An Adaptive Dwell Scheduling Algorithm for Digital Array Radar Based on Pulse Interleaving

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Abstract. According to the characteristics of signal processing in Digital Array Radar (DAR), a dwell scheduling algorithm is proposed. Based on the pulse interleaving technique, the dwell scheduling algorithm can achieve the sparse-aperture cognitive ISAR imaging of precision tracking targets simultaneously during implementing searching and tracking tasks, which gets the full exploitation of transmitting, waiting and receiving durations of radar dwells. Simulation results demonstrate that, compared with the conventional dwell scheduling algorithms, the proposed algorithm can improve the scheduling performance of DAR.

Introduction

With the improvement of radar digitization, digital array radar (DAR) has been widely researched in the radar industry [1]. In order to further improve the resource utilization ratio of the radar system, pulse interleaving technology is proposed. Orman analyzed this method in [2] and proposed the heuristic algorithm to solve the problem of adaptive beam-dwell scheduling for phased array radar. Aiming at the problem of beam-dwell scheduling for DAR, an algorithm based on analyzing scheduling interval is proposed in [3]. However, in almost all existing adaptive resource scheduling methods for DAR, the imaging mission is not taken into account. Joint scheduling imaging tasks with search, tracking and other tasks can not only improve the recognition ability of the radar to the target, but also feedback the target characteristic information obtained by the image to the transmitter radar system, so as to realize the dynamic adjustment of imaging tasks and improve resource utilization ratio [4]. Traditional imaging algorithm require continuous observation of targets for a long time to obtain high-resolution images, but the alternation of different tasks inevitably leads to discontinuous synthetic aperture sampling of the imaging target azimuth.

Based on the above issues, in this paper, we propose an adaptive dwell scheduling algorithm for DAR based on pulse interleaving, which takes the imaging task requirements into account in the radar resource scheduling model by using the compressed sensing (CS) ISAR imaging method.

Task Model and Constraints Based on Pulse Interleaving

Sparse Aperture Imaging Based on Compressed Sensing

The traditional DAR needs to separate part of the continuous long time resources to achieve imaging capabilities in the implementation of the target searching and tracking, which leads to the contradiction of radar resource allocation and the low radar efficiency. Under the framework of CS theory, continuous observation of the target image can be transformed into random sparse observation, and high-quality target ISAR image can be obtained under sparse aperture condition. This provides an effective technical support for incorporating imaging task requirements into the DAR resource scheduling model.

In order to improve the adaptive ability of the radar imaging, the method proposed in [4] can be used to recognize the characteristics of the targets after entering the stable tracking phase, and then
calculate the demand of radar resources for target imaging based on the cognitive results. Suppose that the target is non-maneuvering, the full aperture imaging of the radar needs to transmit \( N_i = PRF \cdot \hat{T}_i \) pulses ( \( PRF \) is the pulse repetition frequency), and the measurement dimension \( M_i (M_i < N_i) \) after dimension reduction is expressed as:

\[
M_i \geq c \hat{K}_i \ln(N_i)
\] (1)

Where \( c \) is a constant associated with the recovery accuracy, usually taken as \( 0.5 \sim 2 \) (let \( c = 1 \) in this paper).

**Radar Dwell Model**

The DAR dwell model is defined as:

\[
T = \{et, st, t_x, t_w, t_r, \omega, M, pri, P, p\}
\] (2)

Where \( et \) denotes the expected scheduling time; \( st \) denotes the actual scheduling time; \( t_x, t_w, t_r \) denote the transmitting duration, waiting duration and receiving duration respectively; \( \omega \) denotes the time window of the task; \( M \) denotes the number of pulse repetitions in the search and tracking tasks, and it denotes the azimuth-oriented observation dimension in the imaging task; \( pri \) denotes the pulse repetition reputation interval; \( P \) denotes the pulse transmitting power; and \( P \) denotes the task priority [5].

**Scheduling Constraints**

Although the overlap of multiple dwell tasks can improve the resource utilization of DAR, the energy consumption of the system is bounded to increase as the radar is in the transmitting state for a long time. In order to avoid the damage of the transmitter due to the long working time, the restriction of energy constraint must be considered in the scheduling algorithm [6]. The transient energy of the system at \( t \) moment can be expressed as:

\[
E(t) = \int_0^t P(x)e^{(x-t)/\tau}dx
\] (3)

Where \( P(x) \) is the power parameter, \( \tau \) is the look-back period. The energy constraint of the system can be defined as that \( E(t) \) cannot exceed the maximum threshold \( E_{\text{max}} \) of instantaneous energy at any time, i.e.

\[
E(t) \leq E_{\text{max}}
\] (4)

**Dwell Scheduling Algorithm for DAR**

In order to measure the performance of the radar resource scheduling, the scheduling success ratio (SSR), the hit value ratio (HVR), the time utilization ratio (TUR) and the energy utilization ratio (EUR) are taken as the criterion [7]. They can be expressed as:

\[
\text{SSR} = \frac{N'}{N}
\] (5)
\[
\text{HVR} = \frac{\sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} P_i}
\]

(6)

\[
\text{TUR} = \frac{\sum_{i=1}^{N} (t_{a_i} + t_{n_i}) \cdot M_i \cdot pri_i}{T_{\text{total}}}
\]

(7)

\[
\text{EUR} = \frac{P_i \cdot \sum_{i=1}^{N} (t_{a_i} \cdot M_i \cdot pri_i)}{P_{av} \cdot T_{\text{total}}}
\]

(8)

Where \(N\) is the total number of tasks for requested scheduling, \(N\) is the number of scheduled tasks, \(T_{\text{total}}\) is total simulation time, \(P_i\) is the peak power of each transmitted pulse and \(P_{av}\) is the average power delivered by the radar.

In terms of the above performance index, assume that there are \(N\) dwell tasks in the scheduling interval \([t_0, t_e]\), an effective model of DAR based on pulse interleaving can be defined as:

\[
\begin{align*}
\max & \{q_1 \cdot \sum_{i=1}^{N} P_i + q_2 \sum_{i=1}^{N} \frac{(t_{a_i} + t_{n_i}) \cdot M_i \cdot pri_i}{T_{\text{total}}} + q_3 \sum_{i=1}^{N} P_i \frac{(t_{a_i} + M_i \cdot pri_i)}{P_{av} \cdot T_{\text{total}}}) \}
\end{align*}
\]

\[
\begin{align*}
\max & \{t_{a_i}, et_i \leq st_i \leq \min(\eta_i, t_e), i = 1, 2, \cdots N \}
\end{align*}
\]

\[
\begin{align*}
\bigcap_{i=1}^{N} \bigcup_{j=1}^{M} \left[ st_i + (j-1) \cdot pri_i, st_i + t_{a_i} + (j-1) \cdot pri_i \right] = \emptyset
\end{align*}
\]

\[
\begin{align*}
\bigcap_{i=1}^{N} \bigcup_{j=1}^{M} \left[ st_i + t_{a_i} + (j-1) \cdot pri_i, st_i + t_{a_i} + (j-1) \cdot pri_i \right] = \emptyset
\end{align*}
\]

\[
\begin{align*}
\bigcap_{i=1}^{M} \bigcup_{j=1}^{M} \left[ st_i + (j-1) \cdot pri_i, st_i + (j-1) \cdot pri_i + t_{a_i} \right] = \emptyset, i, k = 1, 2, \cdots N
\end{align*}
\]

\[
\begin{align*}
E(t) \leq E_{\text{max}}, t \in [t_0, t_e]
\end{align*}
\]

(9)

Where \(N_{se}\) is the number of search tasks and \(q_1, q_2, q_3, q_4\) is adjustment factors. The first constraint gives the scope of the actual execution time of each task; the second constraint indicates that there is no conflict between the transmitted pulses; the third constraint indicates that the search tasks cannot perform pulse interleaving; the fourth constraint indicates that the task dwell received pulse can be overlapped in the same time without colliding with the transmitted pulse; the fifth constraint represents the energy constraint for task scheduling.

The effective algorithm of DAR based on pulse interleaving is summarized as follows:

Step 1: Take \(N\) tasks for requested scheduling in the scheduling interval \([t_0, t_e]\), add \(K\) tasks with the latest scheduled start time less than \(t_0\) to the delete list, discretize the system time; suppose that the length of each time slot is \(\Delta t\), the number of time slot is \(D = \left\lceil \frac{t_e - t_0}{\Delta t} \right\rceil\), introduce time pointer \(t_p = t_0\), initialize the time slot vector \(U = \{u_1, u_2, \cdots u_D\} = 0\) and energy state vector \(E\).

Step 2: Let the remaining \(N - K\) tasks join the application list according to the corresponding
priority from high to low (tasks with the same priority are arranged according to the expected execution time), and let $i = 1$.

Step 3: Determine whether the $i$-th task can be scheduled at time $t_p$.

If the task meets the time and energy constraints in (9), it will be sent to the execution list and removed from the application list. Initialize the time slot vector $U$ and time pointer $t_p$. Update the energy state vector $E = E + \Delta E$ ($\Delta E$ is the system energy consumption change), let $i = i + 1$, and return to step 3.

If the scheduling fails, adjust the actual execution time of the task in the time window, and let $t_p = t_p + \Delta t_p$ ($\Delta t_p$ is the minimum step size of the pointer slide).

Step 4: If $t_p < st_i + \theta$, return to step 3, otherwise the task cannot be scheduled. Add it to the delete list, let $i = i + 1$.

Step 5: If $i \leq N - K$, return to step 3, otherwise go to step 6.

Step 6: The scheduling analysis of the scheduling interval ends.

**Simulation and Analysis**

In the simulation, we choose three kinds of radar working mode: search, tracking and imaging. Typical parameters for various tasks are summarized in Table 1. The total simulation time is 6s, the scheduling interval length is 50ms, and the radar can provide an average power of 400W.

<table>
<thead>
<tr>
<th>Task type</th>
<th>Priority</th>
<th>Dwell time (ms)</th>
<th>Time window (ms)</th>
<th>Update rate (Hz)</th>
<th>Pulse duration (ms)</th>
<th>Transmitting power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-priority searching</td>
<td>3</td>
<td>3</td>
<td>10</td>
<td>20</td>
<td>0.02</td>
<td>3</td>
</tr>
<tr>
<td>Precision tracking</td>
<td>2-3</td>
<td>2</td>
<td>20</td>
<td>10</td>
<td>0.01</td>
<td>4</td>
</tr>
<tr>
<td>Normal tracking</td>
<td>1-2</td>
<td>2</td>
<td>30</td>
<td>5</td>
<td>0.01</td>
<td>4</td>
</tr>
<tr>
<td>ISAR imaging</td>
<td>0-1</td>
<td>1</td>
<td>20</td>
<td>-</td>
<td>0.01</td>
<td>5</td>
</tr>
<tr>
<td>Low-priority searching</td>
<td>0</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>0.02</td>
<td>3</td>
</tr>
</tbody>
</table>

Traditional phased array radar algorithm (traditional algorithm) [8], the pulse interleaving scheduling algorithm (simple task algorithm) which does not consider the imaging tasks [9] and the adaptive dwell scheduling algorithm proposed in this paper (proposed algorithm) are compared in the simulation. Comparison curves of three different algorithms are shown in Fig. 1-4.

![Figure 1. Scheduling success ratio.](image1)

![Figure 2. Hit value ratio.](image2)
From Fig. 1, we can see that when the number of tasks is less than 20, the system resources are relatively abundant; the competition for resources among tasks is not obvious. All the three scheduling algorithms can successfully schedule all tasks. With the further increase of the tasks, the scheduling success ratio of the traditional algorithm begins to decline significantly, while the other two algorithms based on the pulse interleaving can still successfully schedule all tasks. When the number of tasks increased to 65, the simple task algorithm cannot schedule more tasks, but the proposed algorithm can successfully schedule all tasks until the number of tasks reaches 80. This is due to the saturation of radar resources in the simple task algorithm. But in the proposed algorithm, the imaging tasks have the lowest priority, so that the remaining resources of the system can be fully utilized by the dynamic adjustment of the imaging accumulation time and the flexible sparse aperture allocation without affecting the scheduling of the search and tracking tasks. Consequently, the task number of successful scheduling is improved.

From Fig. 2, we can see that when the radar resources are saturated, the hit value ratio of the traditional algorithm and the simple task algorithm starts to decrease when the number of tasks reaches 20 and 65 respectively. In this case, the number of successfully scheduled tasks remains unchanged, and only the higher priority tasks are selected for priority scheduling in the added tasks. The precision tracking task can be imaged with the idle time of searching and tracking in the proposed algorithm, so that it can maintain a high hit value ratio when the number of tasks reaches 80.

From Fig. 3 and Fig. 4, we can see that when the number of tasks reaches 20, the time utilization ratio and the energy utilization ratio maintain at 0.1 because of the resource bottleneck in traditional algorithm. Through the use of the pulse interleaving technology, the simple task algorithm can further utilize the radar system resources, the time utilization ratio can reach about 0.6 and energy utilization can reach about 0.5. On the basis of pulse interleaving, the idle time of search and tracking task is fully exploited in proposed algorithm, so the time utilization ratio and energy utilization ratio can reach about 0.8 and 0.6 respectively.

Conclusion
In this paper, an effective dwell scheduling algorithm has been proposed based on pulse interleaving for DAR. The time and energy constraints are set respectively, and the optimal resource scheduling algorithm is established. The simulation results show that the proposed algorithm can accomplish tracking and search task effectively. It not only makes use of the multi-task cooperative advantage of DAR, but also improves the resource utilization ratio of radar system.

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References


