Targets Imaging Method for A New MIMO Through-wall Radar

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Abstract. The ultra-wideband (UWB) multi-input multi-output (MIMO) radar technique is playing a more and more important role in the application of through-wall detection because of its high resolution, lower antenna requirements, and efficient data capturing ability. A new UWB MIMO sparse array radar system with eight pairs of transmitting and receiving miniaturized Vivaldi antennas is designed in this paper and reverse time migration of the acoustic wave equation based on finite difference is used for target imaging. How to locate the target and reconstruct velocity model is the key in this paper. Finally, we found that this processing method is completely effective for forward single-target imaging, but there is still a lot of research space, and if we want to apply them in practice, further study must be done.

1. Introduction
Through-wall radar (TWR) imaging involves many important issues, including: attenuation and dispersion of walls, array elements and arrays of antennas, beam forming techniques, imaging and positioning of targets behind walls, and so on [1]. TWR can be divided into synthetic aperture radar (SAR) systems and MIMO radar systems, according to the working mode [5,8,10-14]. To get a high azimuth resolution, SAR is extensively used. However, this method requires long data acquisition times. The MIMO radar technology was proposed in 2003 and 2004 [3,7]. It uses multiple transmitting and receiving antennas and transmits orthogonal waveforms, which can expand the aperture of the actual array elements and confer a better spatial sampling ability. In addition, the sparse MIMO array design of switched antenna can also meet the requirements of high scanning speed and detection ability in the practical application of through-wall imaging. Therefore, the switched antenna array radar is often considered as the MIMO radar. What’s more, it is also the hardware base of multisource data acquisition. In recent years, the MIMO radar system has received extensive attention of scholars. Feng et al. [6] developed a MIMO array-based radar system using a SFCW signal, which can effectively improve the data sampling speed, maintain the azimuth resolution, and reduce the hardware costs. However, due to the high frequency range of the antenna used, the penetration depth of the radar system is too shallow for through-wall imaging. Yilmaz et al. [16] designed and manufactured a uniform array radar system to detect and image targets behind a wall with a monostatic configuration controlled by a switcher. However, the effect of the wall on the refraction of EM waves, which produces a position shift of the targets behind the wall, was ignored.

A new UWB MIMO sparse array radar system with eight pairs of transmitting and receiving miniaturized Vivaldi antennas is designed in this paper and reverse time migration of the acoustic
wave equation based on finite difference is used for target imaging. The reverse time migration algorithm is a widely studied, and its velocity modeling is very important. How to position the target and reconstruct velocity model is the key in this paper. The structure of the paper is organized as follows: In Section 2, the prototype of the MIMO radar system is presented. In Section 3, the flow of imaging method is shown, and the point is how estimate wall parameters, locates objects, constructs the velocity model and forms image. In Section 4, simulation data are processed to assess the effectiveness of the imaging methods. Sections 5 and 6 give discussion and conclusions, respectively.

2. The Topology of Through-wall Radar
Sixteen identical Vivaldi antennas were fabricated, and the array was assembled by the proposed design method [9]. All antenna elements were connected to each terminal of the RF switch through SMA connectors and RF cables. For the switch at the center frequency of 1.5 GHz, the insertion loss was about 1.8 dB, and the isolation was greater than 48 dB. The control and the synchronization of VNA and the RF switch were realized by a microcontroller with the help of the PC. Finally, a MIMO radar system for through-wall detection was manufactured. Figure 2 displays the photography of the designed MIMO radar system. And Table 1 shows the setting parameters of the system and VNA.

![Figure 1. Photograph of Designed MIMO Radar Prototype.](image)

### Table 1. System Parameters.

| Parameters                  | Value     |
|-----------------------------|-----------|
| Start frequency             | 0.4GHz    |
| Stop frequency              | 2.6GHz    |
| Number of frequencies       | 256       |
| Number of transmitters/receivers | 8/8    |
| Range resolution            | 0.068m    |
| Azimuth resolution          | 5.8rad    |
| Maximum range               | 17.4m     |
| Length of aperture          | 1.1m      |

For a bistatic MIMO sparse array which contains M transmitters and N receivers, according to the theory of displaced phase center (DPC) approximation, the m-th transmitter at the xm-th position and the n-th receiver at xn-th position are switched on, while all the other paths are switched off. This is equivalent (in far field) to transmitting and receiving with one single ‘virtual’ antenna in the median position (xm + xn)/2 of the axis. The midpoints of each transmit and receive element are regarded as virtual elements for a linear equivalent monostatic array. Hence, we can obtain an equivalent uniform array with MN (MN = M×N) monostatic transceivers, which has expected resolution and low-level grating/side lobes [9].
Figure 2. Equivalent Array of the Sparse MIMO Array.

In addition, the offset of the m-th transmitter at the x_m-th position and the n-th receiver at x_n-th position is (x_m - x_n), and the offset of each channel is also different because of the layout of the transmitters and receivers. Because of the central symmetry of array, we sort the first 32 channels in order of their offsets, and the channel spacing increases equally.

3. Objects Imaging Method

In this work, we assume that the wall is a homogeneous isotropic medium, adapt the seismic velocity analysis method to estimate the wall parameters, establish the velocity model, and further realize reverse time migration imaging. In order to focus the targets well, we also make a rough targets location before velocity modeling. Aiming at applied to the new MIMO through-the-wall radar system designed, many processing methods have been effectively modified and integrated. This section is divided into four subsections each detailing either pre-processing, wall parameters estimate, rough objects location and the migration imaging algorithm. The entire algorithm flow chart can be seen in Figure 3.

3.1. Pre-processing

In order to ensure the accuracy of velocity analysis, the time to start data acquisition must be the same as the signal excitation time. We transmit a signal into the air, extract the arrival time of coupling wave from the data, fit the arrival time and offset linearly, and get the delay of zero offset. In principle, the delay of zero offset is zero and the data is corrected. At the same time, we can remove the coupling wave from the data through the wall by minus the data obtained in the air.

3.2. Wall Velocity Estimate

We assume for simplicity that the wall is composed of a single homogeneous dielectric layer with thickness and relative permittivity. The influence of possible surface roughness was not considered. When the array is parallel to the wall, the signal recorded by different receivers from the same transmitter can be translated to obtain a common center point trace set, as shown in Fig.4. In the same way, the data recorded by the same receiver from different transmitters can also be moved to the same reflection point in parallel. Therefore, the reflection data obtained from different channels can be sorted in order of offset and regarded as a set of common middle point traces. If we sort the data according to the order of offsets, we can get the hyperbola of reflection.
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Figure 4. Diagram of Constructing Pseudo-common Middle Point Traces.

Obviously, the hyperbola formed by reflection response changes relatively gently at small offset. When there is no large offset trace in the common midpoint traces for velocity analysis, the focusing of velocity spectrum energy becomes poor and the velocity resolution decreases. However, the larger the offset is, the larger the deviation between time distance curve and hyperbola is. Then the $t_0$ obtained from all traces time-offset polynomial fitting may seriously deviate from the correct zero offset reflection time. Therefore, in order to obtain a satisfactory velocity spectrum, the offset of traces for velocity analysis should be well distributed. How to determine the serial number and quantity of traces for velocity analysis is of vital importance.

Here, we use polynomial fitting of offset and arrival time, change the start serial number and quantity of traces, and compute standard deviation of the fitting error. We find that different depth of the reflection interface is, different serial number and quantity of traces can be chosen.

Based on the velocity analysis of the reflected wave on the wall, the electromagnetic wave velocity in the wall and the wall thickness are obtained, and the velocity model is established, then the imaging is carried out.

3.3. Rough Objects Location

If the targets are not contained in the velocity model, the focus of the targets will be poor in the reverse time migration, so the position and number of targets must be roughly predicted before imaging. The human body reflection signal is weak compared with the wall reflection signal, and when the wall reflection wave is removed, the human body reflection signal will be more obvious and easier to find.

Figure 6. locate target by use the time delay and distance curve in common receiver traces.
Assume that the distance from the target to the receiver is $S_1$, the travel time is $t_1$, the distance from the target to its projection on the array $O$ is $h$, and the distance from the detection point to the projection $O$ is $z$, for the common receive point traces, we assume that $t_1$ is a fixed value, then the reflection response time distance curve of the target can be written as
\[ v = t_1 + \frac{\sqrt{z^2 + h^2}}{v}, \quad t_i = \frac{S_i}{v} \]

And by transformation, we get
\[ \frac{(t-t_0)^2}{t_0^2} - \frac{z^2}{v^2 t_0^2} = 1, \quad t_0 = \frac{h}{v} \]

Obviously, when $z$ is equal to 0, $t$ is the smallest, and it is the vertex of the hyperbola, the abscissa of hyperbolic vertex is consistent with the projection of the target on the array. When the abscissa of the target is within the range of the transmitters, as shown in Figure 6 (a), the abscissa of the hyperbolic vertex corresponds to the abscissa of the target. However, when the target is out of the range of the excitation point, as shown in Figure 6 (b) and (c), only half of the hyperbola is left. In this case, we need to judge according to the trace where the hyperbola has the minimum delay. Polynomial fitting is carried out to determine the abscissa of the vertex, that is, the abscissa of the target. Eight common receiver traces form eight hyperbolae, and eight hyperbolic vertices are found. Therefore, the lateral position of the target is located by mean of those eight values. At the same time, the delay $t=t_1+t_0$ can be obtained when the receiver is above the target.

Similarly, polynomial fitting can also be used in common transmitter traces to obtain the time delay $t'=t_1'+t_0'$ when the source is above the target. The transmitter and receiver with the minimum offset from the target are selected to calculate the target time delay $T$, $t+t'=T=t_0+t_0'$, where $T=t_1+t_1'$. Then we will be able to roughly estimate the vertical position of the target based on $t_0+t_0'$.

3.4. Reverse Time Migration
The reverse time migration [2,4,15] is a widely studied algorithm in seismic processing. We take the single transmitter recording as the starting source, reverse-time extrapolates wave-fields, applies imaging conditions to obtain the single transmitter imaging result, and finally superimpose imaging results of each shot to obtain the final imaging profile. We won't go into details here. According to the comparability propagation between the electromagnetic wave and the elastic body wave, we apply the migration algorithms of the seismic data into the radar data processing, that is to say the reverse-time migration based on the scalar wave equation. Through the above analysis, we can establish the whole velocity model, and on this basis, reverse time migration can be used for target imaging. Change the longitudinal position of the target to find the best focus the target.

4. Data Processing Result
The velocity field for simulation is shown as Fig.7. The area is $3.2m\times3.5\ m$. The relative permittivity of the wall is 6, and it is 22.5cm thick. There is a human target 1m behind the wall. The array was placed parallel to the wall, 15cm away from the wall, and the transmitters and receivers are arranged according to array parameters.
Then we get the data in the air and through the wall. Removed the first 304 sample points from every channel to make the beginning acquisition time stay in step with the signal excitation time. Remove the coupling-wave, sort the traces in order of the offset. Choose 1-11 channels for velocity analysis based on NMO. Then we get the electromagnetic waves speed in the air is 2.994e8 m/s, the array is 0.1496 m away from the wall, the electromagnetic wave speed inside the wall is 1.2733e8 m/s, in the other word, the relative dielectric constant is 5.5286, the wall thickness is 0.2342 m, and the difference is 0.0092m from the simulation model. Figure 8(a) is obtained by removing the wall reflection, which is transformed into a common receiver traces, Figure 8(b). The horizontal position of the human target is 1.6m, in the middle of the transmitters, and the vertical position is 0.8438m. The velocity model is established with the above data, and then the reverse time migration is carried out. Change the vertical position of target to choose best focus and obtain Figure 9. We can see the image of the target clearly, and the difference of vertical position between image and simulation model is 0.15m.
5. Conclusion

Based on the above analysis, we can real-time estimate the parameters of the wall only by the data from our system, and we can locate the single object by polynomial fitting easily. Also, RTM method is completely effective for forward single-target imaging, and the position of the target is relatively accurate, but there is still a lot of research space, such as time consuming, interference suppression in inverse time migration imaging, the suitability of multi-target imaging, and the improvement of imaging methods. Moreover, the measured data outdoors has a large attenuation and many kinds of interferences. If we want to apply them in practice, further study must be done.

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