The Study of Imaging Methods for Sparse Targets through Walls with Fuzzy Wall Geometry Parameters

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Abstract. Multipath exploitation has been successfully applied in through-the-wall radar imaging given prior knowledge of the room geometry. Actually, the prior information of the walls is generally not known. A Contraposition Subtraction (CONS) algorithm is proposed to solve the problems of poor wall parameter reconstruction accuracy and extremely high initial value requirements of iterative algorithms under fuzzy wall geometry, and the CONS algorithm model is established to solve the problems of high initial value requirements of traditional quasi-Newton algorithms and improved quasi-Newton-particle swarm optimization algorithms. The estimates obtained have large errors and other problems. The CONS algorithm combined with the Block Orthogonal Matching Pursuit (BOMP) algorithm can not only accurately reconstruct the position of the sidewalls, but also reconstruct the moving and stationary targets, which improves the limitations and accuracy of the algorithm to a certain extent. The simulation results and data analysis verify the performance of the proposed method.

1. Introduction
Through-the-wall radar imaging is based on the use of radio frequency (RF) signals through the walls of buildings to sense the target behind the wall and thus recover the scene and geometry behind the obstacle, and its non-destructive detection makes it widely used in both military and civilian applications [1].

In the actual work process of wall-through radar, the emitted signals are mainly reflected between fixed targets, walls, ceilings, and moving targets in the room. Not all signals received by the receiver are returned directly to the receiver, some of which are returned through the above indirect paths, and these signals that return to the receiver through the indirect paths are called multipath signals. In the current research on wall-through radar imaging, on the one hand, the accuracy of imaging can be improved by suppressing the multipath effect [2, 3], and on the other hand, when reconstructing the scene behind the wall and the room geometry, we can make use of some useful information implicit in the multipath effect, which can lead to a great improvement in the image quality of the reconstructed target. This was verified by the work done by Leigsnering M and Ahmad F in the literature [4, 5].

People mostly use the wall location parameters and other information as a priori conditions when reconstructing behind-wall targets and behind-wall scene information with wall-through radar, but in practice, the wall parameters are often unknown. The wrong wall location populate the reconstructed image with false targets. The authors in the literature [6] first assumed equal attenuation in isotropic
targets and all propagation paths, and overcame these limitations by using sparse mixing criteria optimization, resulting in improved image quality of the reconstructions. However, their work still takes the geometry of the building as a priori information. The authors in the literature [7] explored the case where the initial values are very close to the true values of the sidewalls’ location parameters and image the scene behind the wall, although this algorithm requires people to have a very precise prior estimate of the wall location parameters. However, people will not have a very precise estimation of the sidewalls’ location parameters in the actual case. To solve the above problems, this paper proposes an imaging algorithm named CONS, for stationary and moving targets in the case of ambiguous sidewall geometric parameters. This algorithm exploits the multipath effect to accurately reconstruct the behind-the-wall geometric scene and behind-the-wall targets in the case where people are unable to make accurate estimates of wall position information.

2. Emission signal model and multipath model under fuzzy wall parameters

2.1. Emission signal model
The emission model used in this paper assumes that M pairs of antennas are placed parallel to the front wall, with N samples taken at each location. The transmitting antenna $T_m (m = 0, 1, 2, \ldots, M - 1)$ send $G$ Gaussian pulses $s(t)$ to the scan area.

$$s(t) = -2\xi e^{-\frac{\xi}{2} (t - \alpha)}$$  \hspace{1cm} (1)

The receiving antenna $R_n (m = 0, 1, 2, \ldots, M - 1)$ receives the signals, it is sent by the $m$th transmitting antenna and the signal received by the $n$th sampling point can be represented as $R_{mn}$

$$R_{mn}(t) = \sum_{g=0}^{G-1} \sum_{p=0}^{P-1} \sigma_{gp}s(t - \tau_{gp,mn}),$$  \hspace{1cm} (2)

Where $\sigma_{gp}$ is the total reflectivity coefficient of target $p$ when the signal goes through the $g$th path, $G$ is the number of multipath arrivals per target, while $g = 0$ represents the direct path, $P$ is the target number.

2.2. Multipath signal model
The multipath model in this paper is shown in Figure 1. In the real environment, multipath paths are very complex, but higher-order multipaths have less impact on imaging, so we only consider first-order multipaths here. The point target $A$ in the figure has six first-order multipaths, $p_1 \sim p_6$, $p_3$ and $p_4$ are the straight paths. B and C are the virtual targets of target $A$ regarding the symmetry of the sidewalls on both sides. In order to simplify the analysis problem, the multipath effect on the back wall is not considered in this paper.

The imaging region is uniformly divided into $K \times L$ grids and set over the complete dictionary matrix $\mathbf{D} = \text{diag}\{\mathbf{D}^{(0)}, \mathbf{D}^{(1)}, \ldots, \mathbf{D}^{(G-1)}\}$ as a composite dictionary matrix, where $\mathbf{D}^{(0)}$ is a sub-dictionary.
matrix canonical matrix corresponding to either multipath route and \( \alpha^{(p)} \) represents the associated coefficient vector.

\[
\text{Figure 1. Multipath model.}
\]

3. Contraposition Subtraction

Previous estimation algorithms require a high initial estimate of the wall. When the initial estimate is inaccurate, the estimated wall value significantly deviates from the true value. To solve these shortcomings, we propose the CONS algorithm.

The imaging area in the actual imaging process is divided into \( K \times L \) imaging grids along the distance and azimuth directions, where \( g \) represents the index of the grid position. Then the distance between the \( m^{th} \) transmitting antenna position and the \( g^{th} \) grid for the direct path can be obtained by the formula 4.

\[
L_g(Tx_m) = \sqrt{(x_g - (m-1)\Delta x)^2 + (y_g + h)^2}
\]

The distance between the \( m^{th} \) receiving antenna position and the \( g^{th} \) grid for the direct path as:

\[
L_g(Ry_m) = \sqrt{(x_g - (m-1)\Delta x + \Delta L)^2 + (y_g + h)^2}
\]

\( \Delta L \) is the relative fixed distance between the \( m^{th} \) transmitting antenna and the \( m^{th} \) receiving antenna. Then for the \( m^{th} \) scanning position, the electromagnetic wave two-way delay is:

\[
\tau_g(m) = \frac{L_g(Tx_m) + L_g(Ry_m)}{c},
\]

where \( c \) is the rate of propagation of electromagnetic waves in air. The final pixel value corresponding to the grid as:

\[
f_0(x_g, y_g) = \int_{m=1}^{M-1} S(m,t) \delta[t - \tau_g(m)] dt = \int_{m=1}^{M-1} S(m, \tau_g(m)) dm = \sum_{m=0}^{M-1} S(m, \tau_g(m))
\]
When reconstructing the image using left-wall first-order multipath signals, we use paths \( p_1 \sim p_4 \) and coordinate value of point B to find the corresponding echo delay \( \tau_{s_1} \). The final pixel value of the grid corresponding to the first-order path on the left wall is \( f_1(x_{n_1}, y_{n_1}) \). We form the pixel values of each grid into a matrix \( F_1 \), with different left sidewall positions corresponding to different \( F_1 \). Similarly, we derive the pixel values of each grid \( F_2 \) using the paths \( p_1 \sim p_2 \) and the virtual point \( C \) about the symmetry of the right wall. The \( KL \times KL \) matrix \( C_1 \) is used to describe the gap between \( F \) and \( F_1 \), \( C_1 = F_1 - F \). The 1 norm of \( C_1 \) \( S_r(z) \), is used to describe the size of the gap between the reconstructed image obtained using the blurred sidewall position and the reconstructed image obtained using the real wall position, then identify the minimum value of \( S_r(z) \) corresponding to different sidewall positions

\[
S_{r(z_{\text{min}})} < S_{r(z)}, \quad \forall z = 1, 2, ..., Z,
\]

the corresponding wall position to be the most efficient position in the middle. The right wall position is determined in the same way as above.

4. Simulation Results
To evaluate the efficacy of the CONS. Thirty-one antenna scanning positions are set up at 1m from the front wall and one hundred time domain samplings are taken at each position. The emitted signal is a Gaussian pulse with a center frequency of \( f_c = 1.2 \text{GHz} \). The thickness of the front wall is \( d = 0.2m \), the antenna moves in steps of \( \Delta x = 0.25m \). Set two point targets \( Q_1 \) and \( Q_2 \) in the space behind the wall, \( Q_1 \) and \( Q_2 \) correspond to reflection coefficients \( \alpha = 0.1 \), coordinate positions are \( Q_1(2.5m, 2.8m) \), \( Q_2(1.5m, 2.0m) \) respectively, \( Q_1 \) is a stationary target and \( Q_2 \) is a moving target, with the speed of \( (0.0, 0.2) \text{ms} \). The true positions of the left and right sidewalls are in the azimuthal direction \( x_1 = 0.25m \) and \( x_2 = 2.85m \), respectively, the rear wall position \( y_1 = 3.2m \) is a priori condition. The dimension of the imaged scene is 3 m × 2.5 m, with 5 cm a pixel size in both downrange and crossrange. The range of values for the left and right sidewall locations are \([-0.7, 2.7]\) and \([0.4, 3.4]\) respectively.

![The reconstruction of the scene](image)

Figure 2. BOMP imaging after CONS algorithm to estimate wall position.
Figure 2 shows that after the CONS algorithm's estimation of the sidewall position, the reconstruction algorithm can reconstruct the stationary and dynamic targets in the image with great accuracy, when people has no way to estimate the position of the sidewall accurately in advance.

| Scheme       | Left wall | Right wall |
|--------------|-----------|------------|
| Initial value| LBFGS-PSO | LBFGS-PSO  |
|              | 0.26      | -0.4       |
| Estimated value| CONS     | CONS       |
|              | 2.86      | 3.0        |
| True value   | CONS      | CONS       |
|              | 2.85      | 2.85       |

Table 1 shows that the initial value of the LBFGS-PSO greatly affects the estimated value, and when the initial value of the sidewall is not very close to the real value, the estimated value deviates from the real value by a large margin, which results in no way to locate the target behind the wall accurately. The CONS algorithm, on the other hand, has no requirement for the initial wall position, so the exact sidewall position can be obtained regardless of whether the initial value is close enough to the true value or not.

5. Conclusions
In this paper, a novel CONS algorithm is proposed to achieve the reconstruction of sidewall position parameters under fuzzy conditions of wall parameters and to accurately image moving and stationary targets in combination with the BOMP algorithm. Compared with the LBFGS-PSO algorithm, it is able to obtain higher precision estimates of the sidewall position with a very rough initial estimate, which breaks the limitation of the traditional iterative algorithm that requires a high initial value and is more in line with the actual situation. At the same time, the algorithm can still determine the sidewall location accurately in the low SNR scenario. In this paper, we only consider the advantages of the CONS algorithm in reconstructing the sidewall position, but not the wall dielectric constant, which will be further explored in subsequent studies.

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