Sweep Coverage with Return Time Constraint

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***Abstract*—Sweep coverage is an important problem in wireless sensor networks. With sweep coverage, more Points Of Interests (POIs) can be monitored with fewer mobile sensor nodes thanks to the mobility of the nodes. Most existing studies on sweep coverage focus on the trajectory of the mobile sensor nodes to guarantee the sweep coverage of the POIs. Considering the fact that, in many applications, the collected data is only useful during a fixed period, we studied the problem of sweep coverage with return time constraint. This problem requires that the POIs should be covered and the collected data should be delivered to the base station within a preset time window. In this paper, we prove that the problem of finding the minimum number of mobile sensor nodes required to guarantee sweep coverage with return time constraint is NP-hard. In addition, we present two novel heuristic algorithms, G-MSCR and MinD-Expand, to provide sweep coverage with return time constraint in practice. Our experimental results indicate that, compared to MinD-Expand, G-MSCR requires more sensor nodes and leads to shorter return time. To our knowledge, G-MSCR and MinD-Expand are the only algorithms that attempt to solve the problem of sweep coverage with return time constraint.**

I. Introduction

It is expected that Wireless Sensor Networks (WSNs) will be widely deployed in a variety of different applications, such as environment monitoring and intelligent buiding. One of the most important problems in WSNs is coverage. Technically, the coverage problem in WSNs can be classified into three categories: full coverage, barrier coverage, and sweep coverage. The former two types of coverage problems involve stationary sensor networks. Namely, in these problems, stationary sensor nodes are deployed randomly or deliberately in the target area to accomplish monitoring or data collection tasks [1]–[10]. Different than these problems, sweep coverage utilizes mobile sensor nodes to monitor Points Of Interests (POIs). Thanks to the mobility, sweep coverage can cover more POIs using fewer sensor nodes.

Most of the existing studies on sweep coverage do not take the delivery of collected data into consideration [11]–[13]. In practice, the collected data often needs to be transmitted to the base station when a mobile sensor node returns to the base station due to security concerns, signal interference, etc. This requires each mobile sensor node to travel some distance after collecting the data of interest. However, in many applications such as forest fire prevention or climate prediction, the data collected from a POI is only useful over a certain period of time, which results in a constraint that a mobile sensor needs to go back to the base station within a fixed time window. For these applications, the sweep coverage scheme should not only cover the POIs during the sweep period, but also enable mobile sensors to return to the base station under the constraint mentioned previously. Figure 1 includes an example sensor network involving only one mobile sensor node and one base station. In this example network, the mobile sensor node attempts to travel along a sweep path to cover all the POIs within a sweep period. Every POI has a return time constraint and the mobile sensor node must return to the base station under the time constraint after visiting a POI.

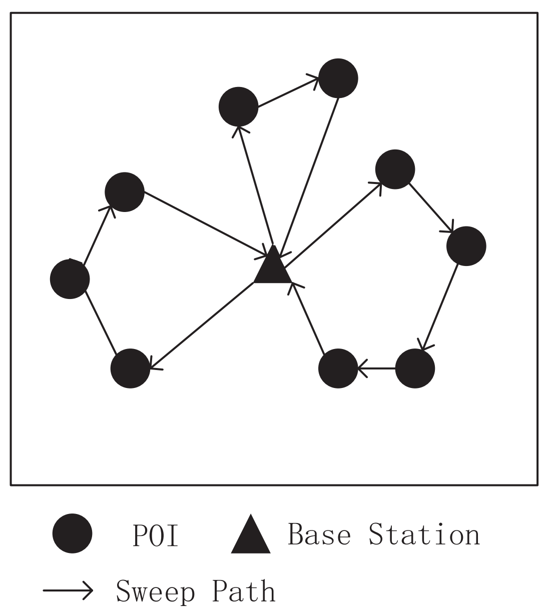

Fig. 1. Example of Sweep Coverage with Return Time Constraints

In this paper, we attempt to solve the problem of sweep coverage with return time constraint. The details of our contributions are summarized as follows:

1) We propose a new problem in WSNs, which is called Sweep Coverage with Return Time Constraint. In this problem, all POIs should be covered within a sweep

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period and the collected data should be transmitted to the base station within a period by the mobile nodes.
2) We prove that finding the minimum number of mobile sensor nodes required by sweep coverage with return time constraint is NP-hard.
3) We design two heuristic algorithms, G-MSCR and MinD-Expand, to solve the problem of sweep coverage with return time constraint.

The rest of the paper is organized as follows. Section II describes the related work. Section III formulates the sweep coverage with return time constraint problem. The proposed heuristic algorithms G-MSCR and MinD-Expand are presented in Section IV and Section V respectively. Our experimental results are included in Section VI. Finally, Section VII concludes this paper.

II. Related Work

Sweep Coverage was first proposed by Cheng $et\ al.$ [11]. Over the past years, this problem has attracted much attention [12]–[27]. Some of the existing studies focus on finding the minimum number of mobile sensor nodes that can provide sweep coverage. Cheng $et\ al.$ proved that determining the minimum number of mobile sensors for sweep coverage is NP-hard and cannot be approximated within a factor of 2 [11]. They also proposed a heuristic algorithm, CSWEEP. Later, Du et al. proposed the MinExpand algorithm with which all mobile sensors are required to follow the same trajectory during different sweep periods [15]. Compared to CSWEEP, MinExpand can significantly reduce the number of required mobile nodes. Furthermore, some of the existing studies focus on the load balance between the mobile sensors. Chu $et\ al.$ proposed the patrol point algorithm which can keep the patrol times of mobile nodes approximate to one another and can meet the monitor requirements [12]. When POIs have different sweep period requirements, some POIs may be visited more frequently than necessary, which is defined as the Over-Coverage problem by Shu $et\ al.$ [23]. They also proposed an algorithm to minimize the number of unnecessary visits. Finally, some of the existing studies extend the concept of POI from a point to an area. Gorain $et\ al.$ studied the problem of area coverage with mobile sensors [19]. Later, sweep covering lines was investigated [20].

Note that all of the studies mentioned previously did not consider the fact that mobile nodes often need to return to the base station when data collection is involved in sweep coverage. To the best of our knowledge, there have been three studies that considered data collection in sweep coverage [16], [17], [21]. Wang $et\ al.$ studied the problem of using mobile nodes to collect data in wireless sensor networks. Although they did not mention sweep coverage in their paper, the scenario under investigation is very similar to sweep coverage [16]. Zhao $et\ al.$ focused on minimizing the movement velocity of mobile sensors under the constraint of sweep period and transmission delay [17]. Yang $et\ al.$ studied the sweep coverage with energy restriction where all mobile nodes should return to the base station periodically due to the energy constraint [21].

III. Problem Formulation

In this section, we formally formulate the problem of sweep coverage with return time constraint. We assume that there are a set of POIs $V = \{v_1, v_2, \ldots, v_n\}$ and a base station v_b that are deployed on a Euclidean plain. A POI is said to be covered by a mobile sensor node when the node is located at the position of the POI. Furthermore, we assume that all mobile sensor nodes move at the same speed. Consequently, we can use the period during which a sensor node moves from POI u to POI v to represent the distance between them. Formally, this distance is denoted as $dist(u, v)$. Note that $dist(u, v)$ is actually a time period. In addition, for every POI v_i, there is a sweep period t_i, which means that the time interval between two visits to this POI must be less than t_i. Finally, there is a return time constraint d_i for every POI v_i. We assume that the $d_i \geq dist(v_i, v_b)$ and $t_i \geq 2dist(v_i, v_b)$. Otherwise, POI v_i can not be covered under the constraint. Formally, we can define t-sweep d-return coverage as follows.

Definition 1 (t-Sweep d-Return Coverage): A POI is said to be t-sweep d-return covered by a coverage scheme if and only if it is covered at least once every t time units and the mobile sensor node with the collected data can return to the base station in less than d time units.

A sweep coverage scheme F specifies how mobile sensor nodes move in detail. Since we assume all the sensors move at the same speed, F only needs to determine the trajectories of mobile sensor nodes. In the problem of sweep coverage with return time constraint, our goal is to design a scheme that minimizes the number of required mobile nodes. Formally, the problem of finding the Minimum number of mobile sensor nodes in Sweep Coverage with Return time constraint (MSCR) can be defined as follows.

Definition 2 (MSCR): Given a set of POIs $V = \{v_1, v_2, \ldots, v_n\}$, a POI v_i is associated with the sweep period t_i and return time constraint d_i. The goal in the $MSCR$ problem is to find the minimum number of mobile sensor nodes so that every POI v_i is t_i-sweep d_i-return covered.

In our research, we found that the MSCR problem is NP-hard. In this paper, we focus on a simplified version of the MSCR problem, in which $t_i = t$ for all POIs. In our research, we call the simplified problem global t-sweep coverage with return time constraint. The detailed proof for the theorem that the MSCR problem is NP-hard is presented as follows.

Theorem 1: The MSCR problem is NP-hard.

Proof: The decision problem corresponding to MSCR is to determine whether there is a route assignment that satisfies the following requirements: that the number of mobile sensor nodes does not exceed K and also can satisfy all the following conditions:

1) Each tour includes v_b.
2) Each POI in V is included in one of the tours.
3) Each POI v_i is t_i-sweep d_i-return covered.

4) The number of mobile sensor nodes does not exceed K (note that K will be explained in details later).

Consider an instance of the decision problem of Vehicle Routing Problem (VRP), which has a base station v'_b and a set of clients denoted as $V' = \{v'_1, v'_2, \ldots, v'_n\}$. An edge $\{v'_i, v'_j\}$ in edge set E' represents the Euclidean distance between two clients v'_i and v'_j. Every vehicle can only travel a fixed distance after it leaves the depot. In the VRP problem, we need to determine whether all clients can be served with no more than K vehicles.

Apparently, the solution to a VRP problem is also the solution to the corresponding MSCR problem when there is no return time constraint and all sweep period $t_i = t$, which is called global t-sweep coverage. Note that this is a simplified version of the MSCR problem. Therefore, the MSCR problem is also NP-hard. ■

IV. G-MSCR: A Greedy Algorithm

In this section, we present the details of the greedy heuristic algorithm G-MSCR. The goal of this algorithm is to calculate the minimum number of mobile sensor nodes required for the t-sweep d-return coverage of all POIs. In each iteration, the algorithm attempts to construct a route for one mobile sensor node. When the algorithm is terminated, all POIs will be covered with the sweep period and return time constraints. In this paper, we adopts the following definition:

Definition 3 (Remaining Time): When a mobile sensor node is used to cover a POI, the collected data must be transmitted to the base station within the return time constraint. Remaining time is defined as the time left to a sensor node in order to go back to the base station under the constraint.

The details of the G-MSCR algorithm are summarized in Alg. 1. Specifically, G-MSCR builds the routes sequentially (i.e. one at a time). The resulting sweep path starts from and returns to the base station. The basic idea of the G-MSCR algorithm is to add one POI with the maximum remaining time to the current route at a time. In our research, we use t_r to denote the remaining time. Every time G-MSCR would like to add a POI, it chooses the POI $v_i \in V$, which maximizes $(\min\{t_r - dist(v_s, v_i), d_i\} - dist(v_i, v_b))$, where v_s is the first POI on the current route. When no more POI can be added to the route, the algorithm assigns one mobile sensor node to this route. This procedure is repeated until all POIs are covered, which means that the sweep paths for the mobile sensor nodes have been generated.

Figure 2 includes an example that illustrates the selection of POI. Initially, the sweep path is $v_b \to A \to B \to v_b$. At this moment, there are two candidate POIs C and D that could be added to the path. With G-MSCR, Δ_C and Δ_D are calculated. Assuming that $\Delta_C < \Delta_D$, C will be included in the path if adding C to the sweep path does not violates the return time constraint. After C is added, the sweep path will become $v_b \to A \to B \to C \to v_b$.

In our research, we found that G-MSCR can guarantee global t-sweep coverage with return time constraint. The detailed proof is presented as follows.

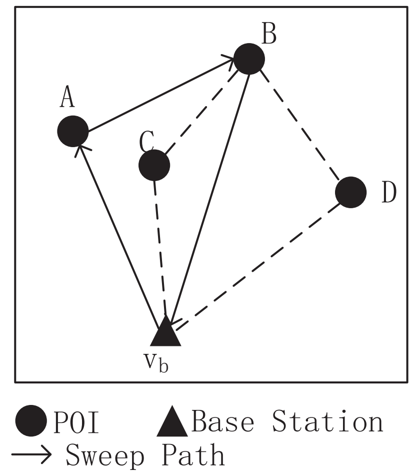

Fig. 2. G-MSCR Example

Algorithm 1 G-MSCR

Input: POI set V, sweep period, and return time constraints

Set $l \leftarrow 1$
while $V \neq \emptyset$ **do**
  Find $v_s \in V$ that has the maximal d_s
  $t_r \leftarrow d_i$
  loop
    Find $v_i \in V$ that can maximize $\Delta = \min\{t_r - dist(v_s, v_i), d_i\} - dist(v_i, v_b)$
    if $\Delta < 0$ or adding v_i will exceed the sweep period **then**
      Quit loop
    else
      $t_r \leftarrow \min\{t_r - dist(v_s, v_i), d_i\}$
      Add v_i into T_l
      Delete v_i from V
    end if
  end loop
  $l \leftarrow l + 1$
end whilereturn l and $T_1, T_2, \ldots, T_l$

Theorem 2: G-MSCR guarantees global t-sweep coverage with return time constraint.

Proof: When a new tour T_l is construced, an initial POI is added to T_l. According to our assumption, covering this POI will not exceed the return constraint. We assume that, when the algorithm chooses next POI, t_r is within the return time constraint. Note that, when a new POI is added to T_l, t_r will be set to the smaller one between current remaining time and next POI return time constraint, which ensures that T_l is still within the return time constraints of all POIs in T_l. By induction, we can prove that the result of the algorithm does not violate the return time constraints.

For the sweep period, we can think of the route T_l as a ring. Since the mobile sensor nodes move at the same speed, every point on the ring will be covered exactly once during a certain time unit. Therefore, we only need to make sure the initial POI is t-sweep covered. Then we can ensure all the rest POIs in the same route are t-sweep covered. For the initial POI in T_l, G-MSCR checks whether it exceeds the sweep period using line 7 when adding a new POI to route. Therefore, G-MSCR can guarantee the sweep period constraint.

From these two aspects mentioned previously, we can conclude that G-MSCR guarantees t-sweep coverage with return time constraint. ■

In Theorem 3, we present the time complexity of Algorithm 1.

Theorem 3: The time complexity of Algorithm 1 is $O(n^2)$.

Proof: In line 6, finding $v_j \in V$ with maximal T_j takes time complexity $O(n)$. And the time complexity of the loop from line 5 to 14 is $O(n)$ since there are at most n POIs can be added in one loop. Hence, the time complexity of Algorithm 1 is $O(n^2)$. ■

V. MinD-Expand: An Alternative Heuristic Algorithm

Algorithm 2 MinD-Expand

Input: Location, sweep period and return time constraints of POIs. Location of base station.

Output: The number l of mobile sensor nodes required and the sweep path $T_1, T_3, \ldots, T_l$.

```
1:  Set l ← 1
2:  while V ≠ ∅ do
3:      T_l ← {v_b}
4:      loop
5:          Find the POI v_k with minimum cost between v_i and v_j using Eq. (1).
6:          if All predecessor can return within the return time constraint then
7:              Insert v_k between v_i and v_j. Remove v_k from V.
8:              l ← l + 1
9:          else
10:             Quit loop
11:         end if
12:     end loop
13: end while
```

In this section, another heuristic algorithm called MinD-Expand is presented. The formal description of MinD-Expand is presented in Algorithm 2. Technically, MinD-Expand is based the algorithm proposed Du et. al. [15]. The basic idea of MinD-Expand is to augment an edge by adding an uncovered POI into the edge in each iteration. When no more POI can be added, the algorithm terminates the current iteration and continues to construct the next route. This procedure is repeated until all POIs are covered. When MinD-Expand constructs a new sweep path T_l, the path only contains the base station v_b at the beginning. In our research, we separate the base station into two nodes: v_b and v'_b, which represent the leaving base station and the returning base station respectively. And we set the return time constraint of v_b as the sweep period. Therefore, the sweep period is guaranteed by constraining the return time. Then for all $v_k \in V$ and $(v_i, v_j) \in T_l$, we find the POI v_k with the minimum cost using the following equation:

$$cost = dist(v_i, v_k) + d_k - dist(v_k, v_j) - len(v_j) \quad (1)$$

, where $len(v_j)$ is the length of the path from v_b to v_j.

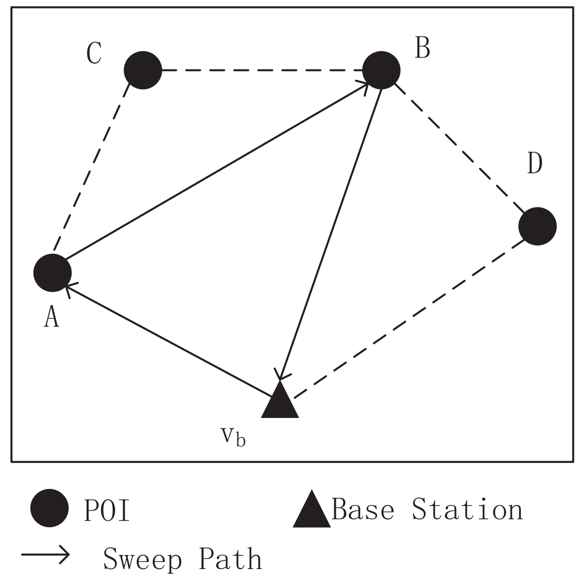

Fig. 3. Edge Augmentation in MinD-Expand

Then the algorithm checks whether it is within the return time constraints. Since the sweep path of the successor POIs on the path does not change when inserting a new POI into the sweep path, the check only involves the predecessor POIs. After determining whether the new POI could be inserted, the algorithm will repeat the augmentation procedure until no more POI can be inserted. Thereafter, the algorithm begins to construct the next sweep path T_{l+1}.

Note that in line 5, the time complexity of finding the POI with minimum cost is $O(n)$. Since in each iteration one POI is added to the current sweep route, the time complexity of the loop from line 4 to line 15 is $O(n)$. Therefore, the time complexity of MinD-Expand is $O(n^2)$.

Figure 3 includes an edge augmentation example. We first calculate $cost_C$ and $cost_B$ using Eq. (1). Assuming that $cost_C < cost_D$, then we check whether inserting C will violate the return time constraint of the predecessor on the sweep path. If not, we insert C between A and B and complete the augmentation.

VI. Experimental Results

In our research, we evaluated the performance of the proposed algorithm via extensive simulations. Specifically, we compared the proposed algorithms, G-MSCR and MinD-Expand, to MinTs1BS-Expand [21]. The detailed experimental results are presented in this section.

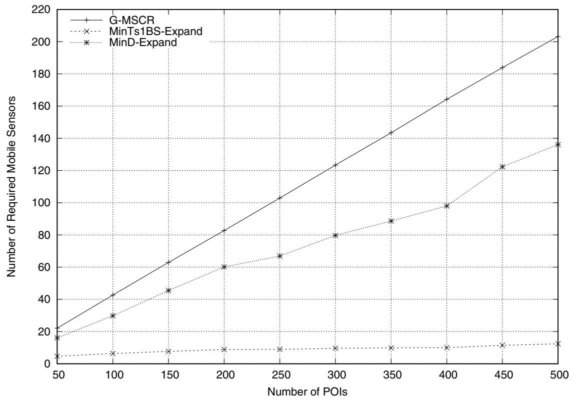

Fig. 4. Number of Required Mobile Sensor Nodes

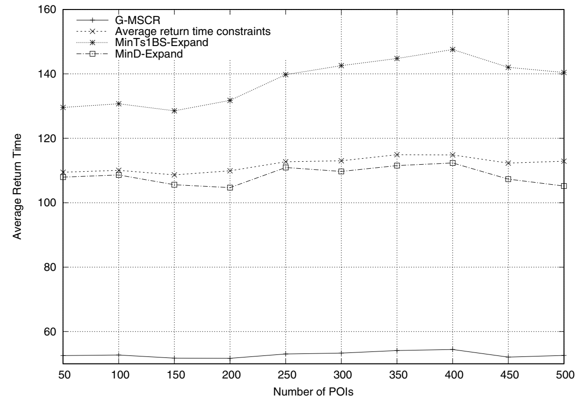

Fig. 5. Average Return Time

In our simulation, we randomly deploy a number of POIs on a 2-D plane with the constraint that the positions are uniformly distributed and no POIs are located at the same position. The number of the POIs variants from 50 to 500. The area of the plane is $100m$ by $100m$ and we set the movement velocity of the mobile sensors to $1m/s$. The sweep period and return time constraints are randomly generated from a fixed range which is as much as two times of the traveling time from the POI to the base station.

The experimental results on the number of required mobile nodes are summarized in Figure 4. Our results indicate that the number of required mobile sensor nodes grows with the number of POIs for all the algorithms under investigation. Specifically, the required number in the case of G-MSCR grows faster than that in the scenario of MinD-Expand. In addition, compared with MinTs1BS-Expand, G-MSCR and MinD-Expand leads to be much faster growth rate. However, we will see that MinTs1BS-Expand can not guarantee the return time constraints in next experimental results.

The experimental results on return time are summarized in Figure 5. Our results indicate that the average return time of both G-MSCR and MinD-Expand are less than the average return time constraints, indicating that they do not violate the return time constraint. Actually, G-MSCR leads to much lower average return time than MinD-Expand. Note that the average return time of MinTs1BS-Expand algorithm is greater than the average return time constraints, which shows that MinTs1BS-Expand can not guarantee that return time constraint is satisfied.

In summary, MinTs1BS-Expand can use a smaller set of nodes to provide sweep coverage. However, it does not guarantee that return time constraints can be satisfied. Both G-MSCR and MinD-Expand are designed for the problem of sweep coverage with return time constraint. As a result, although they need more modes to provide sweep coverage, they can guarantee that the return time constraints are completely satisfied. Between G-MSCR and MinD-Expand, G-MSCR requires more sensor nodes and leads to shorter return time. MinD-Expand needs less nodes, but the resulting return time is longer.

VII. Conclusion and Future Work

In this paper, we focus on the problem of sweep coverage with return time constraint. Specifically, we prove that the problem of finding the minimum number of mobile sensor nodes required to guarantee sweep coverage with return time constraint is NP-hard. In addition, we present two novel heuristic algorithms, G-MSCR and MinD-Expand, to solve the problem. Our experimental results indicate that, with some additional mobile sensor nodes, both the sweep coverage requirement and the return time constraints can be satisfied. Compared to MinD-Expand, G-MSCR requires more sensor nodes and leads to shorter return time.

In the future, we plan to study the scenario in which the sweep period varies for different POIs. We expect that the resulting sweep coverage schemes will be more feasible. The impact of varied velocity on the performance of the proposed algorithms will also be investigated in the next-step research.

Acknowledgement

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