A novel approach for Sparse Imaging of Through-wall Radar

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Abstract: Aiming at the problem of segmented weak orthogonal matching pursuit (SWOMP) imaging blur in the process of through-wall radar (TWR) imaging, a dynamic threshold weak orthogonal matching pursuit algorithm (DWOMP) is introduced in this paper, which can significantly improve the imaging performance. Firstly, the TWR compressed sensing simulation model and over-complete dictionary are established by using Chirp signal radar echo data. Then the specific process of DWOMP algorithm is proposed and used to reconstruct multi-sparse target scenes. Finally, the DWOMP algorithm is compared with Basis Pursuit (BP) algorithm and SWOMP algorithm through simulation experiments. The simulation results show that in the same experimental conditions, the imaging time of DWOMP algorithm is about 3/5 of that of BP algorithm, and the imaging resolution of DWOMP algorithm is better than that of SWOMP algorithm.

1. Introduction
Through-wall radar imaging is a rapidly evolving technique for small-area microwave imaging of obstacles. Through-wall radars can penetrate non-metallic obstacles and can be used to detect, locate, track and image hidden targets behind walls [1, 2]. The resolution of traditional synthetic aperture radar depends on the signal bandwidth, and the data sampling is limited by the Nyquist sampling rate, which is difficult to meet the sampling rate requirement. Compressed sensing (CS) theory is an emerging signal compression sampling technique. This theory breaks through the limitations of the Nyquist sampling theorem [3].

In recent years, the Compressed Sensing reconstruction Matching Pursuits (MP) algorithm [4] has been used for radar imaging. Later, more compression-sensing radar imaging algorithms emerged, such as Orthogonal Matching Pursuit (OMP)[5], Regularized Orthogonal Matching Pursuit (ROMP)[6], Generalized Orthogonal Matching Pursuit (gOMP)[7], etc. But the above method must use signal sparsity as a priori condition, so it is not applicable in practical situations. The Sparsity Adaptive Matching Pursuit (SAMP) algorithm proposed by Doet et al. [8] can reconstruct the target scene in the absence of sparsity, but the imaging accuracy is affected by the step size. The Segmentwise Weak orthogonal matching Pursuits (SWOMP) algorithm proposed by T. Blumensath et al. [9, 10], compared to the segmentation orthogonal matching Pursuits (StOMP) [11] algorithm, whose threshold is looser. Therefore, the radar image formed by the SWOMP algorithm may suffer from problems such as blur, offset, and inaccuracy. Another major category of compressed sensing reconstruction algorithms is the convex optimization algorithm. This type of method finds the approximation of the signal by transforming the non-convex problem into a convex problem. The most common method is Basis Pursuit (BP) [12, 13]. BP algorithm reconstruction is more accurate than the OMP algorithm, but it takes a long time to execute. To solve the above problems, this paper proposes a dynamic threshold weak orthogonal matching Pursuits algorithm (DWOMP). The algorithm retains
the advantages of loose measurement matrix, simple structure, and fast convergence, etc., and can reconstruct the target scene of unknown sparsity.

2. TWR Signal Model

Compressed sensing radar imaging is a new method for through-wall radar imaging based on the finite number of measurements. In actual radar detection, most application scenarios satisfy sparsity. The composition of the scene target matrix is as follows:

\[ X = \begin{pmatrix}
  x(1,1) & \cdots & x(1,M) \\
  \vdots & \ddots & \vdots \\
  x(N,1) & \cdots & x(N,M)
\end{pmatrix} \]

The two-dimensional reflection coefficient matrix is concatenated into a one-dimensional matrix:

\[ X = [x(1,1),\cdots,x(N,1),\cdots,x(1,M),\cdots,x(N,M)]^T \]

The transmitted signal is a chirp signal, the process of constructing an over-complete dictionary as follows.

\[ Y(t) = \exp(2\pi(f_0t + \frac{\nu t}{2})) \]

\( \tau \) is the impulse width, \( B \) is the signal bandwidth, \( f_0 \) is the chirp signal center frequency, the distance between the target and the antenna is \( R \). Then the echo signal expression for the entire scene is.

\[ Y(m,n) = \sum_{i=1}^{N} X_i \times \exp \left( \frac{4\pi BR(m,n)}{Ct} \right) \left( t - \frac{R}{c} \right) + \frac{2R(m,n)}{C} \left( \frac{2f_0 - 2\pi BR(m,n)}{Ct} \right) \]

\( X_i \) is the reflection coefficient of the \( i \)-th grid, \( \tau \) is the time delay of the electromagnetic wave, and \( R(m,n) \) is the distance between the \((m,n)\) grid point and the signal source. Definition.

\[ a_{(m,n,1)} = \exp \left( \frac{4\pi BR(m,n)}{Ct} \right) \left( t_i - \frac{R}{c} \right) + \frac{2R(m,n)}{C} \left( \frac{2f_0 - 2\pi BR(m,n)}{Ct} \right) \]

\( t_i \) is the number of fast time sampling points. The over-complete dictionary: \( a(m,n) = [a_{(m,n,1)},a_{(m,n,2)},\cdots,a_{(m,n,1)},\cdots,a_{(m,n,N)}]^T \). We can get the over-complete dictionary.

\[ A = [a(1,1),\cdots,a(1,N),\cdots,a(M,1),\cdots,a(M,N)]^T \]

The compression-sensing radar imaging expression is:

\[ Y = AX + n \]

3. Dynamic Threshold Weak Orthogonal Matching Pursuits Algorithm

To solve the problem of inaccurate imaging of SWOMP algorithm, a dynamic threshold segmentation weak orthogonal matching pursuit algorithm is proposed. The algorithm sets the micro-variable parameter, the threshold change with the residual value produced by each iteration. The DWOMP algorithm flow is as follows.

1) Let, the initialization residual \( r_0 = y \), setting the micro-variable parameter alpha and set \( \Lambda_t = \emptyset, t=0 \).

2) Calculate \( u = \langle r_{t-1}, A \rangle \), Setting threshold \( th = \left( \frac{\| \text{res}_2 \| }{\| \text{res}_2 + \text{alpha} \|} \right) \cdot \max(u) \), and select corresponding columns from \( A \) based on the magnitude of the elements in \( u \geq \text{th} \). The indexes of the selected elements are added to \( \Lambda_t \), and combine these values with the column number \( j \) of \( A \) to form the set \( \Lambda_t = \Lambda_{t-1} \cup j \). Stopping iteration when \( \Lambda_t = \Lambda_{t-1} \).

3) Calculate an estimate of \( \hat{\theta}_t = \left[ A^T \times A_t \right]^{-1} \times A^T \times y \).

4) Update \( r_t = x - A\hat{\theta}_t \), Return to step (2) until iterations \( S \) times.

4. SIMULATION EXPERIMENT

To verify the imaging performance of the DWOMP algorithm in the through-wall radar model, a MATLAB simulation experiment was carried out with the following simulation conditions.

1) The chirp signal center frequency is \( f_0 = 5.6 \text{GHz} \), the bandwidth is \( 1 \text{GHz} \), and the uncompressed impulse width of the signal is \( t_0 = 1 \text{ms} \).

2) The imaging area is set to a closed geometric space of 6 meters in length and 6 meters in width. A rectangular object with an area of 1 square meter inside the geometric space is located 5cm to 15cm in the horizontal and vertical directions.
3) Use 31 transceiver integrated antennas to form an array, evenly distributed them at (-15cm, 15cm), and the antenna array is 5cm away from the wall.

4) The imaged area is a smooth wall with a wall thickness of 0.3 m, and the dielectric constant value is 8.6F/m. The multiple scattering effects of the wall are ignored.

5) The number of signal observation points is M=64, alpha ∈ (0.45,1), the Number of iterations S=50.

Fig.1 2-D radar image formed by BP algorithm

Fig.2 2-D radar image formed by SWOMP algorithm
Fig. 3 2-D radar image formed by DWOMP algorithm

The imaging simulation is performed by BP, SWOMP and DWOMP algorithms, respectively. Each algorithm is simulated 1000 times, and the average execution time is recorded. Based on the BP algorithm, the imaging time of a single antenna is 12.5018 seconds, based on the SWOMP algorithm is 7.4929 seconds, and based on the DWOMP algorithm is 7.4187 seconds. The imaging time of the DWOMP algorithm is about 0.6 times that of the BP algorithm. The imaging results are shown in Fig.1, Fig.2 and Fig.3.

Fig.1 and Fig.2 show the two-dimensional radar image formed by the BP and SWOMP algorithms, respectively. The BP algorithm has high reconstruction precision and completely reconstructs the post-wall target. The SWOMP algorithm can only roughly locate the target. And Fig.4 shows the two-dimensional radar image formed by the DWOMP algorithm. Using the DWOMP algorithm with alpha = 0.5 will achieve the best imaging results. Comparing BP, SWOMP, and DWOMP, we see that the DWOMP imaging performance is improved compared to SWOMP algorithm and DWOMP imaging time is reduced compared with the BP algorithm.

5. Conclusion
The DWOMP algorithm proposed in this paper changes the threshold value with the residual value generated by each iteration by setting the micro-variable parameters. The experiment proves that the DWOMP algorithm combines the advantages of SWOMP and BP algorithm, and can achieve high-quality effects in the practical application of the through-wall radar scene reconstruction.

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