in this paper, we plot the image intensity with the maximum intensity value in each image normalized to 0dB. Hanning window was applied to the data along the frequency dimension in order to reduce the range sidelobes in the image. We can clearly see the front wall, some of the corners, the bookshelf, and humans 1 and 2. Other humans and furniture items cannot be detected due to the strong front wall return. Fig. 2(b) shows the beamformed image after masking out the regions with known support. Although all the targets are visible in the image, the image is highly cluttered due to the presence of the residual sidelobes of the walls.

Next, we reconstructed the scene using the subspace decomposition based wall mitigation approach. The first two dominant singular vectors of the frequency vs. antenna raw data matrix were used to reconstruct the wall subspace. Finally, DS beamforming was performed on the wall clutter mitigated data and the corresponding image is shown in Fig.



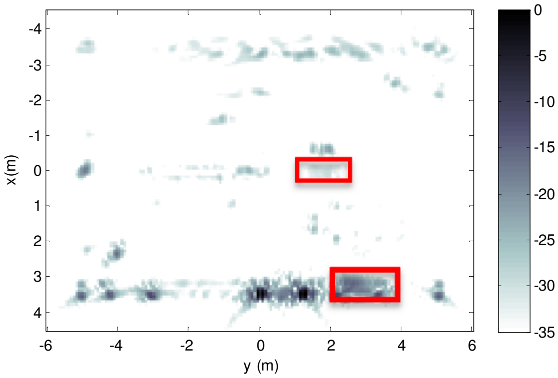
(a)

(b)

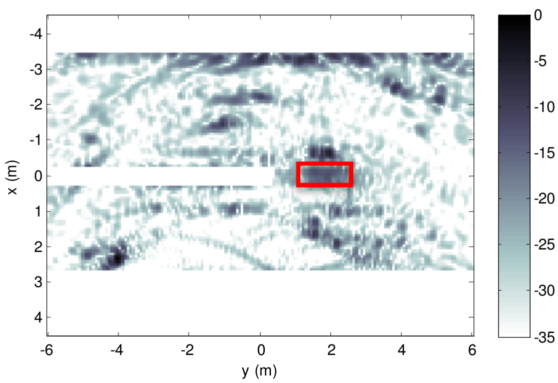
Fig. 2. Results of DS beamforming using raw data. (a) Full image, (b) Image with the support region of exterior and interior walls masked out.

3(a). We observe that although the stationary targets are more visible and the front and interior wall reflections are successfully removed, the corners indicating the presence of doors and windows are still present. So is most of the back wall due to shadowing effects. The approach also removed the reflections from the edge of the couch and only the couch corners survive. More importantly, the presence of discontinuities in the front wall (windows and door) causes the subspace decomposition based approach to introduce artifacts in the image, indicated by the red rectangles. Such artifacts in the interior of the building are more visible in Fig. 3(b), which shows the image after masking out the regions with known support.

Finally, Fig. 4 presents the beamformed image obtained using the proposed approach. Compared to Figs. 2(b) and 3(b),



(a)



(b)

Fig. 3. Results of DS beamforming after application of the subspace decomposition based technique for wall mitigation. (a) Full image, (b) Image with the support region of exterior and interior walls masked out.

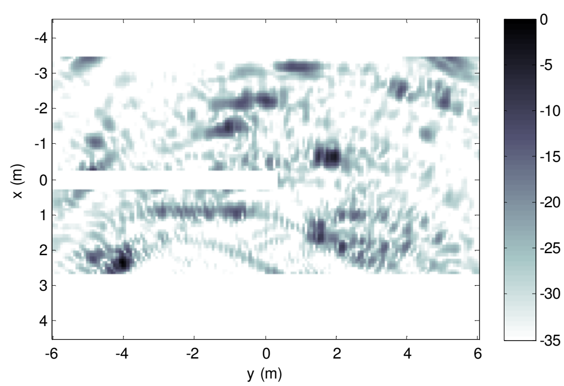


Fig. 4. Results of DS beamforming after application of the proposed technique.

the image in Fig. 4 is the least cluttered since the residual sidelobes, in particular near the back wall, are absent. All of the humans and the furniture items are clearly visible in the image. We, therefore, conclude that the proposed approach provides superior performance compared to the subspace decomposition based wall mitigation approach.

V. Conclusion

In this paper, we exploited the prior knowledge of building layout for indoor scene reconstruction associated with through-the-wall radar imaging of stationary targets. For the underlying problem, the support of the part of the scene corresponding to the building layout was assumed known beforehand. The contributions of the exterior and interior walls were removed through projection matrices, which are determined for wall specific dictionaries. An image of the indoor scene was reconstructed by applying DS beamforming to the wall-free data. Using numerical EM data of a single-story building, we demonstrated the effectiveness of the proposed approach in detecting and locating stationary targets in through-the-wall scenes.

Acknowledgment

This work is supported by ARO and ARL under contract W911NF-11-1-0536.

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