Path Planning Algorithm for UAV Sensing Data Collection Based on the Efficacy Function

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Abstract. Data collection is one of the most fundamental tasks of wireless sensor networks. At present, the information collection methods of the sensor network mainly include static information collection methods and information collection methods based on mobile sink nodes. Static information collection methods have "energy void problem". However, in another method, the movement of sink nodes will be limited by the environmental terrain. Therefore, these two methods are difficult to effectively collect information in many application scenarios for a long time. In order to solve the above problems, we use the UAV to collect sensing data from the sensor network. It can also choose the order of collecting information based on the importance and the demand of information. In order to solve the problem of unmanned aerial vehicle's energy limitation and time delay of data collection in the real environment, an efficiency function is constructed which considered data value, energy consumption, time and risk. An improved A* path planning algorithm based on efficiency function is proposed for planning the flying path between SDG nodes. We also propose a bee colony path planning algorithm for solving the problem of SDG node allocation and access order.

Keywords: UAV · Wireless sensor network data collection · Path planning

1 Introduction

With the development of Internet of Things technology, the Internet of Things is widely used in intelligent transportation [1], military [2], agricultural production [3], emergency transaction processing [4], disaster relief [5] and environmental monitoring. All aspects of application are inseparable from the collection of data. The sensor network, as a carrier of the Internet of Things, plays an important role in the information acquisition of the Internet of Things. The data collected by the sensor nodes from the monitoring scene is a key part of the Internet of Things application. It is the link between the sensing layer and the application layer. If no data is sensed, the IoT network will lose its application value. Therefore, a reasonable data collection method is essential.

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At present, sensor networks mainly use sink nodes to collect data. Sensor nodes transmit data to sink nodes through one or more hops. Therefore, the node near the sink node sends more data packets than the remote node. This causes the energy of the nearby sink node to be quickly depleted, eventually causing the entire network to break and the remote node cannot send data to the sink node [6]. In [6], this phenomenon is called “energy void problem”. In [7], a data collection method based on a mobile sink node is proposed. The electric trolley equipped with the sink node is moved throughout the monitoring area to collect the data.

Although the “energy void problem” has been solved, when the sensor network is deployed in the wild terrain or in dangerous areas such as cliffs and landslides, the sink node cannot move within the monitoring area. When the sensor network is deployed in a fragile ecological environment protection area, the movement of the sink node may cause damage to the environment, so it is not feasible to collect data through the mobile sink node. Therefore, UAV (unmanned aircraft vehicle) can be used to collect data for the special application scenarios. It can not only solve the “energy void problem” but also be free from environmental terrain restrictions.

The sink node is mounted on the UAV. The UAV navigates the monitoring area and collects data. In order to reduce the flying distance, reduce energy consumption and reduce data delays. In [14], the vertical distance between the UAV and the ground sensor node is equal to or slightly less than the maximum effective communication distance, so as to reduce the flying distance of the UAV and optimize flying path. In [15], according to the value of data and the similarity of data to select key nodes with large data value. The UAV only collect the data of key nodes. In this way, UAV data collection tasks are greatly reduced. In [16], in order to minimizes the maximum energy consumption of all sensor nodes while ensuring that the UAV can collect the required data from each sensor node. The author jointly optimizing the wakeup schedule of the sensor nodes and the trajectory of the UAV. In [17], by deploying cooperative relays, instead of being limited to cluster head nodes, the waypoints for the UAV flying can be selected more freely. Data collection can be more efficient and energy consumption can be reduced.

The above references mainly use a single UAV to collect data, but when the scope of the monitoring area is large and the number of sensor nodes is large, a single UAV has been unable to collect data for all sensor nodes within the maximum data delay and energy limit. We need to use multiple UAVs for data collection and plan the flying path so that each UAV can complete the data collection task within the time limit and energy limit.

In this paper, we have established an efficacy function to evaluate the quality of the path. The efficacy function takes into account some factors, such as data value, energy consumption, time and risk. And then we use the improved A-star algorithm and the bee colony algorithm to plan the flying path when the UAV collects data. The A-star algorithm is used to plan the flying path of the UAV from one SDG (Sensing Data Gather) node to another SDG node. Using the bee colony algorithm to assign each SDG node to each UAV and determine the order of data collection.

The rest of this paper is organized as follows. The efficacy function is described in Sect. 2. In Sect. 3, the A-star algorithm is improved and is used to plan the flying path between SDG nodes. In Sect. 4, UAV flying path planning based on Bee Colony Algorithm. The performance evaluation with simulation results is revealed in Sect. 5. Conclusions are drawn in Sect. 6.

2 Efficacy Function

When planning flying path for multiple UAVs, it is necessary to establish corresponding evaluation index for evaluating the quality of the planned flying path. This article uses the efficacy function as an evaluation index. The efficacy function takes into account some factors, such as data value, energy consumption, time and risk.

Multiple UAVs collect data from the wireless sensor network in the monitoring area R. There are several SDG (Sensing Data Gather) nodes in the monitoring area R for transmission of sensing data to the UAV. Before the UAV collecting data, the location of the SDG nodes is known, and the type, quantity, and data value of the sensors in each SDG node are known. The UAV stays in the SDG node area during data collection and communicates with ground sensors to acquire all sensed data. UAVs cannot fly beyond the no-fly zone.

2.1 Data Value

The value of the data that the UAV obtain from each SDG node depends on the number of various types of sensors in the SDG node and the related data value. v^y is the data value of the data sensed by the y type sensor. Therefore, the value of the data collected by the UAV at the SDG node i is:

$$D_i^s = \sum_{y=1}^{J} n_i^y v^y \tag{1}$$

n_i^y is the number of y sensor nodes in the SDG node.

Therefore, the value of the data that the UAV fly from the SDG node i to the SDG node j is:

$$D_{ij} = \frac{1}{2}(D_i^s + D_j^s) \tag{2}$$

2.2 Energy Consumption

Because the energy of UAV is limited. Therefore, we must ensure that the UAV completes its mission and returns safely to its destination before it runs out of energy. The energy of UAV is mainly used for flying and hovering.

d_{ij} is the distance from SDG node i to SDG node j. The energy consumption of each point on the flying path of the UAV is f^e, and f^e is related to the terrain. Therefore, the flying energy consumption from SDG node i to SDG node j is:

$$E_{ij}^f = -\int_0^{dij} f^e dl \tag{3}$$

When the UAV collects data, it needs to hover over SDG nodes for a period of time. The energy consumption of the UAV in the hovering process is called hover energy consumption. We assume that the energy consumption of the UAV hovering per unit time is h^e. The hover energy consumption of the UAV at SDG node i is [8]:

$$E_i^h = -h^e t_s \sum_{y=1}^{J} n_i^y n_y^d \tag{4}$$

n_i^{y} is the number of y sensor nodes in the SDG node i. t_s is the exchange time of a single data packet. n_y^d is the number of data packets in the y sensor.

Therefore, the energy consumption that the UAV fly from the SDG node i to the SDG node j is:

$$E_{ij} = E_{ij}^f + \frac{1}{2}(E_i^h + E_j^h) \tag{5}$$

2.3 Time

The UAV mainly spends time in flying and hovering. $\bar{v}_{ij}^f$ is the average flying speed of the UAV from SDG node i to SDG node j, so the flying time from SDG node i to SDG node j is:

$$T_{ij}^f = -\frac{dij}{\bar{v}_{ij}^f} \tag{6}$$

The time for the UAV to hover over the SDG node i is:

$$T_i^h = -t_s \sum_{y=1}^{J} n_i^y n_y^d \tag{7}$$

Therefore, the time that the UAV fly from the SDG node i to the SDG node j is:

$$T_{ij} = T_{ij}^f + \frac{1}{2}(T_i^h + T_j^h) \tag{8}$$

2.4 Risk

When the UAV flies and hover, it may be at risk. The risk that the UAV encounters while flying, we call it flying risk. The flying risk of each point on the flying path of the UAV is r^f, so the flying risk from SDG node i to SDG node j is:

$$R_{ij}^{f} = -\int_{0}^{dij} r^{f} dl \tag{9}$$

The risk of the UAV hovering over the SDG node to collect data, we call it the hovering risk, Hovering risk for SDG nodes is:

$$R_{i}^{s} = -r_{i}^{h} t_{s} \sum_{y=1}^{J} n_{i}^{y} n_{y}^{d} \tag{10}$$

r_i^h is the risk of hovering within unit time.

So the risk that the UAV fly from the SDG node i to the SDG node j is:

$$R_{ij} = R_{ij}^{f} + \frac{1}{2}(R_{i}^{s} + R_{j}^{s}) \tag{11}$$

2.5 Efficacy Function and Restrictions

M is the number of UAVs for data collection, numbering multiple UAVs. Expressed as $F = \{f_1, f_2, \ldots, f_M\}$. Therefore, the flying path for the m-th UAV data collection is $P_m = \{S_0, S_i, S_j \ldots, S_0\}$. In order to define the efficacy function and describe constraints, define 0-1 decision variables as follows:

$$x_{ijm} = \begin{cases} 1 & \text{The i}-\text{th and j}-\text{th SDG nodes are on the m}-\text{th UAV data collection path} \\ 0 & \text{others} \end{cases}$$

The relevant parameters of the m-th UAV are as follows:

Data value:

$$D_m = \sum_{i=0}^{N} \sum_{j=0}^{N} D_{ij} x_{ijm} \tag{12}$$

Energy consumption:

$$E_m = \sum_{i=0}^{N} \sum_{j=0}^{N} E_{ij} x_{ijm} \tag{13}$$

Time:

$$T_m = \sum_{i=0}^{N} \sum_{j=0}^{N} T_{ij} x_{ijm} \tag{14}$$

Risk:

$$R_m = \sum_{i=0}^{N} \sum_{j=0}^{N} R_{ij} x_{ijm} \tag{15}$$

All UAV related parameters are as follows:
Total data value:

$$D_{ma} = \sum_{m=1}^{M} D_m \tag{16}$$

Total energy consumption:

$$E_{ma} = \sum_{m=1}^{M} E_m \tag{17}$$

Total time:

$$T_{ma} = \sum_{m=1}^{M} T_m \tag{18}$$

Total risk:

$$R_{ma} = \sum_{m=1}^{M} R_m \tag{19}$$

The efficacy function of multi-UAV data collection is as follows:

$$U_m = a \times \frac{D_{ma}}{D_{max}} + b \times \frac{T_{ma}}{T_{max}} + c \times \frac{E_{ma}}{E_{max}} + d \times \frac{R_{ma}}{R_{max}} \tag{20}$$

D_{max}, T_{max}, E_{max}, R_{max} are the maximum value of each parameter which are set in advance.

The restrictions of multi-UAV data collection is as follows:

Ensure that each UAV can complete data collection for all SDG nodes before the limited time and energy are exhausted. So energy and time constraints:

$$\begin{cases} max(E_m) \leq E_{max} \\ max(T_m) \leq T_{max} \end{cases} \tag{21}$$

Ensure that each SDG node's data is collected:

$$\begin{cases} \sum_{m=1}^{M}\sum_{j=0}^{N} x_{ijm} = 1 \quad i \in S \\ \sum_{m=1}^{M}\sum_{i=0}^{N} x_{ijm} = 1 \quad j \in S \end{cases} \tag{22}$$

Each UAV is guaranteed to start from the starting point and eventually return to the end.

$$\begin{cases} P_m(0) = S_0 \\ P_m(end) = S_0 \end{cases} \tag{23}$$

Ensure that each UAV will collect data. No UAVs will be idle.

$$\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ijm} \neq 0 \quad m \in M \tag{24}$$

3 UAV Flying Path Planning Between SDG Nodes Based on A-Star Algorithm

In this section, we use the A-star algorithm to plan the flying path of the UAV from one SDG node to another SDG node.

First, the monitoring area is rasterized, and then an open list is created to record the neighborhood of the evaluated area. A close list is used to record the areas that have already been evaluated, and the estimated distances from the "starting point" to the "target point" is calculated, the closed list holds all the nodes that have been explored or evaluated. In the process of path finding, the nodes are expanded according to the evaluation function. The nodes in the open list and the close list are changed at any time, and the same node may appear repeatedly in the open list and the close list. According to the evaluation function to find the target point, and then through the backtracking way to get the final path from the starting point to the end point.

3.1 Evaluation Function

$$f(n) = k \times (g(n) + h(n)) + \frac{1-k}{3} cost(n) \tag{25}$$

$g(n)$ is the distance from the starting point to the current point, when the node n is in the vertical or horizontal direction of the node n−1, use the formula (26) to calculate, and when the node n is in the diagonal direction of the node n-1, use formula (27) to calculate:

$$g(n) = g(n-1) + 1 \tag{26}$$

$$g(n) = g(n-1) + 1.4 \tag{27}$$

$h(n)$ is a heuristic function that represents the estimated distance from the current node to the end point, the A* algorithm usually uses Euclidean distance to represent $h(n)$:

$$h(n) = \sqrt{(x_n - x_{end})^2 + (y_n - y_{end})^2} \tag{28}$$

$cost(n)$ is the flying cost of the current node:

$$cost(n) = \frac{UAV_{risk}(n)}{UAV_{risk\_max}} + \frac{UAV_{energy}(n)}{UAV_{energy\_max}} + \frac{1}{UAV_{velocity}(n)} \times \frac{1}{t_{max}} \tag{29}$$

3.2 Determination of k-Value in Evaluation Function

The k value indicates the weight value of flying cost in the evaluation function. The flying path planned by the A-star algorithm is different with different k value.

In order to assess the UAV flying path planned by the A-Star algorithm is bad or good, we define the flying consumption from SDG node to SDG node j as:

$$fly_{con} = \frac{E_{ij}}{E_{ijmax}} + \frac{T_{ij}}{T_{ijmax}} + \frac{R_{ij}}{R_{ijmax}} \tag{30}$$

In order to more fully demonstrate the impact of the k value on the planned path, we have shown the time, energy consumption, risk, and flying consumption in Fig. 1.

As can be seen from Fig. 1, when k is larger than 0.6, energy consumption and time tend to decrease as k increases. Because the larger the value of k is, the greater the weight of the distance in the evaluation function is, the length of the planned path will be shortened, and the time and energy consumption of the UAV will be reduced. The risk decreases firstly and then increases, because the larger the value of k, the smaller the weight value of the risk in the evaluation function, and the smaller the impact on the

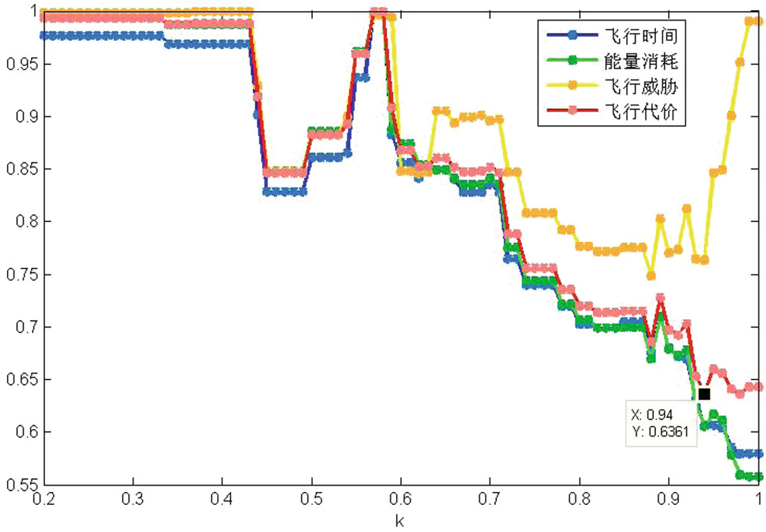

Fig. 1. k value vs. flight consumption graph

planned route, the lower the search distance and the higher the risk value. The area will therefore cause the flight risk to increase.

The node marked in Figs. 3, 4, 5, 6, 7, 8, 9 and 10 is the minimum value of the flying consumption. At this time, the flying consumption is 0.6361, corresponding to the value of k is 0.94. By changing the position of the starting point and the ending point, we found that when the flying consumption is the minimum value, the corresponding k value is mainly distributed within the range of 0.92−0.96. Therefore, we determine the value of k is 0.94.

3.3 Comparison Between A-Star Algorithm and Dijkstra Algorithm

In order to prove the performance of the improved A-star algorithm, we compare the A-star algorithm with the Dijkstra algorithm. We select a starting point and an ending point in the area R, and draw the search range map of the A star algorithm and the Dijkstra algorithm from the start point to the end point respectively.

It can be seen from Figs. 2 and 3 that the search range of the improved a-star algorithm is much smaller than the search range of the Dijkstra algorithm, so that the optimal path can be obtained in a shorter time. And the path of the improved a star algorithm is straighter. Because the UAV is difficult to make a large range of maneuvers, the UVA cannot fly according to the path planned by the Dijkstra algorithm, so the path planned by the improved a star algorithm is more reasonable.

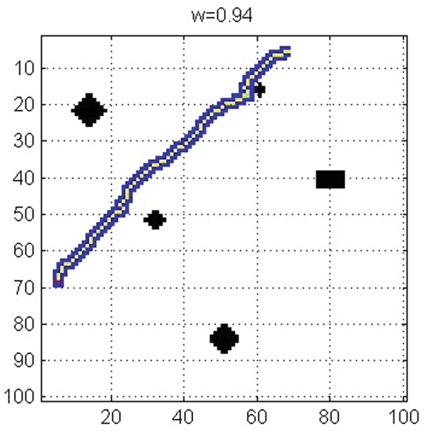

Fig. 2. A star algorithm search range map

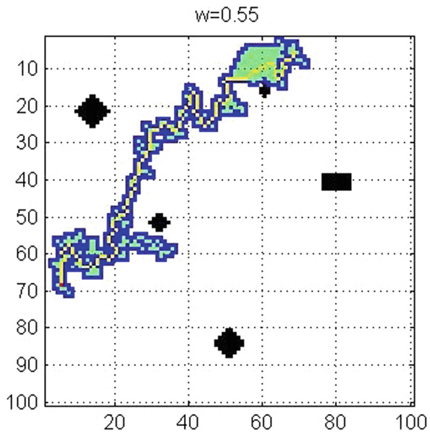

Fig. 3. Dijkstra algorithm search range map

4 UAV Flying Path Planning Based on Bee Colony Algorithm

We use the bee colony algorithm to assign each SDG node to each UAV. The UAVs exchange SDG nodes and change the order of collecting SDG node data, so that the total efficacy value of all paths planned is maximized.

In the bee colony algorithm, bees are divided into three categories: Leader, Follower and Scouter. Each Leader corresponds to a honey source (a feasible solution). The Leaders generate new honey sources according to the neighborhood strategy, evaluate the performance values of the new and old honey sources, use greedy strategies to select, and share this information with others with a certain probability. Follower to select leader following a certain probability value according to the efficacy value of the honey source, and seek for other honey sources in the neighborhood, and try to change the honey source of the leader to be followed to make the efficacy value larger. When a certain honey source cannot be improved after a limited search time (the honey source has been fully utilized), the honey source will be discarded, and the corresponding honey bee will be converted into a scout bee, and the scout bee will randomly generate a new one within the search scope.

4.1 Generation of Initial Solution

We use three UAVs and ten SDG nodes as examples to generate the initial solution. The UAVs are numbered 1, 2 and 3. The SDG nodes are numbered 1, 2, 3, … 9 and 10. In each group of initial solution, each UAV randomly selects one SDG node as the first data collection node. Each SDG node can only be selected once, and then according to the previous SDG node of each UAV, the node with the largest value of the efficacy function of the previous SDG node is found among the remaining unselected nodes. In this way, n groups of initial populations are generated (Table 1).

Table 1. Generation of initial solution

The first UAV	0-1-6-8-0
The second UAV	0-5-7-9-10-0
The third UAV	0-3-2-4-0

4.2 Neighborhood Search Strategy

The neighborhood search strategy is to change the solution by some operations based on the solutions already generated, so as to obtain a new solution. In this paper, we use the reverse strategy, the nearest strategy, and the cross strategy to search neighborhood.

a. Reverse strategy

SDG nodes with two different random positions in the UAV path are reversed.

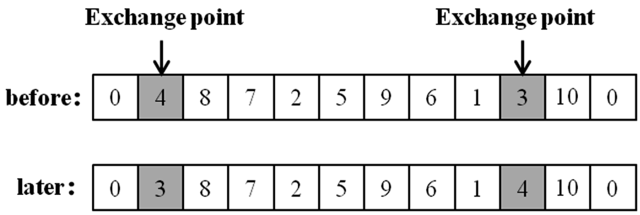

Fig. 4. Reverse strategy

b. Nearest strategy

A SDG node is randomly selected in the path string, we called it as PSDG and then select a SDG which has the highest efficacy value with PSDG and insert it behind the PSDG.

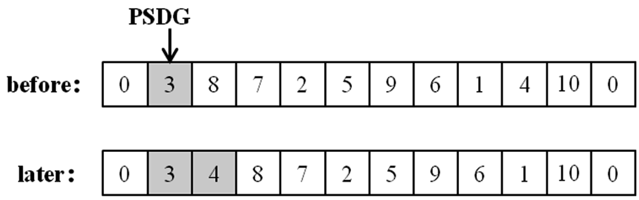

Fig. 5. Nearest strategy

c. Cross strategy

We randomly select one section of the two UAV paths from the same group of solutions to exchange.

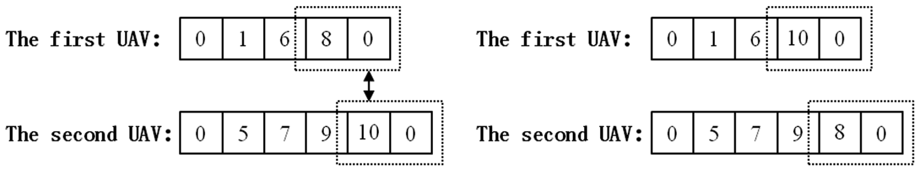

Fig. 6. Cross strategy

5 Simulation Analysis

5.1 The Initial Parameters are Set as Follows

See (Table 2).

Table 2. Initial parameters

Parameters	Symbols	Values
Number of y-sensor in the i-th SDG node	n_i^y	0–5
The data value of y-sensor	v^y	1–3
Velocity	v	8–13 m/s
Energy Consumption	f^e, h^e	10-20
Risk	r^f	0–1
Time limit	T_{limit}	30 min
Energy limit	E_{limit}	4000

5.2 Simulation Steps

Step 1: Enter initial parameters.
Step 2: Using the A-Star algorithm to plan the path between SDG nodes.
Step 3: Using bee colony to assign SDG nodes to each UAV and determining the order in which UAVs collect data.
Step 4: Smoothing the planning path.
Step 5: Draw data collection path map and output simulation results.

5.3 Simulation Result

This section we will show the path planning results when we use multiple UAVs to collect data form SDG nodes. Figures 7, 8, 9, 10, 11, 12, 13 and 14 shows the path planning results of using different numbers of UAVs to collect data form different amounts of SDG nodes. Figure 13 shows the path planning results when the starting node is not in the center of the target area. Figure 14 shows the path planning results when the SDG nodes are relatively concentrated. The red point is the start point (end point), the green point is the SDG node, and the black area is the no-fly area. Different colored lines are the flying paths of different UAVs.

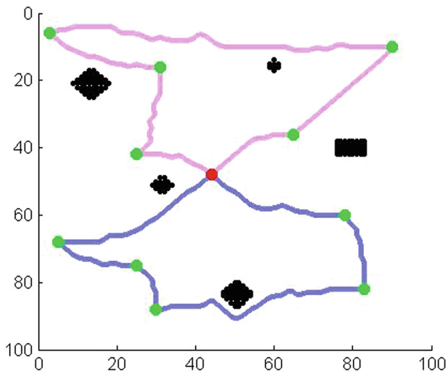

Fig. 7. Two UAVs 10 SDG nodes

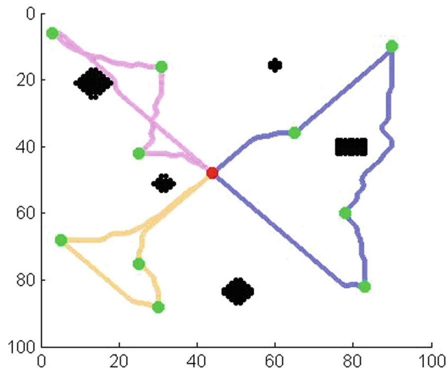

Fig. 8. Three UAVs 10 SDG nodes

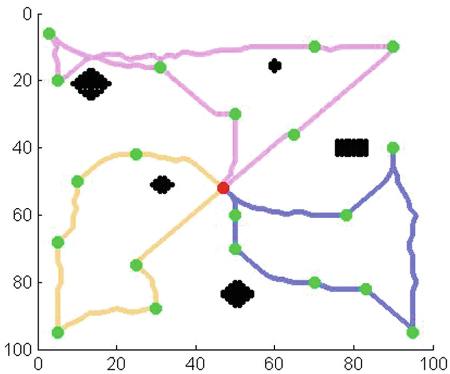

Fig. 9. Three UAVs 20 SDG nodes

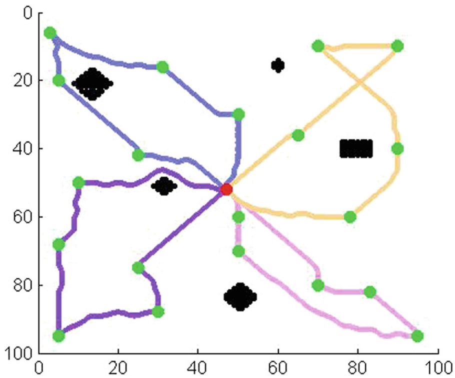

Fig. 10. Four UAVs 20 SDG nodes

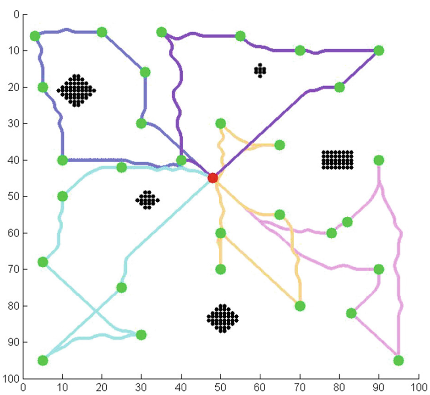

Fig. 11. Five UAVs 30 SDG nodes

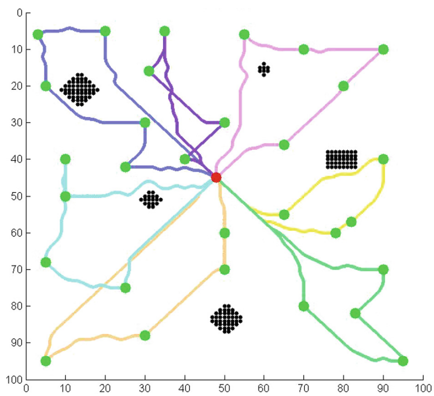

Fig. 12. Seven UAVs 30 SDG nodes

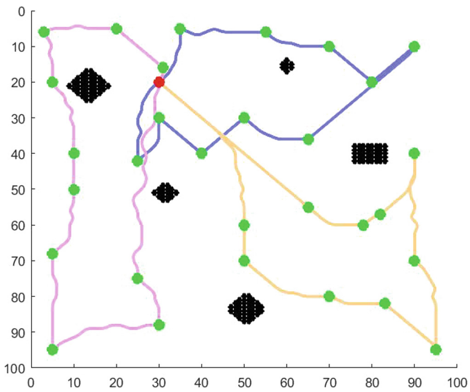

Fig. 13. Change the initial point

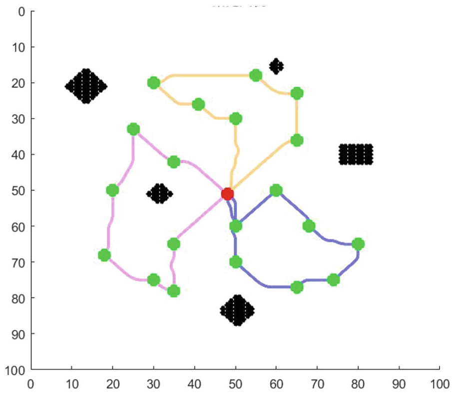

Fig. 14. SDG Nodes are relatively concentrated

In order to further analyze the effect of using different numbers of UAVs on the value of the efficacy function, we use 1–7 UAVs to collect data from 20 SDG nodes and get the total energy consumption, total Time, and total risk. As shown in Tables 3 and 4.

In order to comparative analysis, each parameter is presented in Figs. 15 and 16.

Table 3. Efficacy function simulation result parameters (the initial point is at the center of the target area)

UAV number	Total energy consumption	Total risk	Total time(s)
1	5829.4	119.32	4279.1
2	6340.6	130.43	2595.3
3	7062.2	146.59	1501.4
4	7340.6	153.43	1430.3
5	8243.4	184.72	1199.7
6	9120.2	195.40	1351.0
7	9694.0	210.77	347.9

Table 4. Efficacy function simulation result parameters (the initial point isn't at the center of the target area)

UAV number	Total energy consumption	Total risk	Total time(s)
1	5691.6	118.54	4212.3
2	6803.8	133.75	2389.6
3	7791.2	154.50	1913.8
4	8481.8	171.55	1720.7
5	9495.2	186.90	1123.3
6	10593.6	208.74	1096.3
7	11371.0	220.48	754.5

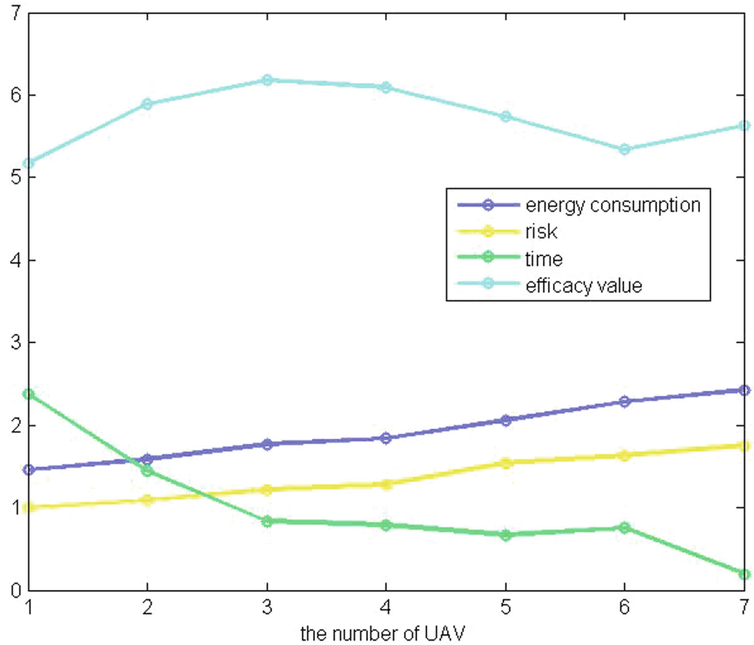

Fig. 15. Simulation result parameters graph (the initial point is at the center of the target area)

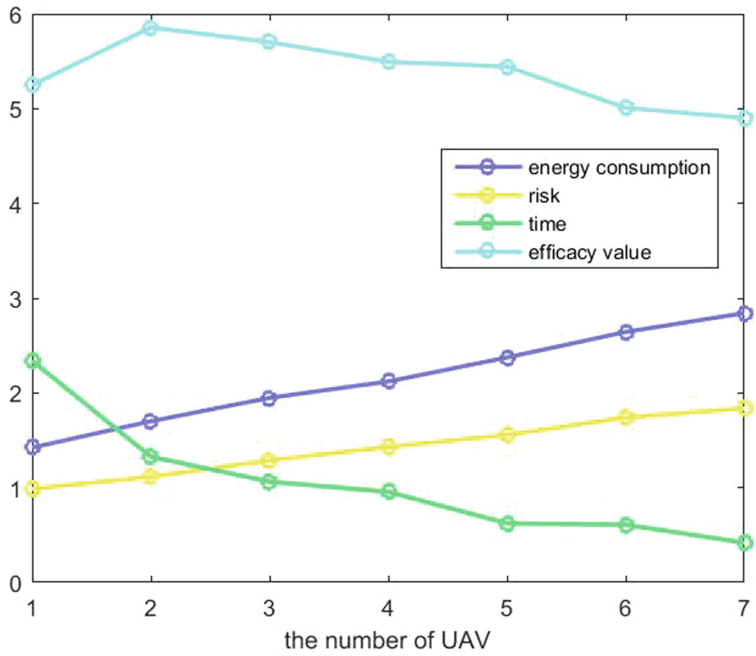

Fig. 16. Simulation result parameters graph (the initial point isn't at the center of the target area)

From Fig. 15, the total energy consumption increases with the increase in the number of UAVs, because each UAV needs to start from the start point and finally return to the start point, so the total distance will increase, and the total energy consumption of UAVs will also increase. Risk values are similar to the energy consumption. As the increase of flying distances, the possibility of risk to UAVs during flight is also increasing. So the risk value increases with the increase in the number of UAVs. Due to the increase in the number of UAVs, the number of SDG nodes that each UAV needs to collect is reduced, so each UAV has a shorter flying distance and less time. Because each UAV departs from the start point at the same time, the flying time of the last UAV that completes the task and return to the start point is the time value of this data collection.

From Fig. 15, it can be seen that the value of the efficacy increases first and then decreases, and reaches the maximum value when the number of UAVs is three. When only one UAV is used for data collection, the energy consumption and risk value are the smallest, but the maximum flying time and maximum energy consumption of a single UAV have been exceeded. The efficacy function value is lower. When seven UAVs collect information, the time required is the shortest, but due to the large number of UAVs, a large amount of energy is required, and the risk value is also large, so the value of the efficacy function is also low. When using three UAVs to collect data, although all parameters are not the minimum value, the time is greatly shortened, and the increase in energy consumption and risk value is small, so the efficacy value is maximum.

It can be seen from Fig. 16 that when the initial node is not at the center of the target area, the trend of energy consumption, risk and time does not change as shown in Fig. 8, but the efficacy value of data collection is the largest when using two unmanned aerial vehicles. Because when the initial node is not in the center of the target area, the UAV needs to fly a long distance to reach the area with the SDG nodes. So the more the number of unmanned aerial vehicles used, the longer the total path length of the UAV flying without the SDG node. Therefore, the UAV consumes more energy and time.

From the above diagrams and analysis, when the initial node is in the center of the target area, it is best to use 3 UAVs collect information from 20 SDG nodes. When the initial node is not in the center of the target area, it is best to use 2 UAVs collect information from 20 SDG nodes.

6 Conclusion

In this paper, we propose an algorithm for UAV data collection in wide IoT sensor networks. The efficacy function is established to evaluate the quality of the path. The efficacy function takes into account some factors, such as data value, energy consumption, time and risk. The A-star algorithm is used to plan the flying path of the UAV from one SDG (Sensing Data Gather) node to another SDG node. Using the bee colony algorithm to assign each SDG node to each UAV and determine the order of data collection. Finally, we obtained the path planning results of data collection by using multiple drones. The simulation results show that our method can optimize the flying path of UAV and reduce energy consumption, also provide basis for multiple UAV data collection.

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