3D imaging of moving targets for ultra-wideband MIMO through-wall radar system

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Abstract
Ultra-wideband (UWB) radar is widely used in static through-wall imaging (TWI). There are still many imaging problems of motion through-wall targets for complex system structure and unknown wall environment. Herein, a motion compensation method based on the reference channel and a modified Kirchhoff migration imaging algorithm are proposed for Ultra-wideband (UWB) MIMO sparse array, which is used for high-precision 3D TWI of moving targets. The channels of the MIMO radar are time-division multiplexing based on microwave switch. Besides, a reference channel is added for motion compensation of moving targets. Performing motion compensation on the target before 3D imaging can effectively avoid the problems of defocus and position deviation caused by target motion. In the proposed imaging method, the backward Green function is used to replace the forward Green function to solve the problem of a large field of view with small arrays. The experiment with a static through-wall target proves that the proposed imaging algorithm can suppress sidelobes well compared with the traditional back-projection algorithm (BPA). Through-wall experiments are carried out for targets with different speeds, and results show that the positioning accuracy and sidelobe level of the proposed compensation method is better than previously proposed methods.

1 | INTRODUCTION

With the development of UWB high-speed electronic devices, UWB radar is widely used in TWI, ground-penetrating radar (GPR), and polar ice exploration due to its excellent medium penetration ability and high range resolution [1–4]. In the 1990s, UWB radar was used to detect targets hidden behind walls or other shelters and played an essential role in disaster relief, anti-terrorism operations, and security inspection, etc. In view of the problem that the previous single-input single-output through-wall radar (TWR) system can only provide 1D distance information and cannot perform 2D imaging. Synthetic aperture radar (SAR) is applied to TWI, a single radar scans along a fixed baseline for the synthetic aperture to obtain multi-angle information. A lot of research has been conducted in clutter suppression and wall compensation [5–7]. MIMO radar uses a real aperture of multiple transceiver combinations to solve the problem of time-consuming and inconvenient use of mobile scanning in SAR TWI applications [8–13]. MIMO radar achieves multi-angle irradiation of the target while maintaining a high speed of data acquisition. A large aperture can be realised with a small number of antennas by excellent array topology design in the MIMO system, which can greatly reduce the system’s complexity. Therefore, UWB radar based on MIMO array with digital beamforming is an essential technology for real-time high-precision imaging. And it presents instant imaging resolution and high clutter suppression capability.

The introduction of MIMO radar can realize real-time imaging of through-wall targets. The imaging quality is mainly determined by the hardware system and imaging algorithm. The azimuth and height resolution of imaging is limited by the aperture of the radar [14,15]. The large radar aperture can obtain high resolution, which requires more channels in the MIMO radar and is challenging to achieve in hardware. Therefore, there is often only a compromise between hardware
systems and imaging quality in engineering. We designed an easy-to-implement multi-channel MIMO radar. The channels of the radar are time-division multiplexing through microwave switch. The locations of the antennas and the equivalent aperture of the MIMO radar are shown in Figure 1. It achieves real-time imaging while improving the radar aperture. The structure of the MIMO radar will be given in detail in Section 4.

Commonly used TWI algorithms include BPA, range migration algorithm (RMA), and compressed sensing (CS) [2,16]. The BPA obtains the inversion result of each pixel of the imaging area by superimposing the echo delay of each antenna transceiver pair. It is not subject to the array structure [17]. However, the BPA is of higher side lobe ratio. The RMA algorithm corrects the distance migration of the echo data in the frequency domain through the fast Fourier transform (FFT), which improves the calculation efficiency significantly. But it can only be applied to MIMO arrays that are distributed uniformly and meet Nyquist sampling law [18]. As for the compressed sensing algorithm, the calculation of which is considerable. Xiaodong Zhuge and others derived the traditional Kirchhoff integral migration algorithm based on the exploding reflector model (ERM) into MIMO near-field 3D imaging of subsurface targets [19]. We derived a modified Kirchhoff 3D imaging formula, which is suitable for TWI of the MIMO UWB radar by including Snell's law and Fresnel equation into the expression of Green's function.

For the real-time 3D TWI of the moving targets in the MIMO system, the influence of target movement on imaging cannot be ignored. The channels of our MIMO radar are time-division multiplexing based on microwave switch to reduce the hardware cost. It can also ensure the consistency of the transceiver channels. However, the channel switching process reduces the scan rate of the system. In time-domain radar, accumulative operations are often necessary to obtain a higher signal-to-noise ratio (SNR). Then the time of acquiring a single-frame of data (contains all channels) will be longer, which may prevent each channel from obtaining data at the same time. The target's position has changed within the time of acquiring a single-frame of data for a moving target. And the migration in the distance often causes position deviation, defocus, and even no results can be obtained. A compensation method of combining hardware and algorithm is presented for TWI of moving targets. In addition to the transceiver antenna array, we introduce a reference channel to estimate the position changing of the moving targets, which is used for the motion compensation of the MIMO channels. Finally, the 3D imaging result can be obtained through the modified backward Kirchhoff migration imaging algorithm. The experimental results show that the proposed method can improve the imaging quality significantly.

Herein, the pre-processing of multi-target data and motion compensation methods is given in section 2. In Section 3, the derivation of the modified backward Kirchhoff formula for the 3D TWI is presented. The experimental data of the designed radar is obtained in Section 4, and the experimental results prove the effectiveness of the proposed method. Finally, Section 5 summarises the results and provides the conclusion.

2 MOTION COMPENSATION IN 3D TWI

As has been mentioned in Section 1, the channels of the MIMO radar are time-division multiplexing through microwave switch to reduce the hardware cost while increasing the aperture. The process of channel switching is time-consuming, which will not have an impact on stationary targets, but it cannot be ignored in motion targets. In the process of 3D TWI of the motion targets, the change of the target's position will cause distance migration. The target will be defocused if the migration is not eliminated. In the traditional SAR imaging, the motion migration is compensated by extracting platform motion parameters and the aligned envelope. In the MIMO radar, the delay difference of each channel is used to obtain the azimuth and elevation information of the target. Then the motion compensation method in the SAR imaging cannot be used in the MIMO echo data directly. In this section, the single-channel motion compensation algorithm (SCMCA) is described firstly, which is a commonly used compensation algorithm reference to the SAR compensation [20]. And its drawbacks are discussed theoretically. Then, a reference-channel motion compensation algorithm (RCMCA) based on the reference channel is proposed to effectively improve the 3D imaging resolution and positioning accuracy of the motion targets. For the 3D imaging of multi-motion targets, the multi-targets should be separated before motion compensation. A segmented constant false alarm rate (SCFAR) method is used to pre-process the echo to extract the position of the target before motion compensation.

2.1 Pre-processing method

SCFAR is used to detect the peak position of the targets before performing motion compensation on the echo of multiple targets. The method SCFAR divides the signal into several time intervals, and then makes CFAR judgements in each interval.

In the process of testing multi-motion targets, the radar collects a total of I frames signals through channel switching. The i-th frame data can be expressed as \( U_i \), which contains data of \( M \times N \) channels of MIMO, \( i = 1,2,\ldots,I \). \( MN \) represent the number of transmitting and receiving antennas, respectively. The data of the \( k \)-th channel in the i-th frame is expressed as \( U_i(x,k) \), \( k = 1,2,\ldots,M \times N \), and \( x \) is the fast-time acquisition data. The background-removed multi-target echo \( U_i(x,k) \) and its Hilbert transformed envelope are shown in Figure 2.

The signal \( U_i(x,k) \) is evenly divided into different time intervals according to the characteristics of the echo envelope, and the length of each interval is \( N_e \). Different targets will be located in different envelope waveforms when their echo delay difference exceeds \( N_e \). Then the multi-target detection problem evolves into a single-target detection problem according to the different intervals.

A sliding CFAR detector, as shown in Figure 3, is used to obtain the adaptive threshold by calculating the arithmetic
average of the reference units in every intervals [21]. A sliding range window of length $N_c+1$ is used in the detector, which is composed of the front window (contains $N_c/2$ clutter samples), the back window (contains $N_c/2$ clutter samples), and the detection unit $x_{cut}$. The target discrimination threshold is calculated as follows

\[
U_{ij}[k] = U_i(x_j - N_c : x_j + N_c, k)
\]

where $x_j$ is the position where the $j$-th target is detected. The data length selected in the target area is $2N_c+1$.

### 2.2 The single-channel motion compensation algorithm

The SCMCA refers to the compensation method in SAR imaging. In each single channel, it combines the echo data of the previous frame and the current frame to extract the position change of the target, which can be achieved through cross-correlation. The cross-correlation can obtain the range difference through the similarity of two frames of data.

\[
D_{ij-Mc} = \begin{bmatrix}
U_{(i-1)/2}(1) \otimes U_{j}(1) \\
U_{(i-1)/2}(2) \otimes U_{j}(2) \\
\vdots \\
U_{(i-1)}(M \times N) \otimes U_{j}(M \times N)
\end{bmatrix}^T
\]
where $D_{ij,\text{Misg}}$ is the target movement distance of per channel in a single-frame time, $U_{ij}^{(t−1)}$ is a frame of data at the previous moment of $U_{ij}$, $\otimes$ is the convolution operator.

The approximate distance of the target position change in single-frame time can be obtained by averaging $D_{ij,\text{Misg}}$. Next, the approximate distance is allocated to each channel to get the position change between two adjacent channels.

$$D_{ij,\text{Aver}} = \text{mean}(D_{ij,\text{Misg}})/MN$$ (4)

The compensated data can be obtained by incorporating target motion data $D_{ij,\text{Aver}}$ into MIMO echo data.

$$U_{ij,\text{com}} = \{\text{Slide}[D_{ij,\text{Aver}}, U_{ij}^{(1)}], \text{Slide}[D_{ij,\text{Aver}}, U_{ij}^{(2)}], \ldots, \text{Slide}[D_{ij,\text{Aver}}, U_{ij}^{(M \times N)}]\}$$ (5)

The function $\text{Slide}[p,q]$ is to shift the sequence $q$ to the right by $p$ positions, $U_{ij,\text{com}}$ is the compensated data of the $j$-th target measured in the $i$-th frame data.

The schematic diagram of the algorithm is shown in Figure 4. The time interval between the two frames of data is the scanning period of a single-frame of the radar in SCMCA. Then the performance of this algorithm is easily affected by the scan rate of the system. The interval between the previous frame and the current frame of a single channel will be longer when the number of antennas is large. The target may have experienced different speeds of motion during the interval, and the above method can only obtain the average speed within that time. Therefore, the SCMCA is suitable for motion compensation of targets with absolute uniform speed. And the compensation accuracy will be greatly reduced when the target moves at a non-uniform speed. The result verification of the algorithm will be given in Section 4.

2.3 The reference-channel motion compensation algorithm

An improved motion compensation method suitable for various motion state scenes is proposed. We add a reference channel in the MIMO system, which is located in the centre of the array. The $N$ receiving channels receive data through time-division multiplexing. The reference channel performs a data acquisition operation after the previous receiving channel finishes receiving data and before switching to the next receiving channel. The interval between the previous and next data acquisition of the reference channel is short, it can accurately detect changes of the target position. Then the target position change of the reference channel can be used to perform motion compensation on the MIMO channel.

The corresponding reference channel data within the scan time of the $i$-th frame MIMO data is $U_{ij,\text{Ref}}(x,w)$, $w = 1,2,\ldots, M \times N$, $w$ represents the $w$-th acquisition of the reference channel within a single frame time. $U_{ij,\text{Ref}}$ is also processed by SCFAR in Section 2.1 to obtain the data matrix $U_{ij,\text{Ref}}$ of the $j$-th target.

![Flowcharts of SCMCA and RCMCA](image)

FIGURE 4 Flowcharts of SCMCA and RCMCA

The motion information of the target is extracted according to the reference channel. The data of the previous moment and the next moment in $U_{ij,\text{Ref}}$ are cross-correlated to obtain the motion information of the $j$-th target.

$$D_{ij,\text{RefMig}}(w) = U_{ij,\text{Ref}}(w) \otimes U_{ij,\text{Ref}}(w + 1)$$ (6)

where $D_{ij,\text{RefMig}}(w)$ is motion information of the $j$-th target. The target motion data $D_{ij,\text{RefMig}}$ is used for motion compensation of the MIMO echo data, and the compensated MIMO data $U_{ij,\text{com}}$ can be obtained.

$$U_{ij,\text{com}} = \{\text{Slide}[D_{ij,\text{RefMig}}^{(1)}, U_{ij}^{(1)}], \text{Slide}[D_{ij,\text{RefMig}}^{(2)}, U_{ij}^{(2)}], \ldots, \text{Slide}[D_{ij,\text{RefMig}}^{(M \times N)}, U_{ij}^{(M \times N)}]\}$$ (7)

Under a certain transmitting channel, only $N-1$ position changes of the target can be estimated according to the echo signals of $N$ receiving channels. The first combined transceiver signal is used as the reference time without compensation. Then there are $M$ target position changes of switching channels that cannot be obtained, which we call the abrupt channels. The value of the abrupt channels can be estimated through its other $N-1$ position changes of the certain transmitting channel by the linear model with the smallest mean square error. Due to the discontinuity of the switch in the MIMO system, it should be mentioned that a large data jump may occur at the point of channel switching, the data of which should be removed. At the same time, the data of a channel where no moving target is detected or the detected target position
deviates too much from other positions should be set to zero to reduce its impact on imaging quality.

The schematic diagram of the algorithm is shown in Figure 4. The comparison of the two methods for motion compensation will be given in the experimental results in Section 4.

3 | 3D IMAGING OF THROUGH-WALL RADAR

3.1 | The modified Kirchhoff imaging algorithm in free space

The traditional Kirchhoff migration algorithm is derived from the explosive reflection model [22,23]. It is mainly used to solve the one-way propagation problem in the far-field. By referring to the Kirchhoff integral migration algorithm of subsurface targets [19], we derive a MIMO TWI algorithm suitable for the near-field. A 2D MIMO array is composed of \( M \) transmitting antennas and \( N \) receiving antennas is shown in Figure 5. The location of transmitting antennas \( T_X \) are denoted as \((x_T, y_T, z_0)\), and the receiving antennas \( R_X \) are represented by \((x_R, y_R, z_0)\). The scattering characteristic \( \sigma_r \) of the target at \((x, y, z)\) can be obtained by the following summation formula.

\[
\sigma_r(x, y, z) = \sum_{M, N} \frac{\partial R_T \partial R_R}{\partial n} \frac{1}{R_T R_R} \times\left[ \frac{1}{\nu^2} \frac{\partial^2}{\partial t^2} U(T_X, R_X, t - \frac{R_T + R_R}{\nu}) + \frac{1}{\nu} \left( \frac{1}{R_T} + \frac{1}{R_R} \right) \frac{\partial}{\partial n} U(T_X, R_X, t - \frac{R_T + R_R}{\nu}) + \frac{1}{R_T R_R} U(T_X, R_X, t - \frac{R_T + R_R}{\nu}) \right]
\]

(8)

where vector \( \mathbf{n} \) represents the unit vector in the forward normal direction of the MIMO array, \( \nu \) is the propagation speed of the electromagnetic wave, \( U \) is the compensated signal in Section 2 corresponding to each transceiver of the MIMO array, \( t \) is the propagation time, \( R_T \) and \( R_R \) are the distances between the \( T_X/R_X \) and the target, respectively.

\[
R_T = \sqrt{(x - x_T)^2 + (y - y_T)^2 + (z - z_0)^2}
\]

(9)

\[
R_R = \sqrt{(x - x_R)^2 + (y - y_R)^2 + (z - z_0)^2}
\]

(10)

Equation (8) is called the modified forward MIMO array Kirchhoff migration integral equation. It is based on the explosive reflector model. According to Huygens principle, the theory is fully valid only when we have a closed or infinite data collection surface that can intercept all the scattered wavefields of the target. Then the forward Kirchhoff migration is only suitable for the imaging scenes of the large aperture with a small field [19].

The antenna aperture cannot cover the detection area, and the outline of the target scatterer cannot be given in TWI. In order to eliminate the influence of the antenna aperture size, the backward Green's function can be used instead of the forward Green's function to compensate for the propagation loss before the summation operation.

\[
G = 4\pi R \cdot \delta\left(t + \frac{R^2}{\nu}\right)
\]

(11)

The modified backward Kirchhoff migration summation equation for the MIMO array based on the backward Green's function of Equation (8) can be expressed as

\[
\sigma_r(x, y, z) = \sum_{M, N} \frac{\partial R_T \partial R_R}{\partial n} \times \left[ \frac{1}{\nu^2} \frac{\partial^2}{\partial t^2} U(T_X, R_X, t + \frac{R_T + R_R}{\nu}) + \frac{1}{\nu} \left( \frac{1}{R_T} + \frac{1}{R_R} \right) \frac{\partial}{\partial n} U(T_X, R_X, t + \frac{R_T + R_R}{\nu}) + \frac{1}{R_T R_R} U(T_X, R_X, t + \frac{R_T + R_R}{\nu}) \right]
\]

(12)

The backward Green's function in Equation (11) uses linear gain to compensate for the propagation loss, which can correct the weaker array response due to a larger distance or limited aperture coverage before imaging. Therefore, the backward Green's function can reduce the dependence of the array response on the aperture coverage.

3.2 | The modified Kirchhoff algorithm of TWI

The scene of TWI is given in Figure 6. The wall is assumed to be a uniform and lossless medium when the transceiver array is closely attached to the wall. \( W_T(x_T^w, y_T^w, z_T^w) \) and \( W_R(x_R^w, y_R^w, z_R^w) \) are the demarcation points in the two mediums from \( T_X/R_X \) to the target. The backward Green's function in the case of TWI according to the Fresnel equation and Snell's law is.

\[
G_s = 4\pi \left( \frac{R_{Ta} + R_{Tb}}{Q} \right) \cdot \delta\left(t + \frac{\sqrt{\varepsilon_r R_{Ta} + \varepsilon_r R_{Tb}}}{\epsilon}\right)
\]

(13)

\[
R_{Ta} = \sqrt{(x_T^w - x_T)^2 + (y_T^w - y_T)^2 + (z_T^w - z_0)^2}
\]

(14)

\[
R_{Tb} = \sqrt{(x - x_T^w)^2 + (y - y_T^w)^2 + (z - z_T^w)^2}
\]

(15)

where \( R_{Ta}/R_{Tb} \) represent the propagation distance of the electromagnetic wave in the wall/air from the transmitting
antenna $T_X$ to the target, $\varepsilon_{r1}$ and $\varepsilon_{r2}$ are the dielectric constants of the two mediums, $Q$ is the wall transmission coefficient calculated by the Fresnel equation, and $c$ is the speed of light. The modified backward Kirchhoff equation of the MIMO 3D TWI can be expressed as

$$
A_T = \sqrt{\varepsilon_{r1}} \frac{\partial R_{Ta}}{\partial n} + \sqrt{\varepsilon_{r2}} \frac{\partial R_{Tb}}{\partial n}, \quad B_T = \frac{\partial R_{Ta}}{\partial n} + \frac{\partial R_{Tb}}{\partial n}
$$

$$
A_R = \sqrt{\varepsilon_{r1}} \frac{\partial R_{Ra}}{\partial n} + \sqrt{\varepsilon_{r2}} \frac{\partial R_{Rb}}{\partial n}, \quad B_R = \frac{\partial R_{Ra}}{\partial n} + \frac{\partial R_{Rb}}{\partial n}
$$

where $R_{Ra}/R_{Rb}$ are the propagation distance of the electromagnetic wave in the wall/air from the target to the receiving antennas $R_X$, then the wall's influence on the echo and the size limitation of the transceiver arrays are compensated in Equation (16). The performance of the modified Kirchhoff migration for 3D TWI will be verified in Section 4.

$$
\sigma_i(x, y, z_1) = 4 \sum_{M \leq N} \frac{1}{Q^2} \left[ \left( R_{Ta} + R_{Tb} \right) (R_{Ra} + R_{Rb}) A_TA_R \right] \frac{\partial^2}{\partial t^2} U \left( T_X, R_X, t + \sqrt{\varepsilon_{r1} R_{Ta} + \sqrt{\varepsilon_{r2} R_{Tb} + \sqrt{\varepsilon_{r1} R_{Ra} + \sqrt{\varepsilon_{r2} R_{Rb}}}} / c \right) + \frac{1}{c} (A_RB_T (R_{Ra} + R_{Rb}) A_T B_R (R_{Ta} + R_{Tb}) + B_TB_R \left( T_X, R_X, t + \sqrt{\varepsilon_{r1} R_{Ta} + \sqrt{\varepsilon_{r2} R_{Tb} + \sqrt{\varepsilon_{r1} R_{Ra} + \sqrt{\varepsilon_{r2} R_{Rb}}}} / c \right)
$$

### 4 | EXPERIMENTAL RESULTS AND ANALYSIS

The structure diagram of the radar system is given in Figure 7, which is mainly composed of the front-end transceiver system, FPGA control board, and PC host. In order to obtain a larger rectangular aperture and achieve a low peak sidelobe ratio and high resolution simultaneously in the azimuth, height and diagonal directions (45° with the azimuth angle). Four transmitting antennas are placed at the corners of the array. In the sparse array of Figure 1(a), the receiving antennas are distributed on two concentric circles since the projections of concentric circles are consistent in all directions, which can ensure the redundancy of 1D projections in each dimension is minimised. It can reduce the sidelobe value. And the reference channel is located in the centre of the array. The antennas are planar Archimedes spiral antennas with a frequency of 0.5–1.5 GHz, as
shown in Figure 8(b), the sidelobe level is about -17dB, the theoretical azimuth and height resolutions are all 0.6995 m, which can meet the actual needs.

The UWB-MIMO radar system designed for 3D TWI is described in detail from the system structure, parameters and radar front-end array. Next, three sets of through-wall experiments (including static target, single-motion target, and multi-motion targets) will be designed to verify the effectiveness of the proposed 3D imaging algorithm and motion compensation method.

4.1 3D TWI of the stationary target

The 3D TWI experiment of a corner reflector is designed in Figure 9(a) to verify the performance of the modified Kirchhoff MIMO imaging algorithm proposed in Section 3. The concrete walls are described by a relative permittivity $\varepsilon_r = 7.0$ and conductivity $\sigma = 0.05 \text{Sm}^{-1}$. The wall is assumed to be homogeneous and frequency independent, and the thickness of the wall is 24 cm. A corner reflector with a side length of 14 cm is placed 1m directly in front of the centre of the radar MIMO array on the other side of the wall. The radar parameters are given in Table 1. The selected 3D image space has a length of 8, 4 and 10 m in the azimuth, height and distance directions, and the number of grids is 81*41*101 according to the resolution.

The 3D imaging and 2D projection results of the traditional BPA and the modified Kirchhoff algorithm are given in Figure 10. We can find that the image quality of the proposed method is better than the BPA under the same environment. The specific sidelobe level comparison of the two imaging methods is shown in Figure 11. The proposed algorithm is of lower sidelobe level, which further verifies the effectiveness and accuracy of the proposed algorithm. The calculation time of BPA and the proposed imaging algorithm are both 3s.
Next, 3D real-time imaging experiments of single-motion target and multi-target motion will be performed under the condition of outdoor wall penetration to verify the effectiveness of the motion compensation methods proposed in Section 2.

### 4.2 3D TWI of the single-motion target

In the 3D TWI experiment of the single-motion target, the wall parameters are the same as those in Section 4.1. As is shown in Figure 9(b), the radar is placed close to the wall. The human target moves at a speed of 1 m/s along the normal direction of the radar on the other side of the wall.

The imaging results of the target moving to the position (0m, 5m) after different motion compensation algorithms are shown in Figure 12. The compensated MIMO data are imaged through the modified backward Kirchhoff MIMO imaging algorithm. Figure 12(b,c,h) show the azimuth-range projections, the imaging position with non-compensation deviates from the actual position of the target and is of large sidelobe level. The focusing of the target is improved and the side lobe is also reduced after SCMCA compensation, but there is still apparent positioning deviation. The measurement positioning is of high consistency with the real target in the imaging result after the RCMCA, and the imaging sidelobe level is low. Figure 13 gives the positioning deviations at different distances of the non-compensation, the SCMCA, and the RCMCA, respectively. The positioning error of the SCMCA gradually increases with distance, while the positioning error of the RCMCA can be kept within 0.4 m.

Table 2 gives the target positioning errors of different compensation methods at different speeds. The positioning errors of 0.3 m/s, 0.6 m/s, 0.9 m/s, 1.2 m/s, 1.5 m/s, 1.8 m/s, and non-uniform speed moving targets are tested at (0m, 5m). The test result is the average value after multiple tests. The target positioning error after the SCMCA is small when the movement speed is low, but the error will gradually increase as the target movement speed increases. The positioning error of SCMCA is almost the same as the non-compensation in the state of non-uniform motion. The proposed compensation algorithm can adapt to various speed scenarios, and the error is within 0.4 m.

### 4.3 3D TWI of the multi-motion targets

The 3D TWI scene of the multi-motion targets is shown in Figure 9(c). The parameters of the radar system and the wall environment in the experiment are the same as the single-motion target. Two human targets are selected in this experiment to move on the other side of the wall. Target 1 and target 2 move away from the radar in two directions, respectively, and the speeds of both targets are 1 m/s.

Figure 14 shows the imaging of the non-compensation, the SCMCA, and the RCMCA for the two targets at (-1.5 m, 7m) and (0.5 m, 3.5 m). It can be seen that the SCMCA can only eliminate part of the sidelobes of the two targets compared to the result before compensation, and there are still positioning deviations of the two targets. The focusings of the two targets are the best and the positioning deviations are minimised after the RCMCA. Figure 15 gives the positioning deviations of the two targets at different distances of the non-compensation, the SCMCA, and the RCMCA, respectively. Although the positioning error of the two targets after the RCMCA still fluctuates with the distance, the positioning error...
FIGURE 9 The experimental scenarios. (a) 3D TWI of the through-wall corner reflector. (b) 3D TWI of the single-motion target. (c) 3D TWI of the multiple-motion targets

FIGURE 10 Imaging results of the corner reflector. (a) 3D imaging of BPA. (b) 2D projection in azimuth-range dimension (x-z) of BPA. (c) 2D projection in azimuth-height dimension (x-y) of BPA. (d) 3D imaging of the modified Kirchhoff algorithm. (e) 2D projection in x-z of the modified Kirchhoff algorithm. (f) 2D projection in x-y of the modified Kirchhoff algorithms

FIGURE 11 The sidelobe levels of different algorithms. (a) The sidelobe levels of the two methods in the azimuth direction. (b) The sidelobe levels of the two methods in the height direction
of target 1 remains within 0.5 m, and the positioning error of target 2 remains within 0.4 m.

Table 3 shows the impact of different speeds on target positioning accuracy. The positioning errors of the targets under the fixed position (-1.5 m, 7 m) and (0.5 m, 3.5 m) are tested at 0.3 m/s, 0.6 m/s, 0.9 m/s, 1.2 m/s, 1.5 m/s, 1.8 m/s, and non-uniform speed movement, respectively. The test results are the average value after multiple tests. The position errors after the SCMCA will gradually increase as the targets' speeds increase in the case of multiple targets, which is consistent with the single-target test result. The errors of the two targets after SCMCA are equivalent to the non-compensation when the movement is non-uniform. The proposed compensation algorithm can adapt to various speed scenarios and ensure that the positioning error of target 1 is within 0.5 m and the positioning error of target 2 is within 0.2 m.
5 | CONCLUSION

A motion compensation method based on the reference channel and a modified backward Kirchhoff migration imaging algorithm are proposed. The modified backward Kirchhoff migration imaging algorithm has smaller sidelobes compared with the traditional BP 3D imaging algorithm. The proposed RCMCA motion compensation algorithm performs motion compensation on the data of the MIMO channel by referring to the position change information of the moving target estimated by the reference channel. The compensated data is used for 3D imaging, which effectively avoids the problems of defocusing and deviation of the target from the real position. The designed MIMO radar system can be used...
FIGURE 15  The positioning deviations of different compensation methods. (a) Deviation of Target 1. (b) Deviation of Target 2

| TABLE 3  |  Position errors at different speeds of the two targets |
|-----------|--------------------------------------------------------|
| Compensation method | Target | 0.3 m/s | 0.6 m/s | 0.9 m/s | 1.2 m/s | 1.5 m/s | 1.8 m/s | Non-uniform speed |
|----------------------|--------|---------|---------|---------|---------|---------|---------|------------------|
| Non-compensation(m)  | Target 1 | 0       | 0.3     | 1.1     | 1.2     | 1.4     | 1.6     | 1.8             |
|                      | Target 2 | 0       | 0.1     | 0.4     | 0.4     | 0.8     | 0.8     | 1               |
| After the SCMCA(m)   | Target 1 | 0       | 0       | 0.6     | 0.6     | 0.8     | 1.4     | 1.6             |
|                      | Target 2 | 0       | 0.1     | 0.2     | 0.2     | 0.5     | 0.6     | 0.8             |
| After the RCMCA(m)   | Target 1 | 0       | 0       | 0.2     | 0.2     | 0.4     | 0.5     | 0.5             |
|                      | Target 2 | 0       | 0       | 0.1     | 0.1     | 0.2     | 0.2     | 0.2             |

for real-time high-precision 3D TWRI of multiple moving targets.

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