An Imaging Algorithm for Burden Surface with T-shaped MIMO Radar in the Blast Furnace

Xin FU,1,2)* Xianzhong CHEN,1,2) Qingwen HOU,1,2) Zhengpeng WANG1,2) and Yixin YIN1,2)

1) School of Automation & Electrical Engineering, University of Science and Technology Beijing, No. 30 Xueyuan Road, Haidian Zone, Beijing, 100083 China. 2) Key Laboratory of Advanced Control for Iron and Steel Process, Ministry of Education, China, No. 30 Xueyuan Road, Haidian Zone, Beijing, 100083 China.

(Received on April 1, 2014; accepted on August 7, 2014)

This paper proposed a new near-field imaging algorithm for Blast Furnace (BF) burden surface imaging. The algorithm was applied in a novel T-shaped MIMO radar. In the process of beam synthesis focusing, the proposed algorithm does precise phase compensation to realize the equiphase surface. It avoids interpolation, reduces the computational complexity, and is convenient for data batch processing concurrently, which greatly improves the efficiency of operations and enhances the real-time performance. Simulation results and the on-line test result demonstrate the effectiveness and high operational efficiency of the proposed MIMO radar imaging method which has great potential in BF burden surface imaging.

KEY WORDS: T-shaped MIMO radar; burden surface; blast furnace.

1. Introduction

Near-field imaging has been extremely concerned for its widespread application in many civilian military and biomedical applications. Present microwave imaging radars being applied for blast furnace burden surface imaging are single radar,1–3) distributed array radar,4,5) mechanically-scanned radar6) and phased array radar.7) In these four radars, we have to say the advantage and disadvantage of the phased array radar on burden surface detection. It employs a group of antennas to realize the antenna beam electric scanning by phase shifter. Imaging resolution and real-time performance can meet the requirements of industrial BF production. But the high angular resolution is attained by increasing the size and cost of the radar.

In recent years, an emerging radar system is explored with the MIMO concept.8) With the introduction of space-diversity and multiplexing techniques, MIMO radar can use less actual antenna elements to form a virtual antenna array and obtain multiplied communication channels and freedom.9) MIMO radar for imaging applications can enhance the imaging resolution and reduce the radar cost significantly. So far, neither MIMO radar used in BF industry nor research for MIMO radar suitable for harsh environment and rough surface imaging is reported.

Many types of microwave imaging algorithms such as the range migration algorithm (RD),10) the chirp scaling algorithm (CS),11) the omega-k algorithm (ω-k)12) and the wave-number domain algorithm are based on a plane wave which are suitable for far-field imaging and the resolutions are limited by classical radar uncertainty principle. These limitations make it difficult to use these conventional algorithms for BF burden surface imaging. How to obtain a more realistic and high-resolution burden surface images in harsh environment is also a hot topic. The near-field imaging algorithm has been well developed. The tomographic imaging algorithm13) is successfully used in the near-field imaging. This algorithm is suitable for wide angle imaging, but it needs summation in the frequency dimension. Also, it is too slow for real time imaging when the span of the angle is large in azimuth. A two-dimensional nonuniform fast Fourier transformation (NUFFT) is applied to the near-field scattered data.14) However the algorithm is only suitable for the narrow angular case. The fast cyclical convolution algorithm15) is also able to create near-field SAR images of the target. In order to save computing time, the author16) presents a near-field linear SAR algorithm based on the use of a focusing operator defined by the measurement geometry. The authors17) studied imaging system based on the combination of ultra-wideband (UWB) transmission, MIMO array, and SAR. However, the imaging algorithm also utilized the range migration which needs 3-D Stolt interpolation and a 3-D IFFT.

The above all near-field imaging algorithms need interpolation for echo data in order that the spherical wave can convert into planar wave. The interpolation is not only time-consuming, but also can cause certain deviation on the edge of the target. Aiming at the problem that these imaging algorithms suffer heavy computational burden and poor real-time capability, a new highly computing efficiency near-field imaging method is proposed based on the assumption of spherical wave. In the process of beam synthesis focusing, the proposed algorithm does precise phase compensation to
realize the equiphase surface. It avoids interpolation, reduces the computational complexity, and is convenient for data batch processing concurrently, which greatly improves the efficiency of operations. The proposed algorithm has great potential in BF burden surface imaging. The image resolution can be also enhanced greatly.

This paper is organized as follows. The principle of beam synthesis focusing for T-shaped MIMO radar is elaborated in the second part. The specific algorithm is described in the third part. The computation quantity of the algorithm in this paper is analyzed in the fourth part. Finally, simulation results demonstrate the effectiveness and high operational efficiency of the proposed MIMO radar imaging method. The on-line test imaging results are also presented to verify that the algorithm can effectively image the burden surface of BF.

2. Near-field Beam Synthesis Focusing Principle of the T-shaped MIMO Radar

In the near-field beam synthesis focusing, phase compensation, which is used in the focus of spherical wave, is applied to the signal received by each element according to the different radius of curvature between target and each array element. We can obtain the focus in-phase superposition for each point of the target to generate a maximum output in a particular beam direction within the area to be scanned. Synthesized beam scans the target plane point by point, and the focusing output would be obtained as the hypothetical source of scanning point, and then the distribution of the target plane could be gained. The target location is the peak output of the focused beam.

Beam scanning can't focus on the target using conventional scanning of the phased array antennas in the near-field. It must align the phase of each antenna element to focus on a point on the target surface along the direction of the main beam. Then the focused beam scans by the distance and azimuth of the target.

The angle information along with the range information gives us the complete information about the target location. The target location can be specified by three parameters \( (r, \theta, \phi) \), where \( \theta \) is the azimuth angle and \( \phi \) is the elevation angle. Figure 1 illustrates these three parameters. In this thesis, we usually deal with only one angle because the two angles \( \theta \) and \( \phi \) can be processed independently. The one-dimensional results provided can be easily generalized to two dimensions.

The T-shaped MIMO antenna arrays with 16 transmit elements and 16 receive elements are arranged by the following Fig. 2. The number of virtual elements is 256. As we all know, the overall performance of a MIMO antenna array is the same as its equivalent array. So, we only consider the virtual array.

\[
r_i = \left(0, \frac{N-1}{4}dr, 0\right)
\]

represents the center of the virtual array aperture. \( \theta \) is the angle shown in Fig. 3. It can be expressed as:

\[
\sin \theta = \frac{x_0^2 + y_0^2 - N^2dr^2 / 4}{x_0^2 + y_0^2 - N^2dr^2 / 4 + z_0^2} \hspace{1cm} (1)
\]

Formula (2) and (3) give the position of the T-shaped MIMO radar and the position of the total virtual array elements.

\[
\begin{align*}
x_{Ti} &= \left(-\frac{M-1}{2} + i\right) dt, (M = 16, i = 0,1,\ldots,M-1, dt = 1.2\lambda_c) \\
y_{Rj} &= j \cdot dr, (N = 16, j = 1,\ldots,N, dr = 1.2\lambda_c)
\end{align*}
\hspace{1cm} (2)
\]

The position of the total virtual array elements are described by a transducer set

\[
P_{ij} = \left\{ P_{ij} \left| P_{ij} = \left(\frac{x_{Ti} + y_{Rj}}{2}, \frac{M-1}{2}, 0\right) \right. \right\} i, j \in \gamma \hspace{1cm} (3)
\]

Fig. 1. Ranger \( r \), azimuth angle \( \theta \), and elevation angle \( \phi \).

Fig. 2. T-shaped MIMO antenna array element distribution and virtual array.
MIMO radar shows the synthetic pattern of 16 antenna radiation and array normal direction. Where, \( \gamma = \{1, 2, \ldots, MN\} \) denotes the index set, \( MN \) denotes the total number of the virtual array elements. The virtual array element spacing is \( \frac{dt}{2} = \frac{dr}{2} = 0.6\lambda \). Single target in \( r_0(x_0, y_0, z_0) \) is considered for a strong point on the burden surface.

The antenna pattern of MIMO radar is equal to the product of the transmitting beam pattern and the receiving beam pattern. That can be expressed as:

\[
F_{\text{MIMO}}(\theta, \phi) = F_T(\theta, \phi) \otimes F_R(\theta, \phi) \quad \text{...... (4)}
\]

Where, \( \otimes \) is Kronecker product. Formula can be written as:

\[
F_{\text{MIMO}}(\theta, \phi) = \left[ \sum_{j=0}^{N-1} a_j \exp \left( j \frac{2\pi}{\lambda} (r_j u + r_j v) \right) \right] \otimes \left[ \sum_{k=0}^{M-1} a_k \exp \left( j \frac{2\pi}{\lambda} (r_k u + r_k v) \right) \right] \quad \text{...... (5)}
\]

where, \( (r_j, v_j) \) and \( (r_k, v_k) \) are respectively the \( j \)th location coordinates of the transmitter and receiver array elements. \( a_j \) and \( a_k \) are the excitation current of the \( j \)th element of the transmitter and receiver array elements. \( u = \sin \theta \cos \phi, v = \sin \theta \sin \phi \) and \( \theta \) and \( \phi \) are the angle between the array antenna radiation and array normal direction. Figure 4 shows the synthetic pattern of 16 \( \times \) 16 elements for T-shaped MIMO radar (\( \theta = 0, \phi = 0 \)).

If the antenna main beam pointing is \( (\theta_0, \phi_0) \), each antenna element should be added to the phase-weighted:

\[
\exp(-jkx_\theta u_0) \quad \text{......... (6)}
\]

Where \( k = 2\pi / \lambda, u_0 = \sin \theta_0 \cos \phi_0 \). We assume a fixed \( \phi_0, x_0 \) is the distance from the center of virtual array to the \( n \)th array element. When \( u = u_0 \), the main beam scans from \( u = 0 \) to \( u = u_0 \).

If we want to focus on the target \( (u_0, R_0) \), the antenna element must add phase weighted linear and quadratic term at \( x_0 \) in order to make all the elements in-phase at \( (u_0, R_0) \) to achieve the vector entirely in-phase accumulation.

So, antenna pattern can be written as:

\[
f(u, R) = \frac{1}{N} \sum_{n=0}^{N-1} I_n \exp \left(-k x_\theta u_0 + \frac{k' x_\theta^2}{2R_0} \right) \exp \left( k x_\theta u_0 - \frac{k' x_\theta^2}{2R_0} \right)
\]

\[
= \frac{1}{N} \sum_{n=0}^{N-1} I_n \exp \left( k x_\theta (u - u_0) - \frac{k' x_\theta^2}{2} \left( \frac{1}{R} - \frac{1}{R_0} \right) \right)
\]

\[
\text{.................... (7)}
\]

Where \( k' = 2\pi \cos^2 \theta / \lambda \). The linear term \(-k x_\theta u_0 \) of \( x_0 \) means the main lobe scanning the azimuth \( \theta_0 = \sin^{-1}u_0 \) and the quadratic item \( k' x_\theta^2 / 2R_0 \) means the focal point aligned distance \( R_0 \). We give with phase compensation according to each array element position to achieve beam scanning after focus on the strong point.

After completing phase compensation for \( \theta \), we use the same method to compensate for \( \phi \). The synthesized beam of T-shaped MIMO radar scans by controlling the phase. Linear array can achieve two-dimension beam controlling and rectangular array can realize the 3D beam controlling. Figure 5 is the schematic diagram of MIMO array antenna near field beam focusing.

3. The Algorithm of Near-field Beam Synthesis Focusing Imaging in the Blast Furnace

We all know the conventional range migration (RM) imaging algorithm performs 3-D Stolt interpolation and 3-D IFFT. That can greatly increase the computation burden of the system. In order to reduce the computational complexity, the delay and sum processing in traditional RM algorithm is transformed into beam-forming and beam-scanning to complete azimuth focusing. The proposed method avoids the Stolt interpolation, avoids seeking the delay of all pixels one by one, reduces the computational complexity, and is convenient for data batch processing concurrently, which greatly improves the efficiency of operations.

The specific algorithm is as follows:

Step 1 initiates the process. \( A_{in} \exp(j \phi_{in}) \) is the complex envelope of the echo from the \( i \)th range bin received by the \( n \)th element. Where \( A_{in} \) denotes the echo signal amplitude. It is dependent on the target’s radar cross section, transmitted power, etc. \( \phi_{in} \) is the echo phase.

Step 2 is the search for \( R_0 \) that is marked in Fig. 3.

Step 3 is the adaptive beam-forming step. The process is to compensate for the phase variations, which are assumed to be due to the first set of factors. For ease of all the received elements and the reference array element being in the same phase, the proper phase shift for the \( n \)th element is the negative of the phase difference \( \Delta \phi_{in} = \phi_{in} - \phi_{00} \). So, the complex signal envelope at the \( n \)th element becomes \( A_{in} \).
exp(jφ0)exp[-j(φ0n − φ0)].

Step 4 compensate for all the distance unit. The sample of the complex envelope from the ith range bin now become $A_n \exp(j(\phi_n - \phi_0 + \phi_0))$.

Step 5 is to focus the array at all ranges simultaneously. It is accomplished for an arbitrary range $R_i$ by refocusing the array from the reference range $R_0$ to $R_i$. The focused results are $A_n \exp(j(\phi_n - \phi_0 + \phi_0))$.

This step requires a knowledge of the range $R_0$. Here, the value of is available in the system for it is measured by the round-trip travel time in equation of the signal to the phase synchronizing source and it is read directly into the signal processor from the radar receiver.

Step 6 imparts a linear phase rotation to the range-focused complex envelope for each scan angle $u$. The phase shift is $\exp(-jkxnu0)$. The last step forms the sum of the linearly phase-weighted, range-focused samples to obtain the image for the ith range bin $\sum_{n=1}^{N} B_n e^{-jkx_n}$. Table 1 gives the computation quantity analysis between the algorithm in this paper and the RM algorithm. 

5. Experimental Results and Discussion

5.1. Simulation Experiment

In this section, point-target simulation is carried out to verify the validity of the proposed imaging algorithm. The imaging system works on X-band with carrier frequency $f_c$.
10 GHz, signal bandwidth about $B = 2 \text{ GHz}$, the Chirp duration $T = 45 \text{ ms}$. We assume that there are three point-targets in imaging area. Their coordinates are respectively $(-1 \text{ m}, 3 \text{ m})$, $(0 \text{ m}, 1 \text{ m})$, and $(1 \text{ m}, 4 \text{ m})$. The sampling number in one chirp duration is 1024. Figure 6 shows the image of three point-targets by algorithm in this paper. The processing time is 0.04 s. The three targets are focused on the positions in accordance with their true locations. So, the proposed algorithm can effectively achieve the focus imaging.

5.2. Image Resolution

In order to analyze image quality of the algorithm, we choose the resolution of the 3 dB level and peak side-lobe ratio (PSLR) as evaluation parameters. We choose the target $(-1 \text{ m}, 3 \text{ m})$ for example. The image quality of different imaging algorithms are compared in Table 2.

We can see that the range resolution of the two algorithms is the same from Table 2. This is because the range resolution is only related to the bandwidth of the signal. The azimuth resolution of proposed algorithm is better than the RM algorithm.\(^{17)}\)

5.3. Operation Time Analysis

We image the three point-targets using the two kinds of algorithm in order to validate the theoretical analysis in section 4. The imaging processing has been done on the same computer. The operation time is shown in Table 3. We can see that the algorithm in this paper can realize focus imaging faster and better able to meet the requirements of real-time.

5.4. Algorithm Test in the Process of Iron Making

The primary goal of the MIMO array design is to construct an array which is able to exhibit the same level of beam-forming performances as the synthetic aperture.\(^{17)}\) Due to the MIMO principle,\(^{17)}\) the total number of antenna elements is reduced from 256 to 32, which largely reduced the radar cost. The total length of the antenna is 187 mm. The size of the waveguide Cavity is 14 mm $\times$ 10 mm and the wall thickness is 2 mm $\times$ 4 mm. The main lobe level is 32.8 dB, side lobe is $-13.1 \text{ dB}$, and HPBW is $5.1^\circ$. The output port of the antenna is covered by PTFE medium which provides the performance of high temperature resistance, high hardness and anti-dust.\(^{19)}\)

The prototype of the 16$\times$16 T-shaped MIMO radar imaging system has been installed on the top of 7th BF in Wuhan Iron and Steel Corporation on April 29th 2012 (Fig. 7). Under the condition of blast furnace smelting anterograde, the radar system has kept running successfully for more than half a year. In this section, we test the imaging algorithm based on the algorithm in this paper against the measured data using the 16$\times$16 T-shaped MIMO radar. An 16$\times$16 antenna array with 1024 sampling rate can produce 256$\times$1024 samples. We use the algorithm of this paper to image 3721 points of the blast furnace and reconstruct the burden surface. The burden surface imaging of BF based on the presented imaging algorithm in different time is shown in Fig. 8. Under the condition of multi-ring burden distribution in bell-less BF top, the

| Evaluation parameter | RM algorithm\(^{17)}\) | Algorithm in this paper |
|----------------------|------------------------|------------------------|
| Azimuth resolution/m | 0.03                   | 0.012                  |
| Azimuth PSLR/dB      | $-15.39$               | $-13.12$               |
| Range resolution/m   | 0.007                  | 0.007                  |
| Range PSLR/dB        | $-13.24$               | $-13.24$               |

Table 2. Comparison for image quality of different imaging algorithms.

| Sampling number      | The total operation time/s |
|----------------------|----------------------------|
| RM algorithm\(^{17)}| Algorithm in this paper |
| 1024$\times$256      | 12.05                      | 0.04                   |
| 2048$\times$512      | 40.89                      | 0.09                   |
| 4096$\times$1024     | 171.64                     | 0.44                   |

Table 3. Time consuming comparison of different algorithms.

Fig. 6. The imaging results using the algorithm in this paper.

Fig. 7. T-shaped antenna array.
optimal surface profile can be achieved with the shape of terrace and funnel. The results demonstrate the effectiveness of the algorithm in this paper.

6. Conclusion

In this paper, a new imaging algorithm for blast furnace based on the T-shaped MIMO radar was presented. The synthetic pattern of $16 \times 16$ elements for T-shaped MIMO radar was derived in theory. Simulation results demonstrate the effectiveness and high operational efficiency of the proposed MIMO radar imaging method. The on-line test imaging result can verify the feasibility of the algorithm which has great potential in BF burden surface imaging. But there are many factors such as dust, spilled material falling blocks and the high temperature plasma gas being full of internal BF in the production process which can cause measured signal attenuation and multipath reflection. These reasons can affect the image quality of the burden surface. So, future work will be on minimizing the influence factors to improve image resolution.

Acknowledgment

This work is partially supported by National Natural Science Foundation of China under grant number 61333002.

REFERENCES

1) H. Saxen and J. Himnella: Miner. Process. Extr. M., 25 (2004), 1.
2) X. Z. Chen and J. Liu: Ind. Inst. Automat., 6 (2005), 10.
3) X. Z. Chen, Y. X. Yin, H. W. Huo, X. L. Li, J. Ma and M. Wang: J. Univ. Sci. Technol. Beijing, 33 (2011), 215.
4) X. Z. Chen, J. D. Wei, D. Xu, Q. W. Hou and Z. L. Bai: ISIJ Int., 52 (2012), 2048.
5) X. Zhou, X. L. Li and D. X. Liu: Intelligent Control and Information Processing (ICICIP) Conf., IEEE Computer Society, United States, (2010), 286.
6) D. G. Johnson: IEEE Radar Conf., IEEE, Piscataway, NJ, (2008), 1.
7) T. Y. Yun and C. Wang: IEEE T. Antenn. Propag., 50 (2002), 641.
8) E. Fishler, A. Haimovich and R. Blum: IEEE Radar Conf., Piscataway, NJ, (2004), 71.
9) X. Zhuge and A. G. Yarovoy: 4th European Antennas and Propagation (EuCAP) Conf., IEEE Computer Society, United States, (2010), 1.
10) J. M. Lopez-Sanchez and J. Fortuny-Guasch: IEEE T. Antenn. Propag., 48 (2000), 5.
11) D. H. Zhang and X. L. Zhang: Synthetic Aperture Radar Conf., Asia-Pacific, Institution of Engineering and Technology, UK, (2009), 1043.
12) Y. Qi, W. Tan, Y. Wang, W. Hong and Y. Wu: Prog. Electromagn. Res., 121 (2011), 409.
13) T. Vaupel and T. F. Elbert: IEEE T. Antenn. Propag., 54 (2006), 144.
14) S. Y. Li, H. J. Sun, B. C. Zhu and R. Liu: IEEE Antenn. Wirel. Pr., 9 (2010), 814.
15) B. L. Ren, S. Y. Li, H. J. Sun and X. Lv: Microwave and Millimeter Wave Technology (ICMWT) Conf., Vol. 2, IEEE Computer Society, United States, (2012).
16) J. Fortuny and A. J. Sieber: IEEE T. Antenn. Pr., 42 (1994), 637.
17) X. D. Zhuge and A. G. Yarovoy: IEEE T. Geosci. Remote, 49 (2011), 599.
18) F. C. Robey, S. Coutts and D. Weikle: 38th Asilomar Conf. on Signal, System and Computer, Pacific Grove, CA, (2004), 300.
19) G. Armbrrecht, E. Denicke, N. Pohl, T. Musch and I. Rolfes: 3rd European Antennas and Propagation (EuCAP) Conf., IEEE Computer Society, United States, (2009), 3090.
20) H. G. Du and K. Z. Guo: Iron Making, 14 (1995), 33.