Wideband MIMO Radar Waveform Optimization Based on Dynamic Adjustment of Signal Bandwidth

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Abstract. Considering the need of multi-target imaging, a method about MIMO radar waveform optimization based on dynamic adjustment of signal bandwidth is proposed. At first, the closed-loop feedback between the range profile and the signal bandwidth is established, which can design the required bandwidth of transmit signal in different directions, according to the range profile of targets. And then, considering the request of beampattern and the bandwidth limitation, a waveform optimization model is established and solved. Therefore, the multi-target observation and the dynamic adjustment of the signal bandwidth are accomplished. What's more, satisfactory imaging results are obtained under the least resource consumption. In the end, the simulation has proved the performance of the algorithm in low SNR circumstance.

Keywords: MIMO radar · Cognition · Waveform design · Range profile
Range resolution

1 Introduction

MIMO radar contains multiple antennas at the transmitter and receiver [1–3] and can be divided into distributed MIMO radar [4] and centralized MIMO radar [5]. Each emitter element of centralized MIMO radar can transmit signal independently. Therefore, centralized MIMO radar possesses good waveform diversity gain [5, 6]. In order to design the waveform self-adaptively and improve the radar performance by taking advantage of the prior information and feedback information, cognitive techniques have been introduced to radar system. The most important feature of cognitive radar is the closed-loop feedback. The cognition of the external environment is achieved based on the feedback information, so the exact match between the transmitting signal and the environment is accomplished [7–9].

There have already been some research results about cognitive waveform design based on MIMO radar at home and abroad. And existing cognitive waveform design

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principles can be summarized into two aspects: the one is based on the SNR [10–13] and the other is based on the MI [14–17]. However, these algorithms are studied for narrowband signal according to the need of radar tasks like tracking and detection, and the need of imaging task is not considered. Target imaging can provide important target features for identification, so it plays an important role among the radar tasks. To obtain the high resolution range profile, the wideband transmitting signal is required. Thus, the wideband cognitive waveform design focused on imaging task based on MIMO radar is studied in the paper.

As is known to all, the greater the signal bandwidth, the larger the transmitting power. And the larger wear and tear will be caused to the transmitter devices. For imaging task, the bandwidth of transmitting signal determines the range resolution. If the bandwidth of transmitting signal is too large and is enough to distinguish each scatterer of the target in the range direction, the bandwidth resource will be wasted and extra wear and tear will be caused to the transmitter; if the bandwidth of transmitting signal is too small, the aliasing will exist in the range profile. So we should design the bandwidth of transmitting signal synthesized in different target directions cognitively according to the need of task.

In conclusion, a method about MIMO radar waveform optimization based on dynamic adjustment of signal bandwidth is proposed. In the paper, the closed-loop feedback between the range profile and the signal bandwidth is established, which can design the required bandwidth of transmitting signal in different directions; and then, considering the request of beampattern and the bandwidth limitation, a waveform optimization model is established and solved.

2 MIMO Radar Signal Model

Suppose the emitter array of MIMO radar is a uniform array, as shown in Fig. 1, which is consisted of M array elements and the antenna spacing is d. The transmitting signal of the m th array element can be expressed as

$$s_m(t) = x_m(t)\mathrm{e}^{j2\pi f_c t}, 0 \leq t \leq T_p \tag{1}$$

where $x_m(t)$ denotes the baseband signal, f_c denotes the carrier frequency, T_p denotes the pulse width. So the transmit signal synthesized at the angle θ can be denoted as

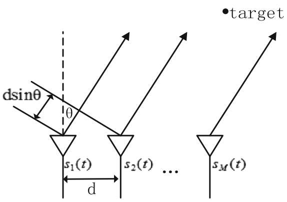

Fig. 1. The diagram of MIMO radar field emitter array

$$s(\theta,t)=\sum_{m=0}^{M-1}x_m(t+\frac{md\ \sin\theta}{c})e^{j2\pi f_c(t+\frac{md\sin\theta}{c})},0\le t\le T_p \tag{2}$$

where c denotes the light speed.

In practical application, discrete baseband signal is considered, that is $x_m(n)=x_m(t)|_{t=(n-1)T_s},n=1,2,\cdots,N$. In which, N denotes the number of sub-pulses in a pulse and T_s denotes the pulse width of sub-pulse. So the spectrum expression of discrete baseband signal can be denoted as

$$y_m(l)=\sum_{n=1}^{N}x_m(n)\mathrm{e}^{-j\frac{2\pi}{N}(n-1)l},l=-L/2,-L/2+1,\cdots,L/2-1 \tag{3}$$

In which L denotes the number of frequency points. Therefore, at the frequency f_c+lB/L the spectrum of discrete baseband signal transmitted by the whole array is $\boldsymbol{y}(l)=[y_1(l),y_2(l),\cdots,y_M(l)]^T=\boldsymbol{X}\boldsymbol{f}_l$. In which, $\boldsymbol{f}_l=[1,\mathrm{e}^{-j2\pi l/L},\cdots,\mathrm{e}^{-j2\pi(N-1)l/L}]^T$ is the transformation vector of DFT at the l th frequency point, $\boldsymbol{X}=[\boldsymbol{x}_1,\boldsymbol{x}_2,\cdots,\boldsymbol{x}_N]$ is the discrete baseband signal transmitted by the whole array, $\boldsymbol{x}_n=[x_1(n),x_2(n),\cdots,x_M(n)]^T$.

According to the analysis above, at the angle θ the power spectrum of the signal at the frequency f_c+lB/L can be denoted as

$$P_l(\theta)=|\boldsymbol{a}_l^{\mathrm{T}}(\theta)\boldsymbol{X}\boldsymbol{f}_l|^2/L \tag{4}$$

in which,

$$\begin{gathered}\mathbf{a}_l(\theta)=[1,\mathrm{e}^{j2\pi(f_c+lB/L)\frac{d\sin\theta}{c}},\cdots,\mathrm{e}^{j2\pi(f_c+lB/L)\frac{(M-1)d\sin\theta}{c}}]^{\mathrm{T}},\\ l=-L/2,-L/2+1,\cdots,-L/2-1\end{gathered} \tag{5}$$

denotes the steering vector at the frequency f_c+lB/L.

3 Waveform Design Based on Dynamic Adjustment of Signal Bandwidth

During the imaging, if the bandwidth of transmitting signal is too large and is enough to distinguish each scatterer of the target in the range direction, the bandwidth resource will be wasted and extra wear and tear will be caused to the transmitter; if the bandwidth of transmitting signal is too small, the aliasing will exist in the range profile. So we should design the bandwidth of transmitting signal synthesized in different target directions. The detailed process is stated as follows

Step1: set arbitrary bandwidth values of signals synthesized in the H target directions, that is $\{B_h\}_{h=1}^{H}$ and design the transmitting waveform. Calculate the main lobe areas of these transmitting signals' point spread function (PSF), which can be denoted as $\{S_{0h}\}_{h=1}^{H}$.

Step2: obtain the range profiles of targets in different directions and calculate the areas of all main lobes in the profiles, that is $\{S_{hi_h}\}_{i_h=1}^{I_h}, h = 1, 2, \cdots, H$, where I_h denotes the number of main lobes in range profile of the target in the h th target direction.

Step3: calculate the number of scattering points included in each main lobe, which can be denoted as $\{N_{hi_h}\}_{i_h=1}^{I_h}, h = 1, 2, \cdots, H$. It is easy to know that

$$N_{hi_h} = [S_{hi_h}/S_{0h}], i_h = 1, 2, \cdots, I_h; h = 1, 2, \cdots, H \tag{6}$$

Step4: set $h = 1$. If $\forall i_h \in \{1, 2, \cdots, I_h\}, N_{hi_h} = 1$, we can know that there is no aliasing existing in the range profile of the target in the h th target direction, so we can set $\rho'_h = d_h$, $B'_h = c/(2\rho'_h)$, where ρ'_h is the range resolution, d_h is the closest distance between the two scattering points, B'_h is the bandwidth of the transmitting signal synthesized in this target direction. At the moment, if $h = H$, then the algorithm is finished; otherwise, set $h = h + 1$ and repeat this step. If $\exists i_h \in \{1, 2, \cdots, I_h\}, N_{hi_h} \geq 2$, then carry out the next step.

Step5: in the h th target direction, suppose the aliasing is existing in the $J_h (J_h \leq I_h)$ main lobes of the range profile. According to the Rayleigh criterion, if the minimum synthesis strength of two diffraction spots is the 0.735 times of the maximum strength of an isolated diffraction spot, we can exactly distinguish the two spots. So calculate the bandwidth of these main lobes at the 0.3675 times of the PSF's peak value, which can be denoted as $\{d_{hj_h}\}_{j_h=1}^{J_h}$. What's more, calculate the bandwidth of PSF's main lobe at the 0.3675 times of the peak value, which can be denoted as d_{0h}. Set $\rho'_h = \min_{j_h}\{(d_{hj_h} - d_{0h})/(N_{hj_h} - 1)\}$ and $B'_h = c/(2\rho'_h)$. At the moment, if $h = H$, then set $\{B_h\}_{h=1}^{H} = \{B'_h\}_{h=1}^{H}$ and back to step1; otherwise, set $h = h + 1$ and back to step4.

3.1 Establishment and Solution of Waveform Optimization Model

In the algorithm above, we should optimize the waveform according to the designed signal bandwidth. From the analysis in part 2, we can know that designing the $P_n(\theta_k), k = 1, 2, \cdots, K; n = 1, 2, \cdots, N$ can determine the bandwidth of transmitting signal synthesized in the target directions and the power distribution on the frequency band, where θ_k is the k th discrete azimuth and K is the number of discrete azimuths.

According to the approximation of the designed waveform and desired waveform, the optimization model can be established as follows

$$\begin{aligned} \min_{\{x_m(l)\}} \quad & \sum_{k=1}^{K} \sum_{l=-L/2}^{L/2-1} |P_l(\theta_k) - p_{kl}|^2 \\ \text{s.t.} \quad & \text{PAR}(\boldsymbol{x}_m) \leq \rho, \quad m = 0, \cdots, M-1 \end{aligned} \tag{7}$$

in which, p_{kl} denotes the desired power spectrum at the l th frequency point at angle θ_k, ρ denotes the pre-set threshold value of PAR. And the PAR of the transmitting signal of the m th array element can be denoted as

$$\mathrm{PAR}(\boldsymbol{x}_m) = \frac{\max\limits_{n} |x_m(n)|^2}{\frac{1}{N}\sum\limits_{n=0}^{N-1} |x_m(n)|^2} \tag{8}$$

$$\sum_{n=0}^{N-1} |x_m(n)|^2 = N, \quad m = 0, \cdots, M-1 \tag{9}$$

From the analysis above, we can know that the bandwidth values of signals synthesized in the H target directions is $\{B_h\}_{h=1}^{H}$, the total bandwidth of transmitting signals is $B = \sum\limits_{h=1}^{H} B_h$ and the number of frequency points occupied by the transmit signal synthesized in the h th target direction is $N_h = round(B_h L/B)$. Therefore, in the h th target direction, we can get the desired power spectrum by distributing the transmit power on the N_h frequency points according to the actual situation. It is important to note that in order to distinguish the echoes from different target directions, transmitting signals synthesized in different directions should be distributed on the orthogonal frequency band.

For the optimization model above, we can solve it by referring to the solving algorithm in [18]. Through dividing the solving process into two stages, we can get the transmit matrix $\boldsymbol{X}$ in the end.

4 Simulation Experiments

Suppose the emitter array is consisted of ten linearly spaced isotropic emitter array elements, that is $M = 10$ and the inter-element spacing is $d = 0.5 * c/(f_c + B/2)$. The carrier frequency is $f_c = 10\,\mathrm{GHz}$, the number of sub-pulses is $N = 400$, the frequency points number is $L = 400$ and the discrete azimuth number is $K = 181$.

Suppose there is a ISS at $-20°$ and its scatterer model is shown in Figs. 2 and 3.

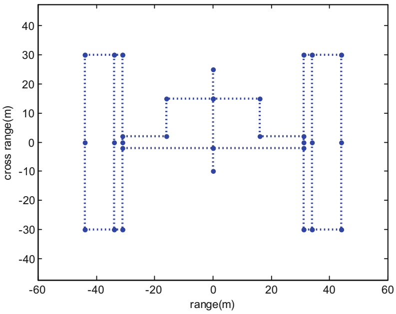

Fig. 2. Scatterer model of the target.

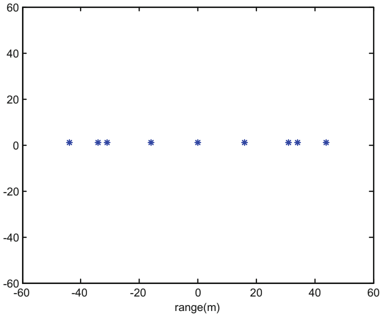

Fig. 3. Scatterer model in the range direction.

Firstly, set arbitrary bandwidth value of the transmitting signal synthesized at $-20°$, that is $B_1 = 30\,\text{MHz}$. The corresponding waveform is designed and is shown in Fig. 4. From the Fig. 4, we can see that parameters of the designed waveform are in accordance with the parameters set before. The PSF of the transmitting signal synthesized at $-20°$ is shown in Fig. 5 and we can get that $d_{01} = 6.8\,\text{m}$, $S_{01} = 4.47$. In low SNR circumstance ($SNR = -10\,\text{dB}$ in the paper), the range profile of the target at $-20°$ is shown in Fig. 6. We can get that the values of $\{S_{1i_1}\}_{i_1=1}^{7}$ are 4.45, 8.98, 4.43, 4.50, 4.59, 8.79, 4.50, so the values of $\{N_{1i_1}\}_{i_1=1}^{7}$ are 1, 2, 1, 1, 1, 2, 1. For the two main lobes that contain aliasing, we can know that the values of $\{d_{1j_1}\}_{j_1=1}^{2}$ are 9.63 m and 9.6 m. So according to the algorithm proposed in the paper, we can make sure the range resolution that can exactly distinguish each scattering point in the range direction is $\rho'_1 = \min_{j_1}\{(d_{1j_1} - d_{01})/(N_{1j_1} - 1)\} = 2.8\,\text{m}$ and the bandwidth of the transmitting signal in this direction is $B'_1 = c/(2\rho'_1) = 54\,\text{MHz}$.

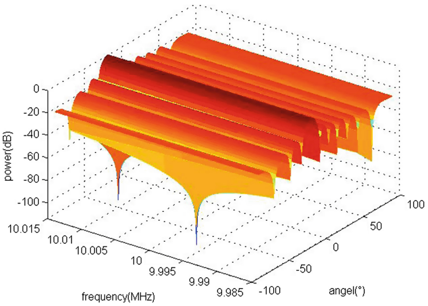

Fig. 4. The designed waveform.

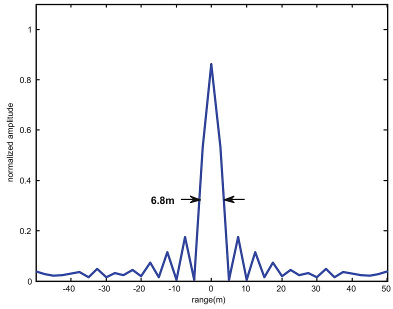

Fig. 5. The PSF of the transmitting signal.

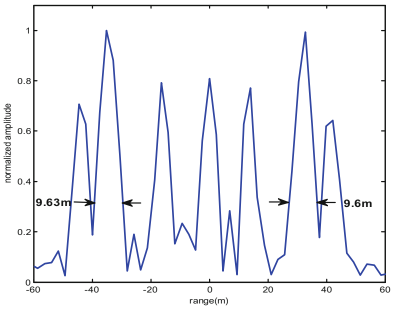

Fig. 6. The range profile of the target.

According to the analysis above, we can know that $B_1 = 54\,\text{MHz}$. The corresponding waveform is designed and is shown in Fig. 7. The PSF of the transmitting signal synthesized at $-20°$ is shown in Fig. 8 and we can get that $S_{01} = 2.75$. In low

SNR circumstance ($SNR = -10\,\mathrm{dB}$ in the paper), the range profile of the target is shown in Fig. 9. We can get that the values of $\{S_{1i_1}\}_{i_1=1}^{9}$ are 2.97, 2.78, 2.68, 2.72, 2.75, 2.71, 2.62, 2.85, 2.80 and $\{N_{1i_1}\}_{i_1=1}^{9} = 1$. That is to say, each scattering point in the range direction is separated. And from the Fig. 9, we can get the closest distance between the two scattering points is 2.95 m, which is approximated to $\rho_1' = 2.8\,\mathrm{m}$ designed by the algorithm in the paper. Therefore, the performance of the algorithm is proved.

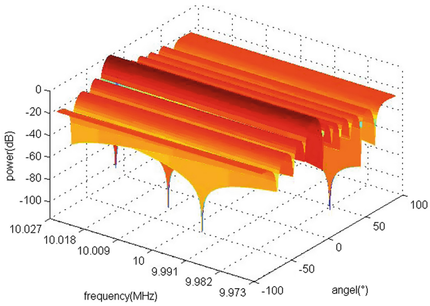

Fig. 7. The designed waveform.

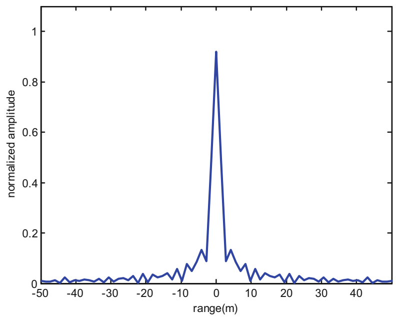

Fig. 8. The PSF of the transmitting signal.

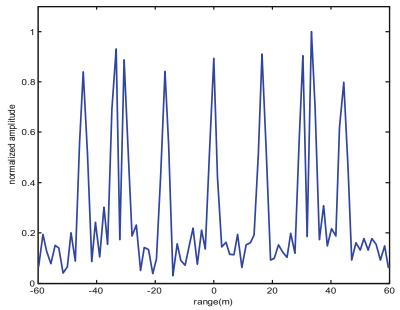

Fig. 9. The range profile of the target.

5 Conclusion

By taking advantage of the good waveform diversity gain of the centralized MIMO radar and the closed-loop feedback of the cognitive radar, a method about MIMO radar waveform optimization based on dynamic adjustment of signal bandwidth is proposed. The simulation results indicate that the method has established the closed-loop feedback between the range profile and the signal bandwidth, which can design the required bandwidth of transmit signal in different directions, according to the range profile of targets. And the simulations have proved the performance of the algorithm in low SNR circumstance in the end.

References

1. Fisher, E., Haimovich, A., Blum, R.S.: MIMO radar: an idea whose time has come. In: Proceedings of IEEE Radar 2004 Conference, PA, pp. 71–78 (2004)
2. Guang, H., Abeysekera, S.S.: Receiver design for range and doppler sidelobe suppression using MIMO and phased-array radar. IEEE Trans. Sig. Process. **61**(6), 1315–1326 (2013)
3. Wang, H.J., Xu, H.B., Lu, M.: Technology and application analysis of MIMO radar. J. Radar Sci. Technol. **7**(4), 245–249 (2009). (in Chinese)
4. Haimovich, A., Blum, R.S., Cimini, L.J.: MIMO radar with widely separated antennas. IEEE Sig. Process. Mag. **25**(1), 116–129 (2008)
5. Li, J., Stoica, P.: MIMO radar with colocated antennas. IEEE Sig. Process. Mag. **24**(5), 106–114 (2007)
6. Stoica, P., Li, J., Xie, Y.: On probing signal design for MIMO radar. IEEE Trans. Sig. Process. **55**(8), 4151–4161 (2007)
7. Haykin, S.: Cognitive radar: a way of the future. IEEE Sig. Process. Mag. **23**(1), 30–40 (2006)
8. Li, X., Fan, M.M., Lu, M.: Research advance on cognitive radar and its key technology. J. Acta Electronica Sinica **40**(9), 1863–1870 (2012). (in Chinese)
9. Jiang, T., Wang, S.L.: Research on the system concept and architecture of cognitive radar. J. Aerospace Electron. Warfare **30**(2), 30–32 (2014). (in Chinese)
10. Wang, S.L., He, Q., He, Z.: LFM-based waveform design for cognitive MIMO radar with constrained bandwidth. EURASIP J. Adv. Sig. Process. **89**(1), 1–9 (2014)
11. Shi, J.N., Jiu, B., Liu, H.W., Wang, S.L.: A beampattern design method for airborne MIMO radar based on prior information. J. Electron. Inf. Technol. **57**(9), 3533–3544 (2009). (in Chinese)
12. Chen, C.Y., Vaidyanathan, P.P.: MIMO radar waveform optimization with prior information of the extended target and clutter. IEEE Trans. Sig. Process. **57**(9), 3533–3544 (2009)
13. Cui, G., Li, H., Rangaswamy, M.: MIMO radar waveform design with constant modulus and similarity constraints. IEEE Trans. Sig. Process. **62**(2), 343–353 (2014)
14. Leshem, A.: Information theoretic adaptive radar waveform design for multiple extended targets. IEEE J. Sel. Topic **1**(1), 42–55 (2007)
15. Yang, Y., Blum, R.S.: Radar waveform design using minimum mean-square error and mutual information. IEEE Workshop Sens. Array Multichannel Process. **2**(4), 234–238 (2006)
16. Yang, Y., Blum, R.S.: Minimax robust MIMO radar waveform design. IEEE J. Sel. Topic **1** (1), 147–155 (2007)
17. Tang, B., Tang, J., Peng, Y.: MIMO radar waveform design in colored noise based on information theory. IEEE Trans. Sig. Process. **58**(9), 4684–4697 (2010)
18. He, H., Petre, S., Li, J.: Wideband MIMO systems: signal design for transmit neampattern synthesis. IEEE Trans. Sig. Process. **59**(2), 618–628 (2011)