Enhanced Imaging of Building Interior for Portable MIMO Through-the-wall Radar

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Abstract. Portable multi-input multi-output (MIMO) radar system is able to imaging the building interior through aperture synthesis. However, significant grating lobes are invoked in the directly imaging results, which may deteriorate the imaging quality of other targets and influence the detail information extraction of imaging scene. In this paper, a two-stage coherence factor (CF) weighting method is proposed to enhance the imaging quality. After obtaining the sub-imaging results of each spatial sampling position using conventional CF approach, a window function is employed to calculate the proposed “enhanced CF” adaptive to the spatial variety effect behind the wall for the combination of these sub-images. The real data experiment illustrates the better performance of proposed method on grating lobes suppression and imaging quality enhancement compare to the traditional radar imaging approach.

1. Introduction

Through-the-wall radar system is widely employed in radar detection by using low-frequency signal for the target detection behind the wall. Besides the detection of human target, through-the-wall radar system is also able to evaluate the structure of building and obtain the interior information. Synthesis aperture radar (SAR) are usually applied for through-the-wall system to illuminate the building from several directions \cite{1,2}, but this operation mode is more suitable for outdoor imaging due to the large and complex system size. For indoor illumination (like the room imaging in a narrow stairway), a portable multi-input multi-output (MIMO) through-the-wall radar system is needed.

The portable MIMO through-the-wall radar system is also able to achieve the illumination of detection scene through MIMO-SAR imaging, while the synthesis aperture is limited in narrow space detection. Behzad et al. propose a separated transmitting-receiving system for all directions of illumination to the building in \cite{3}, which makes the direction of synthetic aperture no longer parallel to the wall, but a circle along the radar system. This method can obtain an imaging result with identical resolution in all directions. However, it is hardly to apply in practical because of the extreme requirement to the system precision.

Since multi-directions illumination is not always available in practical detection, the aperture synthetic pattern of portable MIMO through-the-wall radar system is usually along a single direction parallel to the illumination wall. As to the indoor radar imaging, the distribution of antennas may not satisfy the spatial sampling theorem, which induces significant grating lobes as interference to real targets and decreases the imaging quality. Coherence factor (CF) is one of the most common used corrections to suppress grating lobes, including traditional CF approach, phase CF approach \cite{4}, sign
CF approach [5], etc. While these methods are effective, they may also blank the real targets in the MIMO-SAR system due to the spatial fluctuation of targets in the imaging results of different channels. In this paper, we proposed a two-stage CF method for the enhancement of imaging quality. The imaging results through traditional CF method is further processed by a window function to compute the “enhanced CF” adaptive to the spatial variety effect behind the wall for the combination of these results. The method is validated by real data experiments for a better performance.

2. MIMO-SAR Imaging Method

As mentioned before, portable MIMO through-the-wall radar employs the synthesis aperture technique to combine the images obtain from each spatial sampling position and output the final imaging results. The schematic figure of the system is shown in Figure 1. Different from traditional imaging, the existence of refraction in the wall makes it difficult to calculate the accurate delay of target in MIMO-SAR imaging.

![Figure 1. The schematic figure of MIMO-SAR through-the-wall imaging. Due to the refraction in the front wall, the delay of a target behind the wall will be larger than the situation without the wall. Actually, multi-path effect [6] of transmitted signal exists in a closed indoor illumination, but we do not consider this problem here for simplicity. Besides, this problem can be addressed by the system design of MIMO radar.](image)

Conventionally, the back projection (BP) method is used for through-the-wall imaging [7]. Without loss of generality, when transmitting a step frequency signal, the imaging magnitude of point \( q \) in the detection scene at the \( k \) th spatial sampling point can be expressed as

\[
I(q,k) = \frac{1}{M} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} R(m,n,k) \exp(i2\pi f(m)t(q,n,k))
\]  

(1)

where \( M \) is the frequency sampling number, \( N \) is the number of channel, \( R(m,n,k) \) is the radar return of channel \( n \) corresponding to the sampling point \( m \) at the \( k \) th spatial sample, \( i \) represents the imaginary sign, \( f(m) \) denotes the operation frequency of sampling point \( m \), \( t(q,n,k) \) is the corresponding delay of point \( q \). Note that the accuracy of \( t(q,n,k) \) depends on the thickness and permittivity of the wall, and it can be precisely calculated when these two parameters are accurately known. However, the parameters are almost impossible to measure in a random and unfamiliar detection scene. Besides, although several auto-focusing algorithms [8] are proposed for the calculation of delay considering the refraction, they are all employed for the wall with homogeneous dielectric and structure, while this is hard to guarantee during the MIMO-SAR illumination at different...
directions. Therefore, we still calculate the $t(q,n,k)$ without considering the refraction of wall for simplicity. And ignoring the refraction in the wall, $t(q,n,k)$ can be calculated as

$$t(q,n,k) = \left( |p(q) - p_o(n,k)| + |p(q) - p_r(n,k)| \right) / c$$

(2)

where $c$ is the speed of light, $p(q)$ is the location of point $q$ in the imaging scene, $p_o(n,k)$ and $p_r(n,k)$ are the locations of the transmitting and receiving antenna of channel $n$ at the $k$th spatial sample, respectively. Note that it is reasonable to ignore the defocus caused by the refraction in the wall [9] since the aperture of the portable MIMO through-the-wall radar system is usually small. Next, the final imaging result of point $q$, denoted as $I_s(q)$, is the coherence sum of the sub-images obtained at all the $K$ spatial samples

$$I_s(q) = \sum_{k=0}^{K-1} I(q,k)$$

(3)

3. Two-stage CF Enhancement Method

The antenna number of portable MIMO through-the-wall radar system is limited by its size and cost, while large antenna synthetic aperture is desired for a better azimuth resolution. Besides, the illumination scene of through-the-wall radar usually does not have the character of “far-field” illumination, and the beams along the azimuth is usually not a uniform distribution in the MIMO radar that the transmitting and receiving antennas are separated, which finally invoke obvious grating lobes in the image. The grating lobes may be falsely detected or interfere the imaging of real targets. CF approach [4] is one of the simplest and most widely used methods to suppress the grating lobes. The CF weight of point $q$ in the multi-channel imaging at the $k$th spatial sample is defined as

$$CF(q,k) = \frac{\sum_{n=0}^{N-1} \sum_{m=0}^{M-1} R(m,n,k) \exp(i2\pi f(m)t(q,n,k))}{N \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} R(m,n,k) \exp(i2\pi f(m)t(q,n,k))}$$

(4)

And the sub-image after CF processing is

$$I_{CF}(q,k) = I(q,k)CF(q,k)$$

(5)

Note that the traditional CF approach only suppresses the grating lobes at a certain spatial sample. However, the non-uniform distribution of spatial sampling to the MIMO array may also generates new grating lobes during the synthesis aperture imaging, even if the azimuth samples are uniform distributed. Therefore, it is necessary to add a further CF processing for the suppression of grating lobes when integrating the final imaging result.

It is well studied that traditional CF weighting method is suitable for ideal point targets, while it may also suppress the main lobe of extended targets like walls, household appliances and other strong reflectors, since these targets may fluctuate in spatial in the target profiles obtained from different spatial samples, which results in the decreasing of target coherence. The Parseval theorem illustrates that $CF(q,k)$ represents the ratio between $I(q,k)$ and the energy of radar returns at the corresponding locations in channels (ignore the constant $N$). However, $I(q,k)$ only represents the energy with zero-frequency, but the frequency spectrum of target profile may spread during the integration of imaging results in spatial, thus it is better to extend the frequency interval of the numerator and includes the extended energy of target for the second stage of CF calculation.

It is shown in (4) that the weights of traditional CF method for any channels are all 1, which means that by changing these weights, it is able to change the frequencies included in the numerator. As a
consequence, a window function with larger pass band like Hanning or Hamming window may use to replace the rectangle window, for the extension of frequency interval included in the CF. Denote $C_{v}(q)$ as the weight of point $q$ during the integration of the sub-images, then

$$CF_{v}(q) = \frac{\sum_{k=0}^{K-1} w(k)CF(q,k)I(q,k)}{K\sum_{k=0}^{K-1} CF(q,k)I(q,k)}$$  \hspace{1cm} (6)$$

where $w(k)$ is the value of the $k$th element in the chosen window function with length equals to $K$, then the final output image with enhanced imaging quality can be obtained as

$$I_{E}(q) = CF_{v}(q)\sum_{k=0}^{K-1} I_{CF}(q,k)$$  \hspace{1cm} (7)$$

4. Practical Experiment and Results Discussion

The effectiveness of the proposed method is validated by a portable MIMO through-the-wall radar system with 4 transmitting antennas and 5 receiving antennas, shown in Figure 2. The length of antennas array is 0.4m, a step-frequency signal from 1.5GHz to 2.1GHz is transmitted and the step frequency is 4MHz. Figure 2 also demonstrates the structure of the illumination scene, a meeting room containing some common furniture. Set the left-bottom corner of the scene as the origin of coordinates, and there are 46 azimuth sampling points with the interval 0.1m. The distance between the radar system and the front surface of wall is 2.1m.

![Figure 2. The illumination scene of the experiment. During the experiment, the radar moves along the wall with a constant speed for 4.5m, and makes a spatial sample every 0.1m. The strong reflectors are marked in this figure.](image-url)
The imaging results of traditional BP approach and our proposed method are shown in Figure 3 and Figure 4, respectively, output in normalized dB. The imaginary lines illustrate the actual layout of the scene. Note that the imaging results have an overall range delay to the actual layout since we do not consider the refraction in the front wall. Significant grating lobes can be observed in the BP approach, which are tens of dB higher than the returns of reflectors like wood table, air conditioner, etc. due to the serious signal attenuation when penetrating the front wall. These reflectors are hardly recognized in such strong grating lobes.

On the other hand, the imaging quality is apparently enhanced employing the proposed two-stage CF method (the Hamming window is chosen in (5) for this experiment). The dihedral angles of metal box and pillar are demonstrated by strong magnitude of radar returns shown in Figure 4, and the wood table is well separated from the grating lobes of front wall. The air conditioner is also able to be detected, which is totally submerged in Figure 3. Though the portable MIMO through-the-wall radar certainly performs not as well as those large vehicle-based through-the-wall radar systems, due to the limitation of synthetic aperture size, directions of illumination and the hardware complexity, this experiment still validates its effectiveness of building interior imaging using our proposed imaging quality enhancement method.

5. Conclusions
The paper proposed a quality enhanced method for the imaging of building interior using portable MIMO through-the-wall radar. The pattern of MIMO-SAR is employed for the portable MIMO radar antennas to achieve a larger aperture as well as viewing angle. Besides, a two-stage CF correction is applied for the suppression of grating lobes. The practical experiment results show a better imaging quality than traditional imaging process in terms of lower grating lobes, which is better for the reconstruction of building environment. While different from the optical photo, further detection and classification is needed for the recognition of detail target information, and this will be researched in the future.

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