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Multistatic 3-D microwave imaging with dynamic metasurface antennas: a Fourier-based approach

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ABSTRACT

This paper proposes a novel approach to 3-D microwave imaging using dynamic metasurface antennas in a multistatic configuration. By introducing a panel-to-panel model and a preprocessing technique, raw measurements are converted into the space-frequency domain for efficient data acquisition and reconstruction. Adapting the range migration algorithm in this work enables fast Fourier-based image reconstruction. Simulation results showcase the effectiveness of the proposed method, highlighting its potential for real-world applications.

Keywords: Adapted range migration algorithm, dynamic metasurface antennas, near-field multistatic microwave imaging, 3-D image reconstruction

1. INTRODUCTION

Microwave imaging plays a crucial role in various applications such as biomedical diagnostics, concealed weapon detection and nondestructive testing [1-5]. Traditional imaging systems often rely on mechanical or electronic raster scans (by sequentially switched arrays), which can be slow and power-hungry [6]. Dynamic metasurface antennas (DMAs) [7] offer a promising alternative due to their small form-factor, reduced power consumption, and ease of fabrication [8, 9]. However, the unique radiation patterns of DMAs pose challenges for fast Fourier-based image reconstruction algorithms [10, 11] due to physical layer compression [12]. An effective solution for this issue, using sub-wavelength sampling of the aperture, is detailed in [13-16], which outlines how measurements can be expressed in the spatial domain. These studies employ a panel-to-probe model, utilizing a single 1-D DMA on the transmitter (TX) side and a rectangular waveguide probe (point source) on the receiver (RX) side. In this configuration, either the TX DMA or the RX must physically move to create a large effective aperture and capture 2-D/3-D images of the scene from the collected data. However, this approach lowers data acquisition rates and is not suitable for real-time applications.

Although the approach presented in [17] provides a panel-to-panel model with full electronic scanning, it is limited to a bistatic structure. In this paper, we introduce a panel-to-panel model by employing DMAs in a more general imaging structure (i.e. multistatic) to address the challenges mentioned above. We present a preprocessing technique to convert raw measurements into the space-frequency domain, enabling efficient data acquisition and reconstruction. By adapting the range migration algorithm (RMA) to the imaging system configuration, we achieve 3-D image reconstructions with fast Fourier calculations. Key contributions include introducing a panel-to-panel model in a multistatic structure, presenting a preprocessing technique with data collected from all channels, and deriving a mathematical solution for scene image reconstruction based on fast Fourier computations. The effectiveness of the proposed method is investigated and discussed through numerical simulations.

The rest of this paper is organized as follows. Section 2 covers the proposed approach, detailing the system model, preprocessing procedure and 3-D image reconstruction algorithm. Section 3 presents and discusses the simulation results. Finally, Section 4 offers the conclusion.

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Notation: Throughout the paper, superscripts $(\cdot)^T$ and $(\cdot)^\dagger$ represent the transpose and pseudo-inverse, respectively. The symbols j , δ denote the imaginary unit and Dirac delta function, respectively.

2. PROPOSED APPROACH

Figure 1 depicts a general layout of the proposed multistatic imaging system. This system uses N_T DMAs for transmission along the horizontal x -axis and one DMA for reception along the vertical y -axis. Each TX and RX DMA is a 1-D array with N_x and N_y metamaterial elements, respectively, with d_x and d_y inter-element spacing. The metamaterial elements are loaded with reconfigurable structures, such as PIN or varactor diodes, to control their radiation characteristics [18]. The system varies the radiation patterns by adjusting the operating frequency f [19-21] and/or tuning the voltage of the diodes, which randomly activates or deactivates the metamaterial elements to create different masks [22]. Each TX DMA can generate multiple measurements by cycling through M_T masks. Objects in the scene scatter the incident fields, which are then detected by the RX DMA with M_R masks. The number of masks influences the system's diversity and complexity [23].

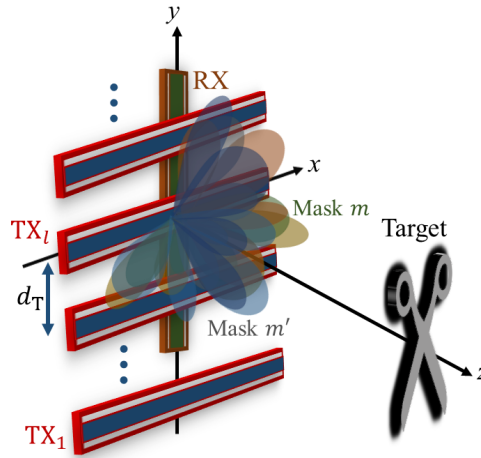


Figure 1. The general layout of the proposed multistatic imaging system.

The measurement signal can be represented as [23]

$$g_{l,m,m'}(f) = \int_V U_m(y_l, \vec{r}, f) \rho(\vec{r}) U_{m'}'(\vec{r}, f) dV, \quad l = 1, 2, \dots, N_T, \quad m = 1, 2, \dots, M_T, \quad m' = 1, 2, \dots, M_R, \quad (1)$$

where $dV = dx dy dz$ denotes a small volume element made of space intervals dx , dy and dz in the directions x , y and z , respectively, $y_l = y_1 + ld_T$ is the vertical position of the l -th Tx, ρ is the target reflectivity [24], and \vec{r} is the position vector to a point in the scene. U and U' are the radiated fields from the TX and RX apertures, which are superpositions of the fields from all metamaterial elements, and are calculated by (2) from [23].

The measured signal on the aperture plane, expanded in terms of fields associated with all masks, is [23]

$$g_{l,m,m'}(f) = \sum_{i=1}^{N_x} \sum_{i'=1}^{N_y} \Phi_{l,m}(x_i, f) s_i(x_i, y_{i'}, f) \Phi_{m'}'(y_{i'}, f), \quad (2)$$

where $s_i(x_i, y_{i'}, f)$ represents the incident field at the location of the l -th TX, and x_i and $y_{i'}$ correspond to the positions of TX and RX, respectively. The fields over the aperture corresponding to the masks, $\Phi_{l,m}$ and $\Phi_{m'}'$, are a function of wave impedance in free space, guided magnetic field, polarizability and propagation constant of the waveguide, the details of their calculation are given in [22, 25].

Assuming orthogonal aperture modes [23]

$$\sum_{i=1}^{N_x} \Phi_{l,m}(x_i, f) \Phi_{l,\tilde{m}}^\dagger(x_i, f) = \delta[m - \tilde{m}], \quad \tilde{m} \in [1, M_T], \quad (3)$$

$$\sum_{i'=1}^{N_y} \Phi_{m'}^\dagger(y_{i'}, f) \Phi_{m'}(y_{i'}, f) = \delta[\tilde{m}' - m'], \quad \tilde{m}' \in [1, M_R]. \quad (4)$$

With dynamic modulation of the aperture using different masks, the measurement signal can be transformed and estimated as [22]

$$s_l(x_i, y_{i'}, f) = \sum_{m=1}^{M_T} \sum_{m'=1}^{M_R} \Phi_{l,m}^\dagger(x_i, f) g_{l,m,m'}(f) \Phi_{m'}^\dagger(y_{i'}, f). \quad (5)$$

This allows fast Fourier calculations for data processing, expressed in matrix form as [26]

$$\mathbf{s}_l(f) = \mathbf{\Phi}_l^\dagger(f) \mathbf{g}_l(f) (\mathbf{\Phi}^{TT}(f))^\dagger. \quad (6)$$

By using the system geometry and 3-D Fourier transforms, the signal in the wavenumber domain is [23]

$$S(k_{xT}, k_{yT}, k_{yR}, k) = \frac{K}{16\pi^2} \int_V \rho(x, y, z) e^{-jk_{xT}x} e^{-j(k_{yT}+k_{yR})y} e^{-j\sqrt{k^2-k_{xT}^2-k_{yT}^2}z} e^{-j\sqrt{k^2-k_{yR}^2}z} dV, \quad k^2 \geq k_{yR}^2, \quad k^2 \geq k_{xT}^2 + k_{yT}^2, \quad (7)$$

where $k = 2\pi f/c$, c denotes the speed of light, and K is the filtering factor in the Fourier domain [23]. Finally, by performing Stolt interpolation and applying inverse Fourier transforms, the reflectivity $\rho(x, y, z)$ can be recovered [23, 26].

Note that in conventional systems with independent antennas, the field is described by Green's function, while DMAs encode scene information through their random transfer function, eliminating the need for point-by-point sampling but requiring more complex signal descriptions. The preprocessing in (6) transforms DMA measurements into data equivalent to that from traditional antenna arrays.

3. SIMULATION RESULTS AND DISCUSSION

In this section, the performance of the proposed approach is evaluated using numerical simulations conducted in MATLAB. The simulations were carried out on a system running MATLAB R2020b on a 64-bit Windows 11 operating system, equipped with 16 GB of random-access memory and a Core-i7 processor clocked at 2.8 GHz. The data used in the numerical examples were generated using the model described in (1), under the first Born approximation [27]. The simulation parameters are listed in Table 1, where λ denotes the wavelength corresponding to the highest frequency in free space, N_f indicates the number of frequency samples, z_0 is the target range.

Table 1. The values of the main simulation parameters.

Parameter	$N_x = N_y$	N_T	$d_x = d_y$	d_T	$M_T = M_R$	f	N_f	z_0
Value	105	3	$\lambda/2$	26λ	105	17.5-22 GHz	51	0.5 m

Before reconstructing the image, it is important to verify the condition outlined in (3) and (4). Figure 2 displays the aperture field matrices $\mathbf{\Phi}_1$, $\mathbf{\Phi}_2$, $\mathbf{\Phi}_3$ and $\mathbf{\Phi}'$ at 22 GHz for a random scenario where half of the elements in each mask are randomly activated. Figures 3(a)-3(d) depict $\mathbf{\Phi}_1\mathbf{\Phi}_1^\dagger$, $\mathbf{\Phi}_2\mathbf{\Phi}_2^\dagger$, $\mathbf{\Phi}_3\mathbf{\Phi}_3^\dagger$ and $(\mathbf{\Phi}^{TT})^\dagger\mathbf{\Phi}^{TT}$ at 22 GHz, respectively, showing that it satisfies conditions (3) and (4), making it viable for the preprocessing step. In addition, Figures 3(e) and 3(f) show $\mathbf{\Phi}_1\mathbf{\Phi}_2^\dagger$ and $\mathbf{\Phi}_1\mathbf{\Phi}_3^\dagger$ at 22 GHz, respectively. The non-orthogonality between the aperture field matrices corresponding to different TXs is the key property used in [23] to recover contributions of TXs in a scenario where they transmit simultaneously. Similar analyzes can be performed for other frequencies.

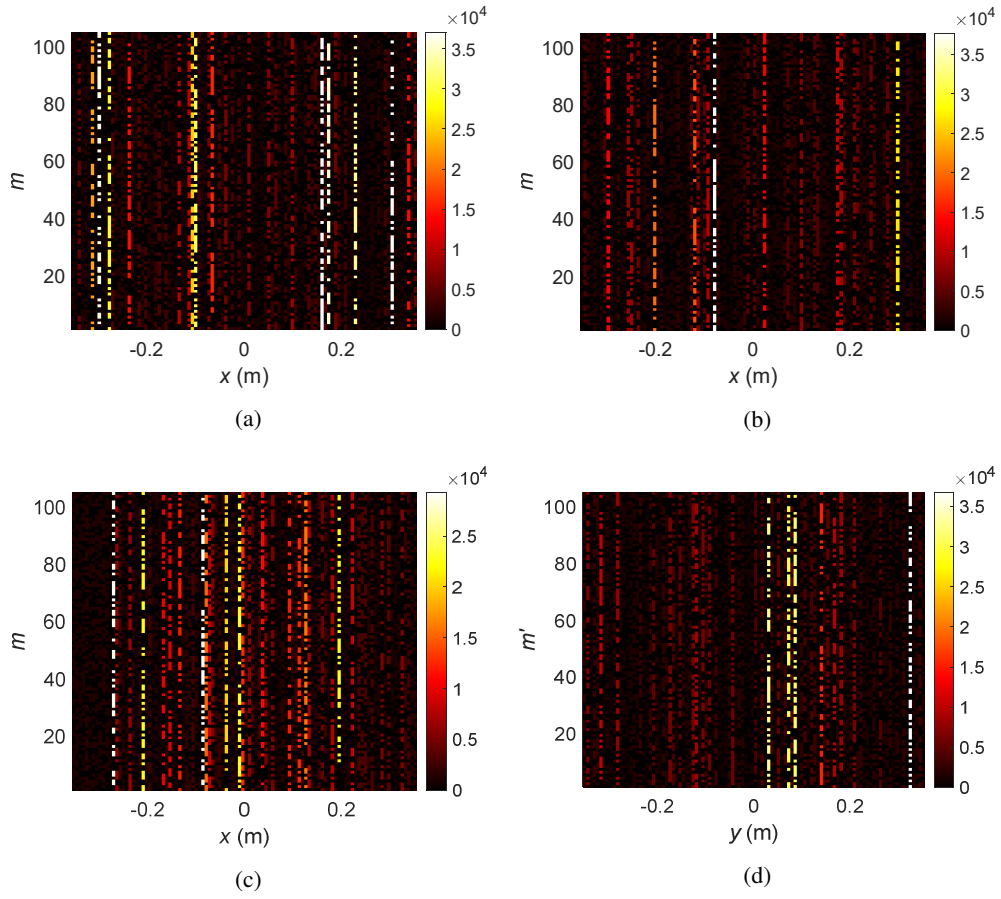


Figure 2. The aperture field matrices at 22 GHz for a random scenario; (a) Φ_1 , (b) Φ_2 , (c) Φ_3 , (d) Φ' .

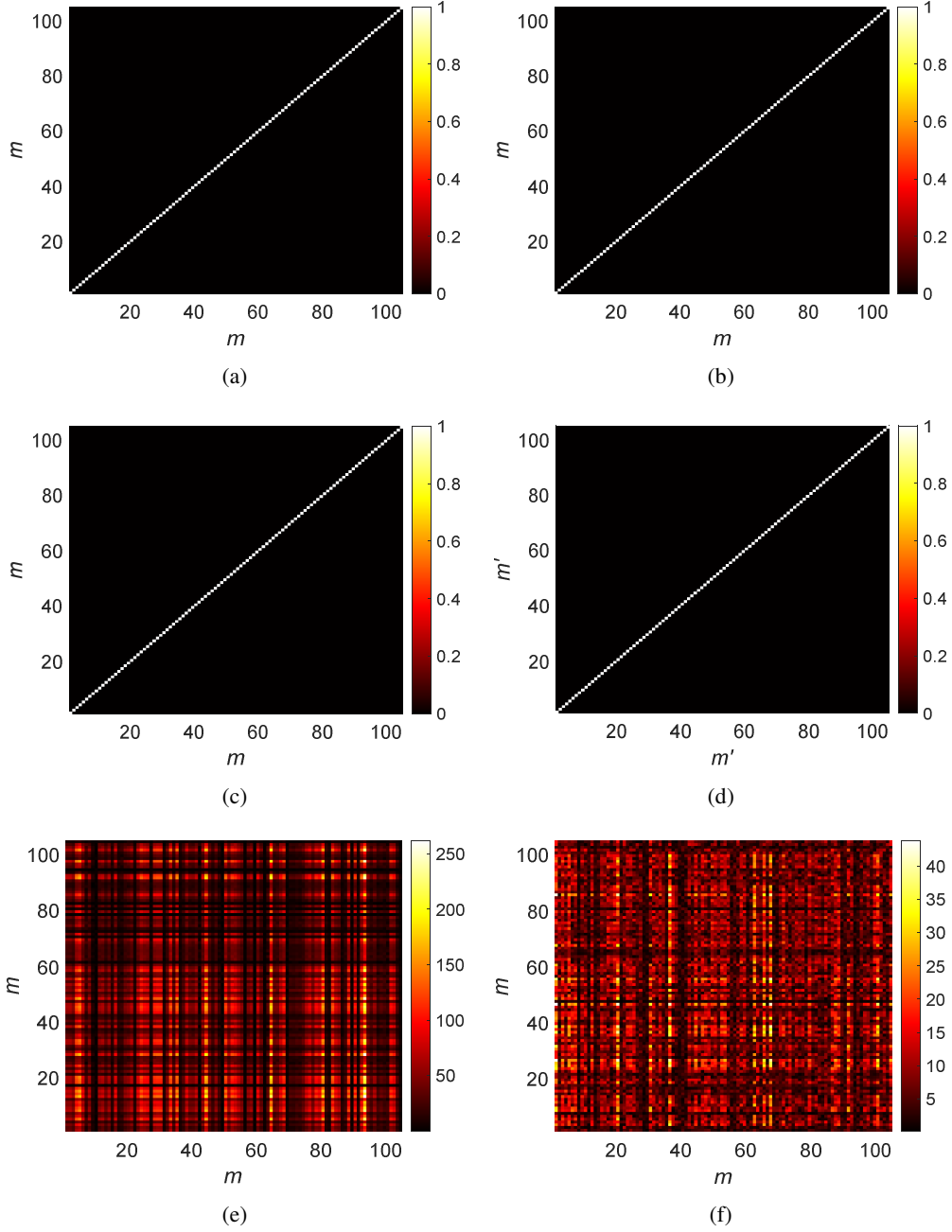


Figure 3. Checking the orthogonality between the aperture field matrices at 22 GHz; (a) $\Phi_1\Phi_1^\dagger$, (b) $\Phi_2\Phi_2^\dagger$, (c) $\Phi_3\Phi_3^\dagger$, (d) $(\Phi^{rT})^\dagger\Phi^{rT}$, (e) $\Phi_1\Phi_2^\dagger$, (f) $\Phi_1\Phi_3^\dagger$.

For further study, we calculated the average value of condition number r , which is defined as the ratio of the largest to the smallest singular values of the aperture field, in 1000 independent experiments for different numbers of masks and percentage of active elements (denoted by P). Ideally, the condition number should be 1, suggesting a flat singular value decomposition pattern [28, 29]. This would mean that the orthogonality of the measurement modes is perfect. The results, shown in Figure 4, indicate that as P increases, the value of r also increases, meaning lower percentages of activated metamaterial elements provide more reliable orthogonality conditions [22]. However, fewer activated elements

also result in lower radiated power, leading to a reduced signal-to-noise ratio [22]. Therefore, a moderate P value (with half the elements activated) offers a balanced trade-off between orthogonality and noise robustness.

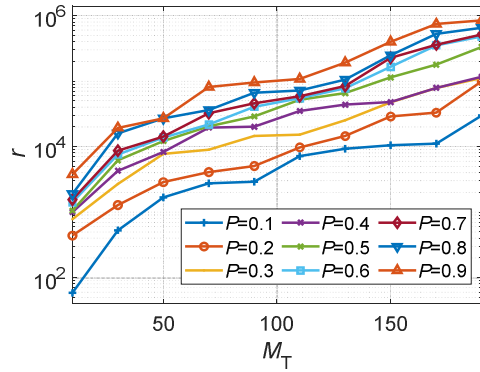


Figure 4. The average value of r in 1000 independent experiments in the case of Φ_1 at 22 GHz.

Now let us examine the performance of the image reconstruction algorithm. A 3-D distributed target (scissors) is considered in the near-field [30] scenario (see Figure 1). Figure 5 shows the successfully reconstructed image of the target using the proposed approach. The total computational time for implementing the image reconstruction algorithm is 13.33 seconds. The main steps of implementing the algorithm, including a preprocessing operation to convert the raw measured data to the spatial-frequency domain, fast Fourier transform (FFT), 4-D to 3-D Stolt interpolation and inverse FFT, take 11.71%, 4.8%, 83.05% and 0.44% of the total computing time, respectively. As can be seen, most of the computational burden is related to the Stolt interpolation step. Note that the computational time of the proposed approach is much less compared to algorithms such as least squares, matched filtering and generalized synthetic aperture focusing technique [31]. For more details on the comparison of computational times and computational complexities, see [23].

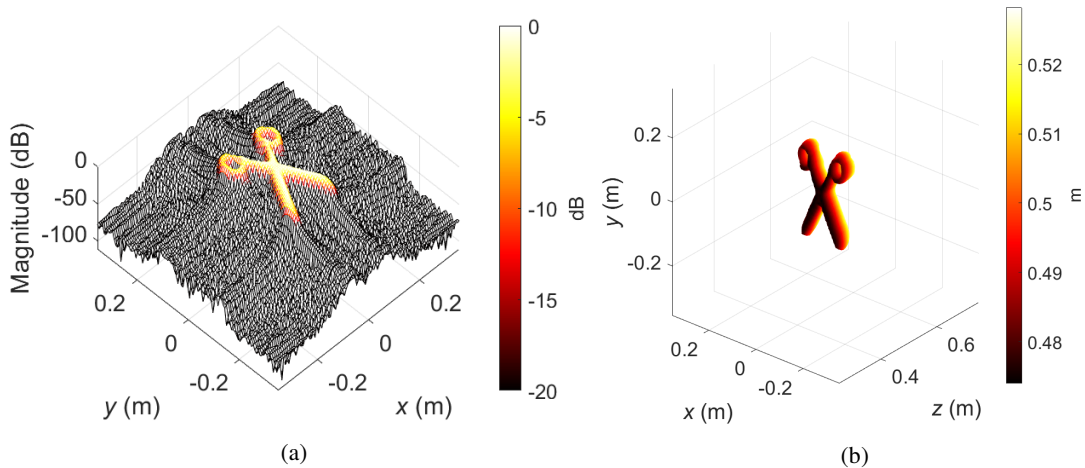


Figure 5. The reconstructed image using the proposed approach; (a) mesh surface plot focused on $z_0 = 0.5\text{m}$ (colorbar is on the dB scale and represents the normalized reflectivity magnitude), (b) isosurface with 3-D view (colorbar is range-coded, representing the distance).

4. CONCLUSION

In this paper, we presented a novel approach to 3-D microwave imaging utilizing DMAs in a multistatic configuration. Our method introduces a panel-to-panel model that significantly improves data acquisition efficiency and enables fast Fourier-based image reconstruction. By employing a preprocessing technique to convert raw measurements into the space-frequency domain and adapting the RMA for this configuration, we demonstrated an effective 3-D image reconstruction. The simulation results validated the proposed method’s efficacy, showing that it achieves accurate imaging with low computational time. This approach opens new avenues for real-time, high-resolution imaging in

various applications, including security screening and biomedical diagnostics. Future work will focus on further optimizing the system for real-world deployment.

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