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# A Survey on Range Migration Algorithm for Near-field Imaging of MIMO Millimeter Wave Radar

Yongsheng Liu, Tao Chen, Yu Jiang, Yanbo Zhang*, Zhongmin Wang

Key Laboratory of UWB & THz of Shandong Academy of Sciences, Institute of Automation, Qilu University of Technology (Shandong Academy of Sciences), Jinan, 250014, China

## Abstract

**With the continuous development of millimeter-wave radar component integration technology, millimeter-wave radar near-field imaging technology has been improved and widely applied in security inspection, through-wall detection and other scenarios. This paper first introduces the research background and significance of multi-input multi-output (MIMO) millimeter-wave radar near-field imaging. Secondly, it summarizes the domestic and foreign development status of millimeter-wave radar and frequency domain imaging algorithms. Then, it introduces the imaging principle of MIMO millimeter-wave radar and deduces the imaging algorithm process of MIMO millimeter-wave radar based on range migration algorithm. Finally, it summarizes the existing problems of range migration algorithm and outlooks the future development.**

## Keywords

**Multi-Input Multi-Output, Millimeter wave radar, Near-field imaging, Range migration algorithm.**

## 1. INTRODUCTION

The millimeter-wave frequency band is generally 30-300 GHz, corresponding to the wavelength of about 1-10 mm. It has the characteristics of infrared and microwave, with shorter wavelength and stronger penetration. Compared with traditional radars, millimeter-wave radars in this frequency band have significant advantages such as smaller volume, lighter weight, and higher spatial resolution, which effectively compensates for many shortcomings of traditional radars. Therefore, the application fields of millimeter wave radar are constantly expanding, especially in the fields of safety detection, automatic driving, industrial automation and other fields, showing great application potential and value. At the same time, millimeter-wave radar can provide safe and reliable environmental perception capabilities for many fields, in which dangerous goods detection is an important direction of current and future research [1-3].

MIMO (Multi-input Multi-output) millimeter wave radar can be used for the design of security doors to scan the human body and detect whether to carry threatening items. Compared with the traditional security door, which can only obtain the contour information of the human body, MIMO radar can obtain the human body image of the three-dimensional photo effect, and intuitively judge the position and shape of the object. In the field of autonomous driving, millimeter-wave MIMO radar can achieve high-precision target detection and tracking, providing key support for vehicle perception environment. Compared with traditional radar, MIMO radar can simultaneously transmit multiple coherent signals and obtain richer target information through digital signal processing. This can improve the resolution of the radar and more accurately detect the position and speed of the obstacle. This is crucial to ensure the safety of autonomous vehicles. According to the detection principle and imaging method of millimeter

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wave radar, millimeter wave imaging technology can be divided into plane scanning, cylindrical scanning and sparse array imaging. According to whether the system actively emits electromagnetic wave signals, it can be divided into two categories: active and passive millimeter wave imaging radar. Compared with the passive system, the active millimeter wave radar imaging system is less affected by the environment. There is a clear distinction between the electromagnetic wave signal reflected from the target and the stray wave reflected by the environment, so the high-quality original echo data of the target can be obtained. Based on these echo scattering coefficient data, combined with efficient imaging algorithms, a high-resolution target image can be reconstructed. Active millimeter-wave holographic imaging technology is particularly prominent. It can form a three-dimensional holographic image with clear targets and has excellent spatial resolution. First of all, the millimeter wave radar signal has good penetrability and strong penetration ability to non-metallic materials. Secondly, millimeter wave has non-ionization characteristics, which can image various hidden objects through non-contact methods, and human health is not affected by it under appropriate radiation power. These characteristics make the millimeter wave imaging technology widely used in the field of human hidden object security inspection and hidden object detection. Therefore, the active MIMO millimeter wave radar imaging system has been developed rapidly.

Radar systems can be divided into two categories: real aperture radar and synthetic aperture radar. The real aperture radar uses the real antenna aperture to transmit the detection beam and receive the echo signal. According to the principle of radar imaging, the size of the antenna aperture directly determines the angular resolution of the radar, thus determining the overall resolution of the imaging. However, in practical applications, the antenna aperture is often limited by factors such as the size and cost of the carrier, and cannot be expanded at will, which limits the improvement of the imaging resolution of the real aperture radar. In order to solve this problem, synthetic aperture radar technology has gradually attracted the attention of researchers. Synthetic aperture radar uses the radar system to continuously transmit and receive multiple pulses during motion. By processing and superimposing the echoes of multiple pulses, an equivalent virtual aperture larger than the actual antenna aperture can be synthesized, thereby obtaining higher resolution than the actual antenna aperture. Traditional single-input single-output (SISO) radar imaging has problems such as low resolution and vulnerability to noise interference in complex environments. For this reason, multiple input multiple output radar imaging technology came into being.

At the same time, MIMO technology also brings further resolution improvement space for the two radar modes. MIMO radar can simultaneously detect targets from multiple angles and collect richer target feature information by using multiple independent transmission and reception channels in a system. Compared with SISO technology, MIMO technology can significantly increase the amount of effective information, whether it is applied to real aperture mode or synthetic aperture mode, thus helping to improve the resolution of radar imaging. Therefore, active MIMO synthetic aperture radar imaging technology has very high imaging quality and has become an important direction for the development of radar systems. With the advancement of radar technology, the range resolution and angular resolution of the radar are improved. When the resolution unit of the radar is smaller than the physical size of the detected target, the radar can construct a two-dimensional image of the target. Compared with single-point targets, image targets can provide richer information about targets, such as size, shape, etc., which is very beneficial to target recognition and classification. The improvement of radar imaging resolution greatly enhances the ability of radar target detection and parameter estimation, and promotes the progress and innovation of radar technology.

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# 2. CURRENT RESEARCH STATUS AT HOME AND ABROAD

## 2.1. Development Status of Millimeter Wave Radar Imaging at Home and Abroad

The prototype of millimeter-wave radar imaging technology dates back to the mid-twentieth century, when it was used in maritime ship navigation and airport control. However, limited by the technical conditions at that time, its development was difficult. It was not until the late 1980 s that European countries started the research of vehicle-mounted millimeter-wave radar. In the early stage of radar technology development, due to the limitation of hardware conditions at that time, the range and angle resolution of radar is low, and the detected target is only presented as a single point target on the radar screen. After the 1980 s, thanks to the improvement of processor computing power and the progress of microwave theory and device integration technology, radar imaging technology has been booming, imaging resolution has been gradually improved, and it has been widely used in various fields. According to the type of transmitted signal, millimeter wave radar system can be divided into pulse radar and continuous wave radar. The latter includes single frequency continuous wave [4] radar and frequency modulated continuous wave (FMCW) radar. Compared with other radars, the MIMO millimeter-wave radar in the form of linear frequency modulation continuous wave can obtain the range, velocity, azimuth and height of the target by transmitting a wider bandwidth linear frequency modulation signal and accurately improving the parameter control of the frequency modulation and initial phase of the signal. Parameter information, resolution and processing gain are significantly improved compared with traditional radars.

MIMO radar imaging technology is a new type of radar system [5] design concept that combines multi-antenna technology in wireless communication systems with digital array radar technology through creative applications. In MIMO radar systems, different radar waveforms are transmitted simultaneously using multiple antennas, and each antenna can receive the echo signals reflected from the target of all the transmitted signals [6,7]. This multi-transmitting and multi-receiving antenna structure can significantly improve the system's signal-to-noise ratio [8] by performing multi-antenna matching at the transmitting and receiving ends, thereby enhancing the target detection probability and anti-interference capability of the radar, and obtaining higher spatial resolution [9]. In addition, the biggest advantage of MIMO radar systems is that they can obtain three-dimensional stereo image information of the target in one fast "snapshot", while traditional single-input single-output radars require multiple two-dimensional scans to obtain three-dimensional target images. MIMO radars significantly improve the real-time performance of imaging. Aiming at the design of two-dimensional antenna array in MIMO radar [10], the imaging resolution of radar can be further improved by optimizing the arrangement of antenna elements [11]. Combining the above advantages of MIMO radar, its technology shows great application prospects and research value in the field of high-resolution imaging of millimeter-wave radar, which can further improve the three-dimensional imaging resolution of millimeter-wave radar. Compared with SISO radar, MIMO radar imaging can achieve better imaging performance under the same conditions. Combining the advantages of millimeter wave and MIMO radar, it is of great significance to study the imaging technology of MIMO millimeter wave radar.

After decades of development, active near-field synthetic aperture radar imaging technology has made great progress in imaging mode and algorithm, and has been widely used in concealed security inspection. At present, imaging modes include ' single-input single-output (SISO) scanning [12] ', ' two-dimensional multiple-input multiple-output (MIMO) [13] ' and ' MIMO scanning [14] '. Among them, the ' SISO scanning ' mode is the most widely used and most mature mode. The Northwest Pacific National Laboratory of the United States is in a leading position in this technology field. The PNNL laboratory has developed the world 's first millimeter-wave holographic imaging system, which uses the ' SISO plane scanning ' mode to

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achieve three-dimensional imaging through a single transmitting antenna and mechanical scanning [15]. Later, MIMO technology was introduced into this field. Compared with SISO mode, MIMO mode has higher antenna utilization efficiency, looser requirements on the number and spacing of array elements, and more flexible system design. The ' MIMO scanning ' mode combines the advantages of the two modes, maintains the low cost and has the advantages of MIMO, which is the current research hotspot. Aiming at the problem that the partial channel failure of the far-field sparse array leads to the degradation of the imaging quality under the near-field imaging conditions, Wei Ming Tian et al. [16] and Lie Chen Yu et al. [17,18] proposed a near-field imaging point spread function low-grating-lobe MIMO two-dimensional array design method by adding transmitting array elements to the far-field sparse array. With the deepening of MIMO radar research, the synthetic aperture radar (SAR) mode of MIMO radar has also been widely studied. In 2007, Ender et al. first proposed the concept of MIMO-SAR [19], that is, coherent signal synthesis is performed using all antenna transmit and receive channels of MIMO radar to achieve high-resolution SAR imaging. In 2012, Alexander G. Yarovoy et al. proposed an algorithm that can be applied to near-field imaging for two-dimensional MIMO arrays. Through the MIMO distance migration technology, the image reconstruction process is performed in the wavenumber domain, and a good three-dimensional imaging effect is achieved. In 2017, Rong Qiang Zhu et al. proposed a MIMO-SAR imaging algorithm based on three-dimensional range migration, and extended the algorithm to near-field imaging according to the principle that spherical waves can be decomposed into infinite plane waves.

## 2.2. Research Status of Radar Imaging Algorithms

As early as 1951, Carl A. Wiley first proposed the idea of using the Doppler frequency shift of the target to improve the azimuth resolution of the radar, which laid the foundation of synthetic aperture radar technology. In the following decades, the synthetic aperture radar imaging algorithm has made great progress, mainly forming two categories: time domain algorithm and frequency domain algorithm. The time domain algorithm is the famous Back Projection (BP) [20], while the frequency domain algorithm is represented by Range Migration Algorithm (RMA) [21] and Range Doppler Algorithm (RDA) [22]. The common characteristics of these frequency domain algorithms are signal processing and parameter extraction in the frequency domain. After a long period of research and experimental verification, the above algorithms have been widely used. It can be said that the development of synthetic aperture radar imaging algorithm is an important symbol of radar technology progress, which plays a key role in improving radar resolution.

In recent years, some new progress has been made in array design and imaging algorithm research for ' MIMO scanning ' system [23-27]. For example, Han Xingbin et al. used the coherent superposition of multiple transmit and receive channels obtained by MIMO radar to reconstruct the two-dimensional target scattering function image. [28]. In 2012, Alexander G. Yarovoy et al. proposed a MIMO-SAR algorithm that can be used for near-field imaging. They used MIMO range-maneuvering technology for wavenumber domain reconstruction and achieved good three-dimensional imaging results. In 2017, Zhu et al. generalized the three-dimensional range-offset MIMO-SAR algorithm to near-field imaging according to the spherical wave decomposition theory, which provided a reference for near-field planar aperture millimeter-wave radar imaging [29]. In 2018, Deng et al. proposed an efficient three-dimensional imaging algorithm based on spherical wave decomposition theory and non-uniform fast Fourier transform [30]. The algorithm is especially suitable for circular-arc MIMO arrays, which can reduce the ranging error in imaging. Firstly, the spherical wave scattered by the target is decomposed into the superposition of plane waves by using the spherical wave decomposition theory. Then, the non-uniform fast Fourier transform is used to realize efficient signal processing, and the accurate three-dimensional image reconstruction of the circular MIMO

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array is completed. This algorithm provides a more efficient signal processing method for the ' MIMO scanning ' three-dimensional imaging mode and expands its application range. Juan M. Lopez-Sanchez et al. proposed a near-field three-dimensional synthetic aperture radar imaging algorithm based on two-dimensional RMA algorithm and theoretical derivation using fixed phase method [31]. Finally, the high computational efficiency and imaging performance of the algorithm are verified by the measured data.

## 3. MIMO-SAR MILLIMETER WAVE RADAR IMAGING PRINCIPLES

Basic principles of MIMO millimeter wave radar imaging: The high-frequency millimeter wave electromagnetic waves transmitted from multiple transmitting antennas will be reflected on the surface of objects and return as echoes. These echoes will be received by multiple receiving antennas. Then, by measuring the time difference of arrival between echo signals of each antenna pair, the range of the target can be calculated. By analyzing the amplitude of the echo signals, the scattering coefficient of that point on the target can be determined, reflecting the reflection characteristics of that point. Finally, by aggregating the parameters of all scattering points and combining the spatial geometric information of the antenna array, two-dimensional or three-dimensional images of the target can be reconstructed. MIMO millimeter wave radar systems can obtain richer target echo information in the same time period, thus greatly improving imaging efficiency and quality.

## 4. RANGE MIGRATION ALGORITHM PROCESS

The multi-input multi-output millimeter-wave scanning imaging model is shown in Figure 1. The radar with co-located transmitter and receiver performs point-by-point scanning under the condition of multi-wavenumber in parallel trajectory mode to achieve the effect of two-dimensional array and obtain millimeter-wave scattering echo information. Millimeter wave radar adopts linear frequency modulation mode, and the frequency modulation slope is $k_0$. Let the coordinates of the static target be $(x', y', z')$, the moving radar scans in the $XOY$ plane with $z = 0$, the coordinates of the time are $(x, y, 0)$, and the distance between the static target and the radar scanning plane is $Z_0$.

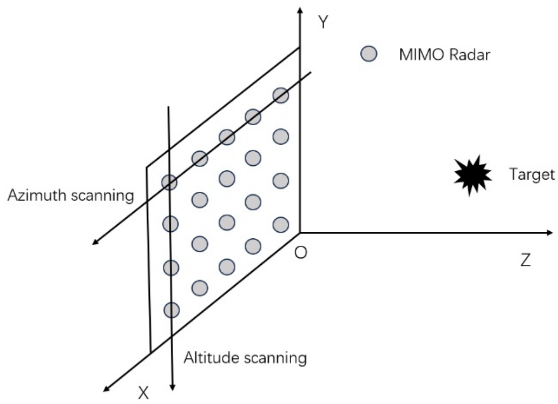


**Figure 1.** Scanning imaging model

The transmitted signal with linear frequency modulation:

$$s_t(t) = e^{j\pi k_0 t^2} e^{j2\pi f_0 t} \tag{2.1}$$

Here, $f_0$ is the carrier frequency of the transmitted signal, $k_0$ is the slope of the frequency modulation signal, and $t$ is the time.

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At a certain moment, the distance between the millimeter wave radar and the static target is $R$:

$$R = \sqrt{(x - x')^2 + (y - y')^2 + z'^2} \tag{2.2}$$

According to the scanning imaging model, The scattering echo signal of the entire imaging region can be expressed as :

$$s_c(x, y, k) = \iiint \xi(x', y', z') e^{-j2Rk} \, dx' dy' dz' \tag{2.3}$$

Where $k = 2\pi f / c$, $\xi(x', y', z')$ represents the scattering coefficient of the point target $(x', y', z')$.

The derivation of this algorithm is based on Weyl 's idea, and the spherical wave is expressed as the superposition of plane waves. Then the RMA imaging method is expressed as

$$\xi(x', y', z') = IFFT_{x',y',z'}\{\text{stolt}_{k \to k_z}\{ FFT_{x,y}\{ s_c(x, y, k)\} \cdot \exp(-jk_z z_0)\}\} \tag{2.4}$$

Finally, the steps of the planar scanning 3D imaging method based on RMA for SAR platform can be summarized as shown in Figure 2:

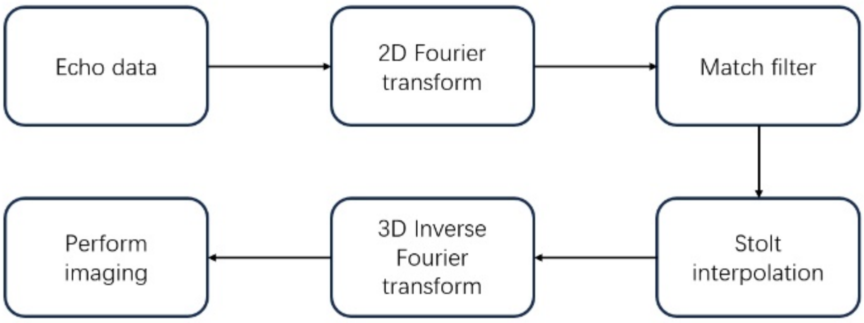


**Figure 2.** Process of distance migration algorithm

## 5. CONCLUSION

The range migration algorithm greatly improves imaging speed by utilizing the high-speed signal processing capability of fast Fourier transforms. Its core idea is to achieve approximate-free decoupling in range and azimuth dimensions using STOLT interpolation. Based on the assumption of spherical wave propagation, the range migration algorithm can image the entire scene at arbitrary viewing angles and arbitrary aperture sizes. Therefore, the range migration algorithm is well suited for large-scene, wide-aperture radar imaging. However, due to the excessive approximations used in the range migration algorithm, its imaging quality is poor. Methods like improving hardware performance and optimizing mathematical formulas of the algorithm can be used to improve imaging resolution. In conclusion, there is huge potential for improving the imaging quality of the range migration algorithm. It is believed that with continuous development, the range migration algorithm will become more and more sophisticated and occupy an irreplaceable position in practical applications.

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Competing interests The authors declare no competing interests.

Authors' contributions Yongsheng Liu: wrote the main manuscript text .

Yanbo Zhang and Zhongmin Wang: Supervision.

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Availability of data and materials All data created and analyzed during this study are included in this published letter.

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