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Dynamic Self-Organizing Leader-Follower Control in a Swarm Mobile Robots System Under Limited Communication

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ABSTRACT The leader-follower model is found efficient for robot swarm exploration tasks. When a swarm of mobile robots collaboratively explore an unknown environment with limited communication, such as communication delay or even message loss, it is necessary to adaptively re-group robots according to the dynamic communication conditions and task goals. In this paper, we propose to analyze the leader-follower topology in a graph fashion and employ Ratio Cut of the proposed graph for membership re-assignment. We take each robot as a node and consider both the communication delay and the goal, i.e., exploring towards unknown area, as the edge weight. Then we use the Laplacian matrix to bipartition the graph repeatedly to optimize group partition. Simulation results validate the effectiveness of the proposed method.

INDEX TERMS Robot swarm, leading-follower, re-organization, graph theory.

I. INTRODUCTION

In recent years, there is a rapid development of mobile robot, such as unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) for a number of application services ranging from delivery of goods to surveillance and smart city monitoring. Despite its advantages in cost and mobility, a single mobile robot is known for sensitive to environment changes and, as a consequent, low efficiency in tasks such as searching, exploring or mapping. To overcome these issues, the employment of a set of collaborative mobile robots, also known as swarm robots, equipped with sensors and communication devices, can be used to improve the robustness and increasing fault-tolerant resilience. In addition, swarm robots are expected to perform better than a single one in terms of exploring coverage and efficiency.

Typically, there are two basic structures of swarm robots [1]: the hierarchical structure, i.e., there is a leader who performs as a commander for a group of other robots and the decentralized structure, i.e., each agent in one group can independently make their own decision. Although the decentralized structure has shown more flexible and autonomous in natural, this kind of structure may suffer from poor stability and controllability because of the independency of each agent. As a result, the exploring efficiency of decentralized swarm is always low. In this paper, we focus on the hierarchical structure, in particular, the leader-follower model.

The leader-follower fashion has the advantage of being simple and low cost [2]. The leader robot determines the desired path of the swarm. All followers only need to communicate with the leader and/or other followers, and act accordingly with the leader. However, the main disadvantage of this kind of structure is that it has a single point of failure that if the leader stops working, the entire group then fails.

One of the most common reasons of a failure approach is the limited communication [3], including communication delay or data loss. In case of delayed communication, it is difficult to accurately estimate the real position of one group member. As a result, the planned path optimized by the leader robot may fall into a suboptimal solution, or even an incorrect one. What is worse, such uncertainty of localization may accumulate during the cruise and, finally, leading to a failure of exploration. Another challenge for leader-follower approach is the erupted human demands, which are always sent to the leader and re-delivered to all agents. In a limited communication environment, some agents may fail to receive the updated path and hence does not act accordingly. The human-interacted leader is popular in autonomous driving

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cars where a manned vehicle always plays the leader role with many unmanned followers following for auxiliary. In this case, the manned leader is highly preferred since it is less prone to failure and relies very limited additional sensors or instruments, which are expensive in general.

As a promising solution, swarm dynamic re-grouping is an efficient solution to the problem. Intra-group communication is always affected by environment, such as walls, doors or neighbor network interference. It is natural to group robots of low communication cost, and in turn to ensure a reliable communication local network. In this paper, we propose to consider the communication condition into account and build and dynamically update a graph for group partition.

The rest of this paper is organized as follows. Section II presents the literature review. Section III shows our main works and Section IV provides the experimental results. We give our conclusion in Section V.

II. LITERATURE REVIEW

A. COMMUNICATION NETWORK

Previous working on wireless swarms robots can be grouped into two categories. The first category studies the intra-swarm communication network design. Works in [4] build a multi-cluster flying ad-hoc network to reduce the power consumption with the cost of a slightly latency on communication for UAV swarms. In [5], a bio-inspired clustering scheme is proposed to ensure energy aware cluster formation. The authors used the hybrid mechanism of glowworm swarm optimization (GSO) and krill herd (KH) for FANETs. For FANETs, works in [6] argue that Bluetooth 5 (802.15.1) is the most favored option because of its low-cost, low power consumption, and longer transmission range, but with the cost of low data rate. To handle this problem, [6] combines 802.11 and 802.15.1 for both transmission rate and power consumption.

Since UAVs typically work in a high speed mode, it poses a greater challenge to FANET routing. In [7], the authors proposed to employ continuous Hopfield neural network to optimize the route. In [8], IEEE 802.15.4 MAC protocol is considered in multi-cluster FANETs with/without beacon. Therefore, an efficient routing strategy is presented. In FANETs, reliable packet forwarding is not always guaranteed due to a possible poor link. Works in [9] proposed a hybrid packet forwarding algorithm to ensure a reliable deliver data packets to ground destination. An alternative solution, as in [10], a cellular Device-to-Device Communications based MAC network is proposed. Such network is able to support high reliable communication and two-hop topology.

The second category pays attention to coordination and control for effective task planning for UAVs. In [11], a disaster aware mobility model is designed to improve the robustness of a flying ad-hoc network. To evaluate the performance of different routing protocols, [12] models the UAVs movement in a Gauss-Markov mobility model and hence is able to examine network parameters dependency. Works in [13] propose an energy management framework for cellular heterogeneous networks. In their works, the UAVs are able to determine the optimal trips of the drones and automatically to turn on/off the power, in a purpose to minimize the total energy consumption. In [14], a heuristic UAVs task planning algorithm is proposed to ensure cellular connected UAVs able to visit all targets in a minimum time. In [15], the authors proposed a behavioral flocking algorithm for distributed flight coordination of multiple UAVs.

B. ROBOT EXPLORATION

The work on multi-robot exploration was started by Yamauchi [20]. Works in [20] introduced a frontier-based robot exploration method. In their works, a grid map with laser- and sonar- detected frontier, which is the region boundary between explored area and unknown space, is built. Then, one robot is able to navigate to the nearest possible frontier for further exploration. They tested on a Nomad 200 mobile robot to cruise the area of 45 feet long and 25 feet wide. They completed the exploration in 0.5 hours.

As an extension from a solo robot to multiple ones, Yamauchi in [21] proposed to multi-robot system. They adopted the decentralized architecture where a local map is maintained and updated by each robot. The local map is integrated with the swarm's global one and delivered to all linked agents. Once a robot receive a global map, that robot then knows the relative positions of all neighbours and hence is able to optimize the path for exploration.

Similar to the frontier fashion, Simmons *et al.* [22] developed a semi-distributed multi-robot exploration algorithm. The most distinguished difference of Simmons's work is the employment of a central agent, rather the decentralized architecture used by Yamauchi. The central agent is able to communicate with all the other robots and hence receive status of all other ones. A global optimization over the time cost or the traveling distance thus can be achieved.

Recently, the communication condition is considered for swarm robot exploration. Banfi *et al.* [23] proposed an asynchronous strategies that work with arbitrary communication models. For a robust sampling of AUVs in a limited communication environment, Kemna *et al.* [24] used a dynamic Voronoi partitioning approach to repeatedly calculate weighted Voronoi partitions for the space. To satisfy the maximize the number of packages completed in the unit of time, Farinelli *et al.* [25] built a distributed constrained optimization problem and provided a solution based on the binary max-sum algorithm.

III. DYNAMICALLY GROUP SELECTION

A. COMMUNICATION DELAY ON A GROUP OF ROBOTS

In swarm robot exploration, a group of robots is expected to collaboratively explore an unknown area with minimum cost in time and/or power consumption. The leader-follower model is a popular swarm robot control method. In practice, however, the communication delay may significantly depress the overall group performance. We take Fig. 1 as an example.

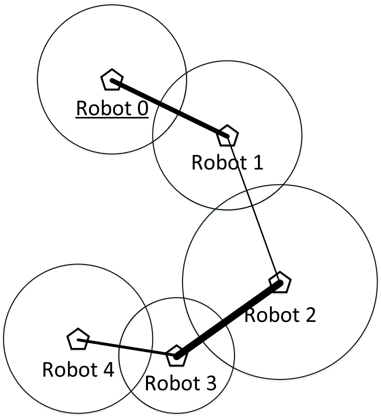

FIGURE 1. Communication in a leader-follower group. Circle indicates communication range. Edge means communication link and the width of each link means the signal strength: a narrow edge implies low signal strength. Robot 0 is assigned the leader and deliver the commands to all four followers via the links.

In Fig. 1, five robots are assigned as a group and robot index 0 is the leader. The circle of each robot is the communication range and edges between any two robots are the links. The width of each link indicates the signal strength, or the communication delay, where a narrow link means a possible high communication delay. In Fig. 1, if the leader robot 0 sends a new message to all the four followers, that message will deliver through a path of [0,1,2,3]. That means, when robot 3 receives a new command from the leader, there exists a delay as the sum of all the delays along the path. In a high-speed cruise mode, as used in many time-sensitive tasks, such delay may result in suboptimal group behavior.

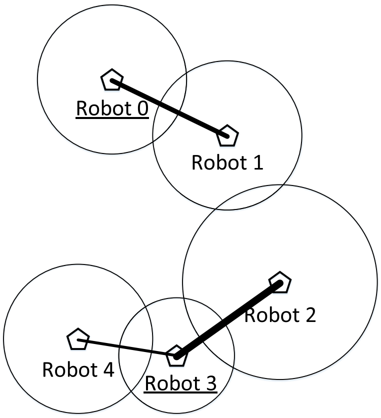

FIGURE 2. Re-grouped robots where robot 0 and 3 are assigned as the leader of the couple individual groups.

To deal with this problem, it is desired to re-group the robots in Fig. 1, as shown in Fig. 2. In Fig. 2, the swarm is grouped into two groups, with leader robot 0 and 3 respectively. After re-grouping, the intra-group communication delay is significantly reduced and, as a result, the entire swarm then can obtain more accurate moving and localization than before.

B. OPTIMAL PARTITION OF ONE GROUP

The first problem is to decide that whether or not one group should be divided. Intuitively, if the cumulative communication delay of one or more robots is too large, then a partition of that group is desired. To this end, we first calculate the communication delay of each node to the leader. We employ the Dijkstra shortest path algorithm to find out the shortest path of the leader node to all the rest nodes and record the overall cost, $C_i, i = 1, 2, \ldots, n-1$ along the i-th shortest path of node i. Thus, we can use this cost, C_i, to evaluate the communication delay of the i-th robot of delivering a message from the leader to the i-th node.

Other than the cumulative communication delay, the balance of group sizes is also important to the swarm. Since it is the leader of one group to percept status of all the in-group followers and optimize the path for the group, the computation load of the leader then is significant if too many followers in its view. Thus, it is required to balance the number of agents among groups, to reduce the burden of the leaders.

For a group of robots and the intra-communication delay among the robots, we propose our re-grouping determination and the optimal partition method. Given n robots of a swarm and e_{ij} the signal strength between robot i and j, we construct a graph $\mathcal{G}$ with these n nodes and edge e_{ij}. Define a function $W(A, B)$ as

$$W(A, B) = \sum_{i \in A, j \in B} e_{ij} \tag{1}$$

and $|A|$ as the number of nodes in set A. It is easy to see that $W(A, B)$ calculates the sum of inter-set edge weights and, in our problem, the sum of inter-group communication delay between group A and B.

For a given number k of groups, the group partition approach simply includes the selection of k disjoint sets $A_1, A_2, \ldots, A_k$ which minimize the cut function that

$$cut(A_1, A_2, \ldots, A_k) = \frac{1}{2} \sum_{i=1}^{k} W(A_i, \bar{A}_i) \tag{2}$$

where $\bar{A}_i$ means the complement of A_i. Then, we define the cost function $C(A_1, A_2, \ldots, A_k)$ considering both communication delay and the group volume balance that

$$\begin{aligned} C(A_1, A_2, \ldots, A_k) &= \frac{1}{2} \sum_{i=1}^{k} \frac{W(A_i, \bar{A}_i)}{|A_i|} \\ &= \sum_{i=1}^{k} \frac{cut(A_i, \bar{A}_i)}{|A_i|} \end{aligned} \tag{3}$$

In Eq. (3), the numerator $cut(A_i, \bar{A}_i)$ indicates that we consider the sum of delays group members to all other agents, and the denominator $|A_i|$ is a normalization part to normalize each group with its volume. Thus, the optimal partition of Eq. (3) is the solution to our aforementioned re-grouping problem.

C. RATIOCUT RE-GROUPING ALGORITHM

It is natural to take the optimal solution to Eq. (3) as our re-grouping solution. Unfortunately, the optimal solution to Eq. (3) is NP hard [16]. With a relatively large group size n, the huge burden in computational cost to solve Eq. (3) prevents Eq. (3) for practice.

As a solution, spectral clustering [16]–[19] solves a relaxed version of Eq. (3) where the membership indicator, $\{-1, +1\}$ in original, is relaxed to $[-1, +1]$. Then, Eq. (3) is a Ratio Cut problem which is well studied in [16]. Define a affinity matrix W as $W_{ij} = e_{ij}$, we then is able to solve Eq. (3) in a relaxed fashion. Alg. 1 shows the way to obtain the optimal solution to Eq. (3).

Algorithm 1 RatioCut Solution to Eq. (3)

```
INPUT: Undirected graph $\mathcal{G}$ with the corresponding affinity matrix $W$, desired number of groups $k$.
OUTPUT: The optimal partition $A_1, A_2, \ldots, A_k$ as the solution to Eq. (3).
Calculate the diagonal degree matrix $D$ of $W$, $D_{ii} = sum_i W_{ij}$
Calculate the Laplacian matrix $L$ of $W$, $L = D - W$
Compute the eigen-decomposition of $L$, $L = V \Lambda V^T$
Pick the leading $k$ eigenvectors of $V$ and run $k$-means to obtain membership indicator and then partition all $n$ robots
Re-group the robots according to the obtained $A_1, A_2, \ldots, A_k$.
```

D. GROUP MERGING

In robot exploration, if some groups move close, then it is desired to merge those neighbor groups. The merged group then is able to have a wider receptive field than individuals and, in turn, to achieve a global optimization over the pathes. A simple demonstration of the group merging is shown in Fig. 3.

As mentioned above, an oversized group is a heavy burden to leader robots equipped with limited computation and communication resources. Thus, it is necessary to estimate and prevent, if needed, the size as well as the communication delays of the merged group. In this paper, we adopt a two-step scheme, proposal and approval/disapproval model, to determine the merging of multiple groups.

In each iteration, if two or more previously disjoint groups moved close enough and connected, then a group merging candidate occurs. In other words, at time t1, two (or more) disjoint graphs $\mathcal{G}_1$ and $\mathcal{G}_2$ are connected and we want to determine to maintain two disjoint graphs or to merge both into one. Once a new connection is detected by a leader to a non-follower agent, the leader then extract the weighted graph $\mathcal{G}_2$ of the new agent group, and construct the merged graph $\mathcal{G} = \mathcal{G}_1 \cup \mathcal{G}_2$ with $n = n_1 + n_2$ nodes. We take this graph $\mathcal{G}$ as a proposal.

To approve or deny such proposal, we employ two criteria: a) communication delay of the merged group and b) the overall volume of the group. The proposal is approved only if both criteria are satisfied. In our works, we first check validity of the merged group volume, $n = n_1 + n_2$ that if $n \leq N$, where N is the maximum group volume, and deny this proposal if $n > N$. In case a small merged group, we then run the Dijkstra shortest path algorithm to obtain the shortest path cost c_i for each node in $\mathcal{G}$ and compare with the communication delay threshold ϵ. The merging proposal $\mathcal{G} = \mathcal{G}_1 \cup \mathcal{G}_2$ is approved if and only if both $n \leq N$ and $c_i \leq \epsilon, i = 1, 2, \ldots, n$ are satisfied.

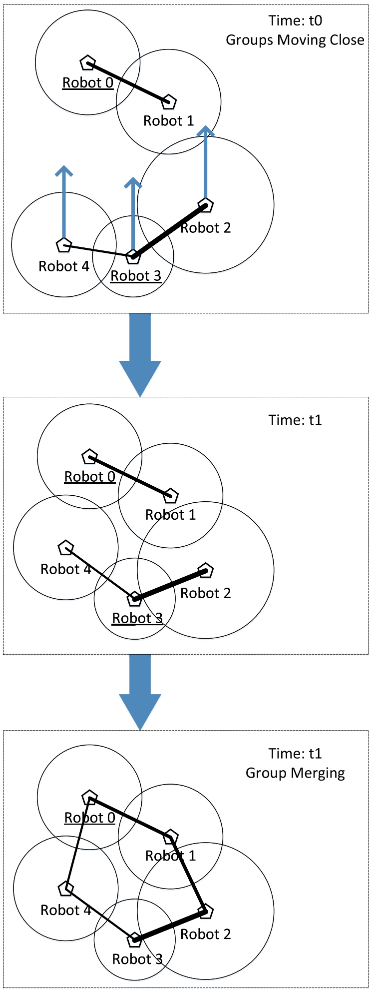

FIGURE 3. A demonstration of group merging. At time t0, there are two disjoint groups, with leader 0 and 3 respectively. Group of leader 3 moves towards the other group at t0 and finally several agents fall into the communication range of leader 0. Then the two groups can be merged into one large group since the highest communication delay of followers is limited in this case.

To improve the efficiency of swarm exploration, we run the merging process in a high frequency and the partition in a low frequency, in particular, 20 iterations vs 1 iteration in our application. Combine both partition and merging of groups, we summarize our Dynamic re-grouping method in Alg. 2.

IV. EXPERIMENTS

In this section, simulations are conducted to demonstrate the effectiveness of the proposed dynamic re-grouping method

Algorithm 2 Adaptively Re-Grouping Method

INPUT: Communication delay values e_{ij}, intra-group topology links T, desired number of groups k, the communication delay threshold ϵ, maximum group size threshold N.

OUTPUT: Re-grouped subsets $A_1, A_2, \ldots, A_k$.

```
for each time stamp t do
    for each group do
        Construct the undirected graph $\mathcal{G}$ with $n$ nodes and edges $e_{ij}$ of one group
        for each node in $\mathcal{G}$ do
            Run Dijkstra shortest path algorithm to obtain the shortest path cost $c_t$ of the $t$-th node
        end for
        if Any $c_t > \epsilon$ then
            Run Alg. 1 for re-grouping
        end if
    end for
    for $\forall t \in \{t | t \mod 20 = 0\}$ do
        if Group $p$ and group $q$ are connected then
            Build the proposal graph $\mathcal{G} = \mathcal{G}_p \cup \mathcal{G}_q, n = n_p + n_q$
            Run Dijkstra shortest path algorithm to obtain the shortest path cost $c_t, t = 1, 2, \ldots, n$ for all $n$ nodes in $\mathcal{G}$
            if $\forall t, c_t \leq \epsilon$ AND $n \leq N$ then
                Replace $\mathcal{G}_p$ with $\mathcal{G}$; delete $\mathcal{G}_q$
            end if
        end if
    end for
end for
```

for swarm robots exploration. The test results are aimed for evaluating the performance of exploration, in terms of efficiency and coverage, with/without re-grouping. We limited our simulation in an indoor environment although for outdoor environment our method is also valid. In all tests, we assume that each robot has the necessary sensing, communication, calculation and control capacity.

A. EXPLORATION UNDER LIMITED COMMUNICATION

In the first simulation, we build a series of 5 target areas for exploration and randomly place 7 robots inside one area. Fig 4 shows the shape of all the 5 areas. The first two subfigures in Fig 4 displays two areas in rectangle shape with/without wall obstacles. Subfigures on the second row of Fig 4 show the non-rectangle shape with walls. The last area in Fig 4 contains several convex obstacles, which may be caused by house furniture.

We compare our method with the greedy searching method of fixed group assignment in this test. The time-coverage curves are shown in Fig. 5.

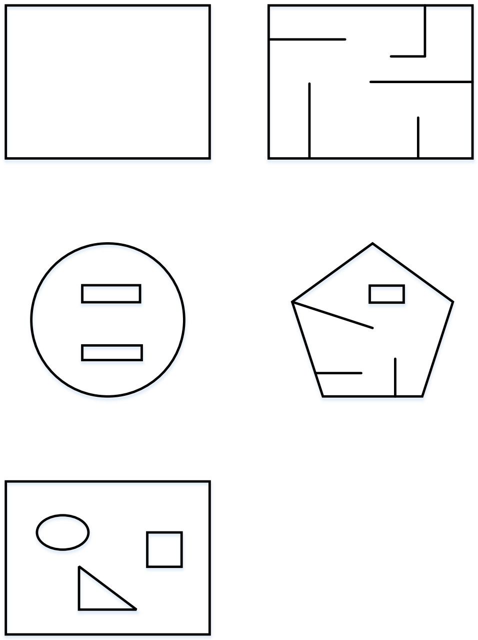

FIGURE 4. A demonstration of 5 target areas used for exploration.

From Fig. 5 we can see that, the proposed method is more efficient than the competing method in all five test areas. At the beginning of exploration, the visited areas of both methods grow linearly since most of the area-in-sight of each agent is new to the map. Challenge occurs when most areas are known but only several, if not some, losing pieces of the map are unexplored. The fixed group exploration method, however, intends to be inefficient in this case and the area coverage curve then becomes flat, indicating more time consumption is needed for a full-map exploration. In contrast, our method shows its efficiency in all 5 tests and completes the exploration early than its counterpart.

B. EFFECTS OF COMMUNICATION DELAY

Communication delay is an important parameter in our method. In this test, we analyze the effect of communication delay to our exploration task. We use all 5 maps in Fig. 4 for exploration. We manually add a random delay, uniformly drawing form $[0, \tau]$ second, to all communication links and test the performance of our method. Since our goal is to build a full-scale map of the environment, in this test we take the full-map time, the time cost to explore 99% of the area, as the evaluate metric. We set $\tau = 0.5, 1, 2, 4$ in our experiment and show the full-map time costs in Tab. 1.

From Tab. 1 we can see that, our proposed method is robust to communication delay that only a limited additional cost on full-map time consumption is required. The fixed group method needs more much more time to explore the entire area, especially in the case of a high communication delay.

C. EFFECTS OF GROUP SIZE

Group size is also a critical parameter in swarm robot exploration. In this test, we valid our method with different number

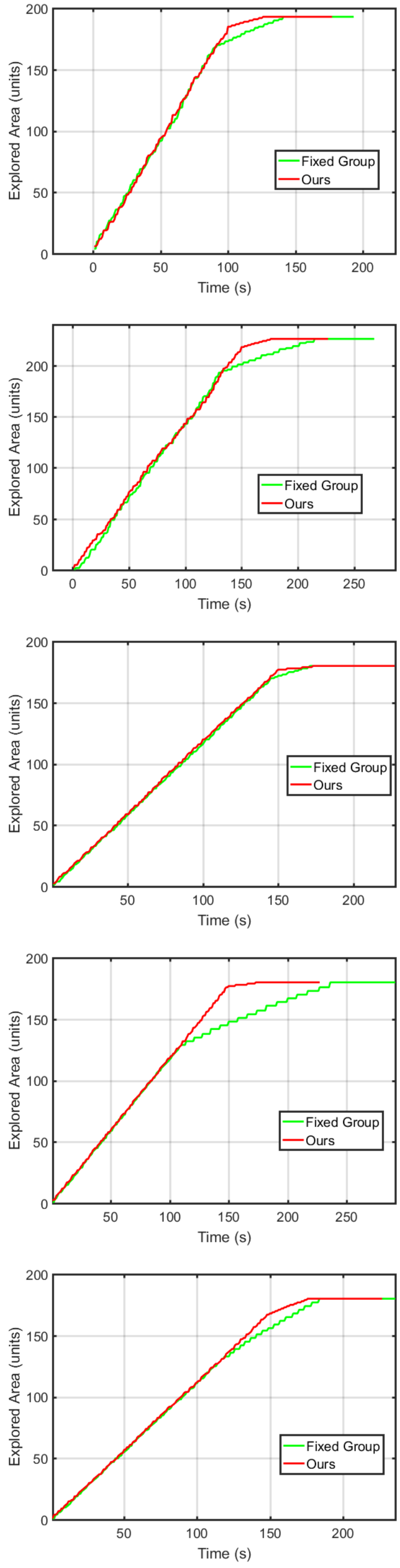

FIGURE 5. Comparison on exploration tasks.

of robots in the field. We set 1, 2, . . . , 12 robots in the target area and record the time cost when the robot(s) reveal(s) 99% of the area. Experimental results of the first target area in Fig. 4 are shown in Fig. 6

TABLE 1. Full-map time cost under different communication delay.

		$\tau = 0.5$	$\tau = 1$	$\tau = 2$	$\tau = 4$
Map 1	Fixed group	148	161	189	202
	Ours	130	144	156	178
Map 2	Fixed group	220	229	243	286
	Ours	182	193	204	219
Map 3	Fixed group	176	188	206	221
	Ours	171	183	198	209
Map 4	Fixed group	245	266	284	302
	Ours	173	191	207	226
Map 5	Fixed group	192	199	213	228
	Ours	181	197	209	223

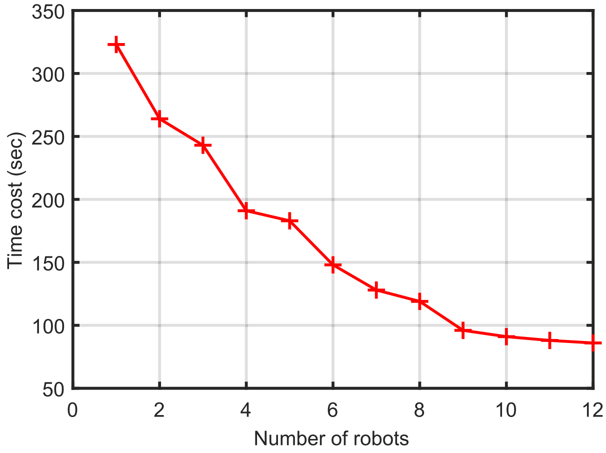

FIGURE 6. Comparison on different number of robots.

As shown in Fig. 6, the more robots in a swarm the less exploration time is needed. The benefits by using more robots, however, become lower when more robots are involved. For example, add one more robot as the second one, i.e., number of robots from 1 to 2, to construct a team will get 59 seconds in reward, or 18.2% less time cost than the solo robot exploration. If we add the twelfth robot to a swarm, the time cost is only reduced by 2 seconds, or 2.27%. Thus, it is a user-problem to find a balance between efficiency and expenditure.

V. CONCLUSION

In this paper, we propose to re-group a swarm of robots dynamically. We adopt a leader-follower structure in our works and take into account the communication condition, the delay in particular, and group size balance, in a purpose to limit the burden of each leader, to determine the partition and merging of groups. Our method is robust to target area shape and communication delay, a critical property in many exploration tasks. In addition, our proposed works are found scalable with the swarm volume. Experimental results show that our method outperforms the popular fixed group exploration method. Since the proposed model does not require additional hardware/sensors, our solution to improve the efficiency and reliability of a swarm in exploration is low cost and easy to be deployed. Our method is able to benefit many UAVs or UUVs exploration applications such as searching or rescuing.

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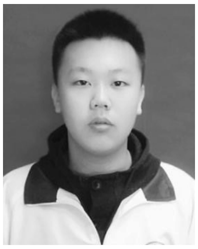

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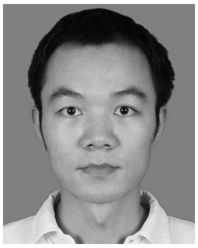

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