ISAR imaging resource-scheduling algorithm in network radar based on information fusion

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Abstract: Aiming at the application requirements of three-dimensional (3-D) fusion imaging of network radar, this study proposes an ISAR imaging resource-scheduling algorithm for network radar. Based on the feature recognition of each radar to each target, a projection-based method is first used to fuse the 3-D information of targets. Then according to the fused information, the demand of time resources for each radar is analysed. The radars selected for each target imaging are determined. Finally, the scheduling model of the imaging task for network radar is established, and time resources for each radar are randomly allocated. The simulation results show that the scheduling success rate of the proposed algorithm is two times on average than that of the traditional algorithm under the situation when the resources are near-saturated for both algorithms, which can improve the efficiency of network radar.

1 Introduction

The network radar system can share information, command, and control the radar nodes in real time, increase the reliability of combats, expand the power range of radar system, and provide the overall battlefield situation, which is one of the current research hotspots. In the case of a large number of tasks such as searching, tracking, and imaging, the radar resources will be saturated. Therefore, in order to improve the adaptive scheduling ability in network radar, it is necessary to introduce cognitive ideas [1, 2].

At present, a few studies have extended the idea of cognitive radar to imaging by adaptively adjusting the number of sub-pulse signals in the single radar imaging resource scheduling. Chen Yijun et al. [3, 4] introduced the idea of cognitive imaging into the adaptive scheduling of radar resources and proposed an adaptive radar resource-scheduling algorithm based on sparse aperture cognitive ISAR imaging, and gave specific performance evaluation index. Meng Di et al. [5] proposed a pulse-interleaving-based imaging radar resource-scheduling algorithm for the scheduling problem of multi-functional phased array radar imaging. In order to solve the resource-scheduling problems of searching, tracking, and imaging in digital array radar, an optimisation-scheduling algorithm for digital array radar (DAR) task [6] is proposed.

At the present stage, the research of resource scheduling for distributed network radar mainly focuses on multi-target radar resource scheduling [7] and radar power allocation [8], and aiming at target tracking and searching, but not the imaging task. Therefore, this paper will focus on the issue of multi-target imaging tasks in network radar, which is of great significance in the intelligent allocation of imaging resources.

2 Target feature cognition

This system generally uses the data processing centre to comprehensively process the target information collected from different radars. Therefore, this paper establishes the network radar system model as shown in Fig. 1 for 3-D fusion imaging.

Assume that each radar is 2-D ISAR imaging radar, where $O_i$ is the global coordinate system, $R_{ai}(i = 1, 2, …, m)$ is the $i$th radar in the network, $nyi(i = 1, 2, ..., m)$ indicates the direction of the sight line from each radar to each target. The target feature recognition mainly includes the following steps.

2.1 Determine the characteristic parameters

When a radar is imaging multi-targets, it is necessary to allocate the limited time resources reasonably so as to optimise the overall performance of the radar. The optimisation criterion comes from the fact that each radar in the network radar transmits a small number of pulses, receives the echo signal of the target, and then recognises the target characteristics. The main steps are as follows:

(i) By using traditional radar algorithms, we can obtain whether each radar detects each target or not, and the position of the target, including the distance from each radar to the target $R_{ij}$, the target velocity $V_j$, and the angle between each radar and the target flight direction $\theta_{ij}$, where the subscript $i$ denotes the $i$th radar and $j$ represents the $j$th target, so as the remainder of this paper. The priority $P_{ij}$ can be weighted by the parameters such as $R_{ij}$, $V_j$ and $\theta_{ij}$.

(ii) Determine azimuth coherence accumulation time $T_{ci,j}$

According to the echo information received by each radar, the coarse resolution image $s_{pi,j}(f, f_m)$ can be obtained. By processing the $s_{pi,j}(f, f_m)$, the range size $S_{pi,j}$, the azimuth size $S_{ai,j}$, the

![Fig. 1 Network radar system model](image-url)
estimated size $\hat{S}_{ij}$, and the azimuth sparsity $\hat{K}_{ij}$ can be determined. Set the reference azimuth $S_{\text{ref}}$ and the reference azimuth resolution $\rho_{\text{ref}}$ of each radar to the target, and then obtain the azimuth coherent accumulation time $T_{\alpha ij}$ as:

$$T_{\alpha ij} = \frac{S_{\text{ref}}}{S_{\alpha ij}} \times \frac{\hat{K}_{ij}}{V_j |\cos(\theta_{ij})|} \times \frac{\lambda}{2\rho_{\text{ref}}} \quad (1)$$

where $\lambda$ is the wavelength of the transmitting signal.

(iii) Determine azimuth observation dimension $M_{ij}$

According to compressive sensing theory [9], in order to reconstruct the original signal with high probability, the observation dimension must satisfy:

$$M_{ij} \geq c_i \hat{K}_{ij} \ln(N_{ij}) \quad (2)$$

where $c_i$ is a minor constant and $N_{ij}$ is the number of required radar pulses to achieve the imaging task.

2.2 Target size information fusion

A 2-D ISAR image can be achieved by a single radar, while 3-D image can be fused by 2-D images from network radar. This article does not focus on the 3-D fusion algorithm, but use the amount of information required in each dimension for 3-D fusion as the standard of network radar resource scheduling.

Reference [4] pointed out that the resource scheduling of a single radar in time is related to the size of the target in the azimuth direction. Therefore, a projection-based method (maximizing the sum of the projected size) can be used to estimate target size in each dimension. The specific analysis is shown in Fig. 2. Fig. 2a shows the geometry of the target motion, and Fig. 2b shows the projection analysis of the target on the $x'$-axis.

From the above figure, the estimated size on $x'$-axis is:

$$\hat{S}_{x'i} = \max \left\{ \hat{S}_{xij} \times |\cos \varphi_{xij}|, \hat{S}_{yi} \times |\cos \varphi_{yij}| \right\} \forall i \in (1, m) \quad (3)$$

Similarly, the estimated size on $y'$ and $z'$ axes are:

$$\hat{S}_{y'i} = \max \left\{ \hat{S}_{yij} \times |\cos \varphi_{xij}|, \hat{S}_{yi} \times |\cos \varphi_{yij}| \right\} \forall i \in (1, m) \quad (4)$$

where $\varphi_{xij}$, $\varphi_{yij}$, and $\varphi_{zij}$ are the angles between the azimuth of the $i$th radar and each of three dimensions, respectively. $\Theta_{xij}$, $\Theta_{yij}$, and $\Theta_{zij}$ are the angles between the sight line of the $i$th radar and each of three dimensions, respectively.

2.3 Determination of the required observation dimension

The 2-D ISAR image achieved by each radar can be regarded as the projection of the 3-D target onto the 2-D imaging plane formed by the radar sight line and the radar azimuth. Therefore, we exploit the projection of the target onto each radar-imaging to determine the required observation dimension in global coordinate system. First, given the target 3-D size, use the projection method to obtain the projection size on radar imaging plane both in azimuth and sight line, represented by $I_{\alpha ij}$ and $I_{\beta ij}$. Then based on the relationship among azimuth size, azimuth coherent accumulation time, and azimuth observation dimension, obtain the observation azimuth dimension $M_{ij}$ that the $i$th radar needs for imaging the $j$th target. The specific equations are as follows:

In order to image the target, it must be ensured that the target can be detected by the radar. It can be expressed as

$$\text{crad}\{j\hat{S}_{xij} > 0, i = 1, 2, \ldots, m\} \leq N \quad (6)$$

where $N$ is the total number of radars in the network.

(ii) When the target flies through the radar detection area, the azimuth size of the target increases first and then decreases. A large azimuth dimension obtained by the radar indicates that the target is flying into the radar detection area or close to the centre of radar detection area. Therefore, the radar with larger azimuth dimension should have a higher priority. That is

$$\text{Pr}_{ij} > \text{Pr}_{k_j}, \forall \hat{S}_{xij} > \hat{S}_{xk_j} \quad (7)$$

where $\text{Pr}_{ij}$ presents the priority of the $i$th radar for the $j$th target.
Table 1  Target imaging task assignment

|      | Ra1 | Ra2 | Ra3 | Ra4 | Ra5 | Ra6 |
|------|-----|-----|-----|-----|-----|-----|
| target1 | 0   | 1   | 1   | 0   | 0   | 1   |
| target2 | 0   | 1   | 1   | 0   | 1   | 0   |
| target3 | 1   | 1   | 0   | 0   | 0   | 1   |
| target4 | 0   | 1   | 1   | 0   | 1   | 0   |
| target5 | 1   | 1   | 0   | 0   | 0   | 1   |
| target6 | 0   | 1   | 1   | 0   | 1   | 0   |

Table 2  Required observation dimension of the target

|      | Ra1 | Ra2 | Ra3 | Ra4 | Ra5 | Ra6 |
|------|-----|-----|-----|-----|-----|-----|
| target1 | 0   | 145 | 220 | 0   | 0   | 194 |
| target2 | 0   | 176 | 180 | 0   | 201 | 0   |
| target3 | 214 | 208 | 0   | 0   | 0   | 207 |
| target4 | 0   | 203 | 189 | 0   | 0   | 200 |
| target5 | 153 | 231 | 0   | 0   | 210 | 0   |
| target6 | 0   | 194 | 208 | 0   | 0   | 200 |

(iii) The selected radar needs to meet the minimum requirements for signal reconstruction.

\[ M_{h,j} \geq M_{i,j} \]  \hspace{1cm} (8)

Considering the fact that the smaller the \( M_{h,j} \) is, the fewer resources the radar consumes, the radar with minimum \( M_{h,j} \) in (8) is selected as the preferred with low resource consumption.

(iv) 3-D imaging of a target in network radar requires at least three radars. In order to save the resources of the network radar, three non-collinear radars are used. Let \( X_{i,j} = 1 \) indicates that the \( j \)th radar is selected for imaging the \( i \)th target. We can obtain that

\[
\begin{align*}
\sum_{i=1}^{N} X_{i,j} &= 3 \\
Y_{i} - Y_{j} \neq Y_{i} - Y_{k} & \quad X_{i} - X_{j} \neq X_{i} - X_{k} \neq X_{j} - X_{k}
\end{align*}
\]  \hspace{1cm} (9)

where \( R_{a}(X_{i}, Y_{i}, 0) \), \( R_{a}(X_{j}, Y_{j}, 0) \) and \( R_{a}(X_{k}, Y_{k}, 0) \) are the coordinates of the selected three radars, respectively.

3.2 Determine the model

Assuming that each radar’s scheduling interval is \( T \) and the scheduling starting time is \( t_{i,j} \), the scheduling model of each radar is as follows:

\[
\max \left( \sum_{i=1}^{m} (X_{i,j} \times P_{i,j}) \right) \]  \hspace{1cm} (10)

(see (11)), where \( N_{k} \) is the number of schedulable targets for the \( k \)th radar. The first five constraints are the requirements for radar selection; the sixth constraint is to ensure that the starting time of the \( j \)th target imaged by the \( i \)th radar is within the radar’s scheduling interval; the seventh constraint is to ensure that the total resources of the schedulable targets are less than the total resources provided by the radars; the eighth constraint is to ensure that the target with higher priority is processed earlier.

4  Simulation

Consider a network radar system contains six non-collinear radars on the ground, denoted as \( R_{a}(i = 1, 2, \ldots, 6) \), and six targets \( (j = 1, 2, \ldots, 6) \). The radars in each part of the network have reached time synchronisation, they all use the identical LFM signal with carrier frequency \( f_{c} = 10 \) GHz, pulse width \( T_{p} = 1 \) μs, signal bandwidth \( B = 300 \) MHz. The pulse repetition frequency is \( PRF = 1000 \) Hz, and the number of observation points is 1000 (equivalent to observation time 1 s). The target imaging task assignment is shown as Table 1, where the imaging task is the imaging target, so as the remainder of this paper. The simulation results show that, for each target, there are three radars using for imaging. The required observation dimensions of the target imaging task are shown in Table 2.

The total priority of the \( j \)th target is weighted by the priority of the selected radar. The equation is as follows:

\[
P_{j} = \sum_{i=1}^{m} (X_{i,j} \times P_{i,j}) \]  \hspace{1cm} (12)

Its corresponding priority is shown in Table 3.
According to the resource-scheduling model for network imaging, the resource allocation of the above six targets and the time sequence diagram of the resource scheduling can be obtained shown in Fig. 3. If the summation of the azimuth observation dimension applied by all targets is greater than one resource-scheduling interval of the radar, the target with small priority must be discarded. Fig. 3a shows scheduling sequence for all radars in an interval. It can be seen from the figure that radar 2 does not perform observation imaging for target 3. The reason is that the total observation dimension radar 2 is 145 + 176 + 203 + 231 + 194 = 1157, which is >1000, so target 3 with the lowest priority is discarded and not imaged. However, for the allocation of other radars, collisions like multiple targets use the same sub-aperture or resources insufficient do not appear. Fig. 3b shows the resource sequence of all radars in the first 100 ms.

At the same time, scheduling success rate (SSR) and resource consumption rate (SCR) are defined as the performance indicators of radar resource scheduling. The expressions are as follows:

\[
SSR = \frac{N'}{N} \quad (13)
\]

\[
SCR = \frac{\sum_{i=1}^{m} \sum_{j=1}^{N'} (X_{i,j} \times M_{i,j})}{mI} \quad (14)
\]

where \(N'\) is the number of targets successfully scheduled; \(N\) is the total number of imaging targets applied for scheduling.

The simulation compares the scheduling algorithm proposed in this paper (abbreviated as the proposed algorithm) with the traditional network radar resource-scheduling algorithm (abbreviated as the traditional algorithm) in which the selection of radar by the imaging task is not considered. Fig. 4 shows the comparison of the performance of the two algorithms.

From Fig. 4a, it can be seen that when the number of imaging targets is small, the time resources are sufficient for both algorithms to complete the scheduling of imaging tasks. After the number of imaging targets increase to six, the proposed algorithm schedules more imaging targets than the traditional algorithm. As the number of imaging targets increase to 50, the SSR of the traditional algorithms has dropped dramatically to 20%; however, the SSR of the proposed algorithm can still remain nearly 57%. What can be seen from Fig. 4b is that within a scheduling interval,
the total resource consumption for all radars increases with the number of imaging targets. When the number of imaging targets is 18, the proposed algorithm has a lower SCR than the traditional algorithm. The reason is that the radar in the network consumes the resources as long as it achieves ISAR imaging. However, for the proposed algorithm, radar only consumes the resources of the selected radar to complete the imaging of the target. When the target number is larger than 18, the consumption rate of the two algorithms are both up to 90%. Nevertheless, the successful scheduling rate of the traditional algorithms is between 20 and 30%, while the successful scheduling rate of the proposed algorithm is over 57%.

Combined Fig. 4a with Fig. 4b, it can be seen that, for the traditional algorithm, when the number of imaging tasks are >6, the resources are close to saturation leading to that some targets need to be discarded; while, for the proposed algorithm, the resources are close to saturation when the number of imaging tasks are >8. Under the situation when the resources are near-saturated for both algorithms, e.g. the number of imaging tasks are >8, the SSR of the proposed algorithm is two times on average than that of the traditional algorithm under the situation when the resources are near-saturated for both algorithms, which can improve the efficiency of network radar. The signal-to-noise ratio (SNR) mainly impacts the quality of CS-based ISAR imaging [10–12]. This means, under the same conditions, the sparsity of the echo signal of the target reduce as the SNR decrease, resulting in the deterioration of the reconstructed target ISAR image quality. As for the computational complexity, in the process of ISAR imaging resource scheduling with network radar, it mainly comes from compressive sensing imaging, leaves the computational complexity of resource allocation very low, so the computational complexity of the proposed algorithm is consistent with the traditional algorithms.

5 Conclusion

This paper proposed an ISAR imaging resource-scheduling algorithm for network radar. The algorithm employs the maximum value of the projection sum as the criteria to establish the selection model of network radar and realises the scheduling of network radar imaging resources. The simulation results show that, under the situation when the resources are near-saturated for both algorithms, the SSR of the proposed algorithm is two times on average than that of the traditional algorithm under the situation when the resources are near-saturated for both algorithms, which can improve the efficiency of network radar.

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7 References

[1] Haykin, S.: ‘Adaptive radar: evolution to cognitive radar’. IEEE Int. Symp. on Phased Array Systems and Technology, Boston, MA, USA, 2003, p. 613
[2] Haykin, S.: ‘Cognitive radar: a way of the future’, IEEE Signal Process. Mag., 2006, 23, (1), pp. 30–40
[3] Chen, Y.J., Luo, Y., Zhang, Q., et al.: ‘Adaptive scheduling algorithm for phased array radar based on cognitive ISAR imaging’, J. Electron. Inf. Technol., 2014, 36, (7), pp. 1566–1572
[4] Chen, Y.J., Zhang, Q., Luo, Y., et al.: ‘Adaptive scheduling algorithm for radar based on sparse aperture ISAR imaging’, J. Projectiles Rockets Missiles Guid., 2013, 3, pp. 171–176
[5] Meng, D., Xu, H.Y., Zhang, Q., et al.: ‘Adaptive scheduling algorithm for ISAR imaging radar based on pulse interleaving’. Int. Conf. on Machine Learning and Intelligent Communications, Weihai, China, 2017, pp. 169–178
[6] Meng, D., Zhang, Q., Luo, Y., et al.: ‘An effective scheduling algorithm for digital array radar based on pulse interleaving’, Hangkong Xuebao/Acta Aerosp. Astronaut. Sin., 2017, 38, pp. 1–10
[7] Prokopenko, I., Vovk, V., Prokopenko, K.: ‘Fast resource management algorithm for multi-position radar systems’. IEEE Radar Symp., Dresden, Germany, 2015, pp. 1045–1051
[8] Yan, J., Liu, H., Pu, W., et al.: ‘Joint threshold adjustment and power allocation for cognitive target tracking in asynchronous radar network’, IEEE Trans. Signal Process., 2017, 65, (99), pp. 1–1
[9] Baranishk, R.G.: ‘Compressive sensing [lecture notes]’, IEEE Signal Process. Mag., 2007, 24, (4), pp. 118–121
[10] Bu, H.: ‘Research on CS-SAR imaging theory and algorithms based on sparse representation in the fractional Fourier domain’. PhD Thesis, Beijing Institute of Technology, 2015
[11] Zhang, L., Zhang, L., Xing, M.D., et al.: ‘A new method of high resolution ISAR imaging under low SNR based on improved compressive sensing’, J. Electron. Inf. Technol., 2010, 32, (9), pp. 2263–2267
[12] Chen, W.F., Li, S.D, Ying, J., et al.: ‘Fast recovery algorithm for complex sparse signal with arbitrary sparse structure and its inverse synthetic aperture radar imaging’, J. Optoelectron. Laser, 2015, 26, (4), pp. 97–804