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Modified 2D Backprojection Decomposition for 3D Imaging in Through-the-Wall Applications

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Abstract—Through-the-wall (TTW) radar imaging techniques are a promising research area for the radar community. These techniques are useful for detecting and identifying objects that are hidden behind walls making them a valuable tool for a variety of applications. The present study aims to develop a method for achieving 3D imaging using TTW radar by rotating 2D Backprojection (BP) planes. This approach is expected to provide an efficient and effective means of obtaining 3D images of hidden targets.

Index Terms—synthetic aperture radar, electromagnetic simulations, Snell-Descartes laws, 3D imaging, backprojection.

I. INTRODUCTION

Through-the-wall (TTW) radar techniques involve electromagnetic (EM) waves to detect, characterize, and image targets that are located behind obstacles such as walls. By analyzing the scattered waves produced when an EM wave encounters an object, it is possible to infer various properties of the object, such as its permittivity, size, and position. This information can be used to create an image of the object and its surroundings, allowing the operator to identify and track targets even when they are hidden from view.

One specific type for TTW radar imaging system is Synthetic Aperture Radar (SAR). Using SAR systems, one can determine the position of the hidden target by considering the characteristics of the wall and spatial positions of the Tx/Rx antennas. Snell-Descartes laws, which describe the behaviour of EM waves as they travel through different materials, are often used to identify the shortest wave trajectory [1] between Tx/Rx antennas and target (i.e. the round-trip delay). The Backprojection (BP) imaging algorithm [2] can then be used to compensate for this delay in order to locate the target.

In this study, the BP algorithm is proposed for determining the target shape using 2D assumptions instead of more complex 3D imaging techniques such as Diffraction Tomography (DT) [3] or Kirchhoff Migration (KM) [4]. The second section presents the problem formulation, and the third one details the characteristics of the analyzed scene, including a comprehensive discussion of walls, targets, and the relevant radar system. Numerical validations of the model are presented and discussed in this section.

II. PROBLEM FORMULATION

The geometrical optics assumption [5] is utilized as illustrated in Fig.1.a. In the 3D assumption, the idea is to generate new BP planes by rotating the BP 2D plane around the stripmap axis (here x -axis). As shown in Fig.1.b, a new

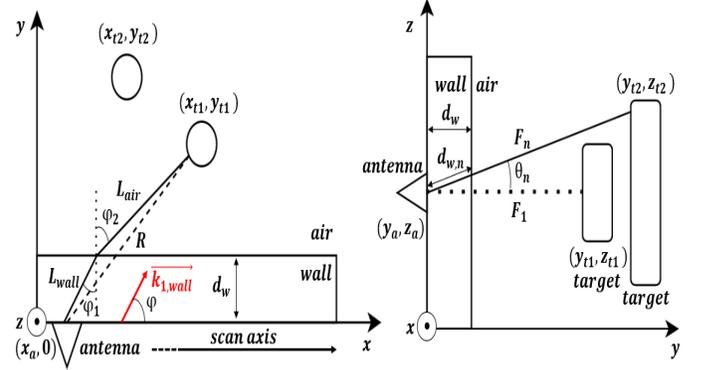


Fig. 1. 2D representations, (a) left: top view, (b) right: side view.

plane is defined and the BP algorithm is performed on it. To do so, the horizontal plane is defined as the first frame F_1 . Then the rotation matrix $R_{\theta_n}(x)$ is applied to F_1 to obtain every other frame F_n that is required, as shown in Fig.1.b.

$$F_n = F_1 \times R_{\theta_n}(x) \quad (1)$$

$$\text{with } R_{\theta_n}(x) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_n & -\sin \theta_n \\ 0 & \sin \theta_n & \cos \theta_n \end{pmatrix}.$$

Let define $k_{1,wall}$ as the wave vector inside the wall of the frame F_1 . In a 2D incident case, thanks to Snell-Descartes laws, the wave vector can be written as:

$$k_{1,wall} = \begin{pmatrix} k \cdot \sin \varphi \\ k \cdot \cos \varphi \\ 0 \end{pmatrix} \quad (2)$$

with $k = \frac{2\pi f}{v}$ the wavenumber, f the frequency, $v = \frac{c}{n_{wall}}$ the speed of the wave inside the wall, c the free space light celerity, n_{wall} the wall refractive index, and φ the refraction angle due to the index difference between the wall and the air.

Using the rotation matrix, it is possible to determine $k_{n,wall}$ (the wave vector inside the wall of the frame F_n) from $k_{1,wall}$ (the wave vector inside the wall of the frame F_1):

$$k_{n,wall} = \begin{pmatrix} k \cdot \sin \varphi \\ k \cdot \cos \varphi \cdot \cos \theta_n \\ k \cdot \cos \varphi \cdot \sin \theta_n \end{pmatrix} \quad (3)$$

Initially, the x component of $k_{n,wall}$ does not depend on θ_n which means the $k_{n,wall}$ is invariant along the x -axis. Yet

the y component can be rewritten as $\cos \theta_n = \frac{d_w}{d_{w,n}}$, where d_w is the wall thickness and $d_{w,n}$ the optical length through the wall of the frame \mathbf{F}_n . Then, to use the 2D BP algorithm for the proposed 3D extension, one has to use $d_{w,n} = \frac{d_w}{\cos \theta_n}$ for the evaluation of the propagation delay of the wave along the frames \mathbf{F}_n .

This rotation allows us to determine the duration time $\tau_{p,n}$ needed for the wave to travel from the transmitting antenna to the point of interest in the frame \mathbf{F}_n :

$$\tau_{p,n} = \frac{1}{v} \frac{d_{w,n}}{\cos(\varphi_{n,1})} - \frac{1}{c} \frac{d_{w,n}}{\cos(\varphi_{n,1})} \cos(\varphi_{n,1} - \varphi_{n,2}) + \frac{1}{c} \sqrt{(R_n^2 - \frac{d_{w,n}^2}{\cos(\varphi_{n,1})^2} \sin(\varphi_{n,1} - \varphi_{n,2})^2)} \quad (4)$$

with R and $d_{w,n}$ shown Fig.1.a and $\varphi_{n,1}$ and $\varphi_{n,2}$ the refraction angles of the scene of the frame \mathbf{F}_n due to the index difference between the wall and the air.

III. NUMERICAL VALIDATION

A. Scene

Radar data are generated using gprMax [6], an FDTD solver. The scene shown in Fig.1 is a rectangular cuboid of $2.5 \times 2.5 \times 1$ meters. The wall is homogeneous, it measures 2.5m by 1m with its thickness $d_{w,1} = 0.2$ m and has a relative permittivity $\epsilon_r = 3$. The radar system has a monostatic configuration composed of collocated Tx/Rx antennas emitting monopulses with a center frequency of 2 GHz expressed as $g(t) = -2\xi(t - \chi)e^{-\xi(t-\chi)^2}$, with $\xi = 2\pi^2 f^2$, $\chi = \frac{1}{f}$ and t the time. The radar system travels along the 2.5m of the wall at a height of 0.5m with a step of 0.025m. The targets are perfect electrical conductor (PEC) cylinders, one of 0.7m length and 0.2m diameter with the centre located at $x_{t1} = 1.6$ m and $y_{t1} = 1.7$ m and the other one of 0.5m length and 0.1m diameter with the centre located at $x_{t2} = 0.9$ m and $y_{t2} = 1.8$ m.

B. 3D Backprojection imaging

Applying the 2D BP algorithm on the frame \mathbf{F}_1 (Fig.1.a), the actual position of the targets are identified using 2D imaging as seen in Fig.2. In addition, looking at the cutting planes located on the coordinates of the target positions makes it possible to distinguish the shapes of the two cylinders on each plane. In Fig.3.a the reconstructed spot corresponds to a smaller and thinner cylinder. Contrarily to the one shown in Fig.3.b that corresponds to a longer and thicker cylinder. Yet, for small dielectric targets, the result is still the same. In this context, the targets are symmetrical with respect to the scan rotation axis. In order to use the same imaging technique for non-symmetrical targets, it is sufficient to break the symmetry axis.

IV. CONCLUSION

A technique has been proposed for achieving 3D imaging while relying only on 2D assumptions. This approach results in reduced computation and measurement time. Using the right

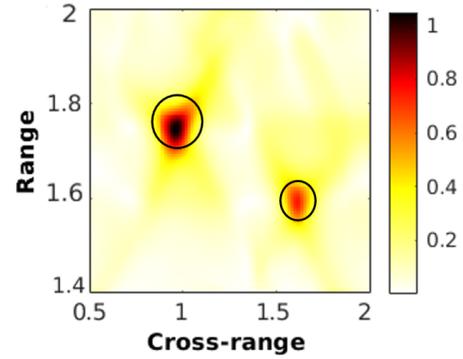


Fig. 2. 2D Backprojection imaging at $z = 0.5$ m (linear representation).

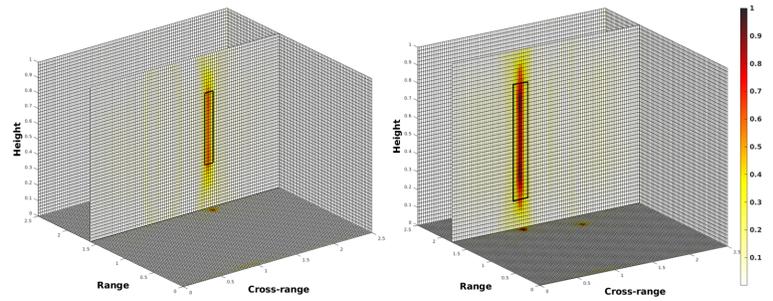


Fig. 3. 3D Backprojection imaging (a) of target 1 and (b) of target 2 (linear representation).

acquisition/probing strategy, it is even possible to image non-symmetrical shapes.

However, as noted earlier, this method is applicable to small angles around the SAR system axis. Future research could focus on exploring the impact of the z -component of the wave vector and devising methods to compensate for it. Currently, efforts are underway to develop the necessary hardware to perform measurements and test the algorithms.

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