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Hierarchical and Distributed Patrol Strategy for Robotic Swarms with Continuous Connectivity

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Abstract: This paper proposes a hierarchical and distributed strategy for patrolling missions by robotic swarms, including a fixed base station. One of the essential requirements for autonomous robotic swarms is predictability from human operators. As a clue to satisfy this requirement in patrolling missions, the strategy employs hierarchized algorithms to maintain continuous connectivity to the base station by (i)global patrol and (ii)local patrol. Each robot selects the location to patrol by one of the two algorithms, according to the robot's role. The paper also introduces a performance metric for the base station's situational awareness, which may indicate the swarm behaviors' predictability. The simulation study tested the proposed strategy and compared it to an existing strategy. The proposed strategy demonstrated successful patrol behavior with continuous connectivity to the base station. Though the existing strategy performed better in some aspects, the proposed strategy effectively covered the whole mission area and provided the base station with higher situational awareness.

Keywords: Swarm Robotics, Patrolling, Multi-Robot System, Hierarchical Control, Situational Awareness

1. INTRODUCTION

This paper proposes a strategy for robotic swarm patrolling with continuous connectivity to a base station (BS). The algorithm is hierarchized into two algorithms: (i)global patrol by a group leader robot of the swarm and (ii)local patrol by other robots. Both algorithms are distributed, independent of the BS instructions and global knowledge.

Swarm robotics is a technology to operate multiple robots distributedly, including emergent behavior by local interactions between robots. It has several advantages, such as robustness, flexibility, and scalability [1]. Furthermore, operating multiple robots has an advantage in mission efficiency by distributing robots widely into the mission area and working simultaneously [2].

Patrolling areas such as disaster areas, border areas, and important facilities are the possible applications of this technology. A robotic swarm may be a low-cost and efficient solution, as well as relieving human burdens in patrol missions.

On the other hand, there are few real-world applications of robotic swarms, and most depend on centralized control with less or no distributed nature [3]. One of the concerns of real-world applications is the lack of predictability from human operators. Robotic swarm behaviors frequently emerge from local interactions between robots, which are invisible or complex to grasp by humans. This concern is a barrier to robotic swarms' real-world applications, especially in complicated or life-threatening situations [4].

Continuous connectivity between the swarm and the base station (BS) can relieve this concern. In this context, the BS corresponds to human operators or interfaces to humans' authority to make high-level decisions. Though the BS still cannot grasp all local interactions among robots, it can continuously supervise swarms at least so that it can observe or intervene in robots' decisions and behaviors. In these manners, monitoring mission progress and system status may lead to the predictability of the swarm systems' next action. Another possible advantage is that the BS or humans at the BS may enhance the system capability by providing support such as advanced environmental recognition and permission to engage in high-risk tasks [5]. Furthermore, communication among robots is an essential assumption for robotic swarm operations. The connectivity may not be a significant extra constraint in this aspect.

From these viewpoints above, this paper proposes a strategy to maintain connectivity to the BS during patrol missions by robotic swarms. Our contributions are:

- Developed a distributed and hierarchical patrol algorithm with continuous connectivity.
- Introduced a quantitative performance metric to measure situational awareness (SA) by the BS.

The following sections describe the related works (section 2), the proposed strategy (section 3), the simulation results (section 4), and the conclusions (section 5).

2. RELATED WORKS

Huang et al. reviewed studies on patrolling [6], and Amigoni et al. reviewed exploration with communication constraints [7] by robotic swarms. The existing studies on patrolling frequently assume the availability of communications, while they have not regarded connectivity as a purpose or constraint. The studies on exploration sometimes consider the BS, but still, they have not considered the SA of the BS. Among these studies, Yanmaz-Adam et al. proposed two methods with different priorities for target detection by drones: coverage-based and connectivity-based [8]. The study compared two methods regarding the possibility of target detection and the notification speed of the detection to the ground station. However, notification speed is only valid at the moment of target detection and is insufficient to show the degree of SA on detailed mission progress. Our previous study also studied patrolling by robotic swarms with continuous connectivity to the BS [9], while it employed a kind of random walk as a patrol strategy. Also, it assumed the SA of the BS as given and evaluated the overall system's performance under the supervision of the BS.

† Kazuho KOBAYASHI is the presenter of this paper.

With these backgrounds, this paper proposes an algorithm for robotic swarm patrolling with continuous connectivity. The paper also introduces a metric that quantitively indicates the degree of BS's SA. The following section describes the detailed method.

3. METHODOLOGIES

3.1 Problem definition

This section defines the problems and systems in the scope of this paper. The paper assumes robotic swarms patrolling a two-dimensional grid map. Each grid corresponds to the point of interest that should be patrolled.

3.1.1 Mission field and basic performance metrics

The map is defined as $G \coloneqq \{g^k \mid k = 1,2,\dots,K\}$, which g^k corresponds to each grid. The superscript is an identifier for grids by location or other elements, and K is the total number of grids.

As a performance indicator for patrolling, this paper introduces the metric *idleness* [10]: i^k for each g^k. The idleness is the elapsed time since the grid g^k has last been patrolled. When the grid has been patrolled by a robot at time: t^k and no other robots has patrolled since t^k, then the idleness of the grid at the current time: t can be shown by: $i^k(t) = t - t^k$. One of the purposes of the patrol mission is to reduce idleness, or in other words, arriving at each grid as frequently as possible. This paper employs graph idleness I_G in Eq.(1) and worst idleness as performance metrics in terms of idleness. Eq.(1) shows that graph idleness is the average of the idleness over all grids and mission duration.

$$I_G = \frac{1}{T \cdot K} \sum_t^T \sum_k^K i^k(t) \qquad (1)$$

The worst idleness is the largest idleness over whole grids and mission duration. The larger worst idleness means that a certain grid is not patrolled for a long time compared to other grids.

3.1.2 Robotic swarm

The assumed mission operates a robotic swarm: $R \coloneqq \{r_n \mid n = 1,2,\dots N\}$, which r_n indicates each robot. The superscript identifies each robot by its ID or other identifiers, and N corresponds to the total number of robots. This research assumes that robots have capabilities of self-localization and communication.

Each robot r_n holds an assumption for the map status: $G_n(t) \coloneqq \{(i_n^k,\ t_n^k) \mid k = 1,2,\dots K\}$ according to the mission progress. i_n^k and t_n^k corresponds to the assumed idleness of the grid g^k and update time of the item, respectively. Since the idleness is NOT observable by sensors, each robot refreshes its assumption: G_n according to its arrival to the grids. Each robot also refreshes its assumption by other robots' mission achievements through inter-robot communications. Section 3.3.1 describes the details of these refresh procedures.

3.2 Connectivity maintenance by role switching

Each robot acts as one of the four roles: base station, repeater, group leader, and explorer. The base station (BS) is a special role: it corresponds to the operator or is an interface to the operator, fixed at the point where the mission starts. Repeaters maintain the network between the BS and the group leader. The group leader makes local decisions, representing subgroups of the swarm consisting of explorers. Explorers are swarm members as actors for tasks. For simplicity, this study assumes that the tasks are limited to arriving at each grid to be patrolled. Fig. 1 shows the typical form of the swarm in this research.

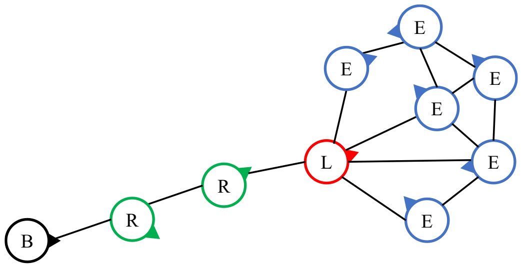


Fig. 1 A typical form of a swarm. The circles, triangles, and lines show the robots, their orientation, and communication connections, respectively (B: BS, R: Repeater, L: Group leader, E: Explorer). The figure is cited from [11] and modified by the authors.

The swarm maintains continuous connectivity through connectivity maintenance between the BS and the group leader, and connectivity maintenance among explorers and the group leader. The former method adopts the role-switching algorithm developed in [12]. The algorithm switches the role of robots between a repeater and a group leader to deploy/surplus repeaters according to the network status. The latter method keeps explorers near the group leader (described in section 3.3.2) and forms a network topology by the scheme also introduced by [12]. Explorers and the group leader form the network topology by this scheme, determining whether to connect other robots in the sensing range: d_s and whether to continue connection to already connected robots in the communication range: d_c.

3.3 Proposed patrol strategy

This section describes the proposed strategy. Since the idleness is not observable by external sensors, each robot r_n determines the location to patrol according to its assumed idleness in G_n.

3.3.1 Idleness assumptions and their refresh

Each robot r_n refreshes its assumption: G_n at every timestep through Algorithm 1, a similar procedure to the DTA-greedy method [13]. First, each robot increments its assumption on i_n^k over time since it is obvious that the ground truth: i^k grows overtime unless the grid g^k is patrolled by other robots (line 1-3). When the robot arrives at a certain grid, refresh the item on the grid in G_n by the achievement (line 4-6). Next, it sends the G_n to the other robots that are directly connected to share their achievements (line 7-10). $A_n(t)$ denotes the list of directly connected ro-

Algorithm 1: procedure to refresh the assumption G_n	
1	**for all** $i_n^k(t) \in G_n$
2	$\quad i_n^k(t) \leftarrow i_n^k(t-1)+1$
3	**end for**
4	**if** r_n have just arrived a grid g^j at time: t
5	$\quad \{i_n^j, t_n^j\} \leftarrow \{0, t\}$
6	**endif**
7	**if** $A_n(t) \neq \emptyset$
8	$\quad$ send $G_n(t)$ to all $r_m \in A_n(t)$
9	$\quad$ send current patrol target to all $r_m \in A_n(t)$
10	**endif**
11	**for all** G_m sent from $r_m \in A_n(t-1)$
12	$\quad$ **for all** $g^k \in G_n(t)$
13	$\quad\quad$ **if** $t_m^k > t_n^k$
14	$\quad\quad\quad \{i_n^k, t_n^k\} \leftarrow \{i_m^k, t_m^k\}$
15	$\quad\quad$ **endif**
16	$\quad$ **endfor**
17	**endfor**

bots to a robot r_n. Sharing its current patrol target in line 9 avoids duplicating the patrol target in Algorithm 2 in the following section. Finally, the robot refers to the update time of all items in the received assumptions and refreshes its assumptions if there are newer items. The assumption of each robot reflects the achievements of other robots and is forwarded to the other robots. Through this procedure, all robots can share their assumptions with each other.

3.3.2 Hierarchical patrol strategy

The proposed strategy is hierarchized by two layers of patrol algorithms: global and local patrolling. Each robot determines its patrol target by one of the algorithms according to its role. Under both strategies, each robot selects the new patrol target after arrival at the current target based on its assumption. Currently, the BS/repeaters do not participate in the patrolling.

The group leader: r_L, with global patrol algorithm, refers all items in G_L to select the next patrol target. In other words, r_L considers the whole mission area to find the target: g^k with the highest utility U_L^k in Eq. (2).

$$U_L^k = (i_L^k)^2 / \Delta t^k \tag{2}$$

Δt^k denotes the estimated time to travel to g^k. Unlike Eq.(3) in the later part of this section, the square of the estimated idleness in Eq.(2) boosts the utility of the grid, which is far, but with high idleness, to avoid leaving such grids for a long time.

Each explorer: r_E, on the other hand, runs the local patrolling algorithm. It stays close to the group leader to maintain connectivity while choosing its patrol target. Algorithm 2 shows the details of this process. $\boldsymbol{x}_E{}'$ denotes the position of the virtual robot: $r_E{}'$, closer to the group leader than the current position. In order to assume this virtual robot, r_E offsets its position: $\boldsymbol{x}_E$ by the group leader r_L's position: $\boldsymbol{x}_L$ and velocity input: $\boldsymbol{u}_L$ (line 1). α, β is a scaling factor to adjust the significance of the current

Algorithm 2: local patrol algorithm to select patrol target	
	when an explorer r_E have arrived at the current target
1	assume $r_E{}'$: $\boldsymbol{x}_E{}' = \boldsymbol{x}_E + \alpha(\boldsymbol{x}_L - \boldsymbol{x}_E) + \beta \boldsymbol{u}_L$
2	$G_E{}' := \{g^j \mid \lVert \boldsymbol{x}^j - \boldsymbol{x}_E{}' \rVert < \delta\}$
3	**for all** $g^j \in G_E{}'$
4	$\quad$ **if** g^j is a current target for robot: $r_m \in A_E$
5	$\quad\quad G_E{}' = G_E{}'$¥$g^j$
6	$\quad$ **endif**
7	**endfor**
8	$g_E^{next} = \mathrm{argmax}_{g^j \in G_E{}'} U_E^j$

and the future position of r_L to offset $\boldsymbol{x}_E$, set as 0.6 and 0.4, respectively, in the current settings. Next, r_E selects its next patrol target from grids within the distance: δ from $\boldsymbol{x}_E{}'$ so that it stays close to r_L and maintain connectivity (line 2, 8). The centroid of each grid g^j represents its location $\boldsymbol{x}^j$. The explorer excepts the grid targeted by the other robots from the target candidates to avoid duplicating the targets (line 3-7). Eq. (3) shows the utility of each grid: U_E^j.

$$U_E^j = i_E^j / \Delta t^j \tag{3}$$

Fig. 2 shows the schematic diagram of this hierarchical algorithm above. The group leader: r_L selects the next patrol target from the whole map (red dashed rectangle) by the global patrolling. Each explorer: r_E assumes its virtual position: $\boldsymbol{x}_E{}'$ and select the patrol target from the candidate grids within the distance: δ from $\boldsymbol{x}_E{}'$ (blue dashed circle) by the local patrolling.

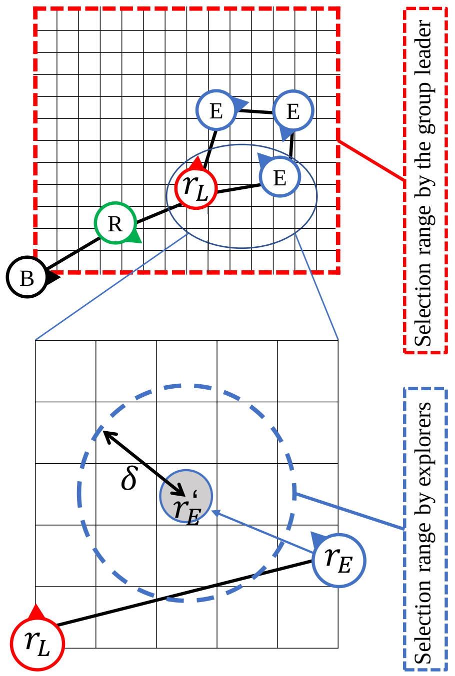


Fig. 2 Hierarchical algorithm for the next patrol target selection. The solid black lines indicate connections between the robots. The figure is cited from [11] and modified by the authors.

3.4 Metric for situational awareness (SA) of the BS

As a metric of SA on a grid g^k by the BS r_B, this research introduces the metric: Delay of SA denoted as D_{SA}^k. D_{SA}^k is the difference between the refresh time t_B^k of the assumption in $G_B(t)$ and current time t: $D_{SA}^k(t) = t - t_B^k$. D_{SA}^k denotes how long the BS has not updated its awareness on a grid g^k which leads to degrade SA. The BS acquires t_B^k by Algorithm 1, which is the same as the other robots. As a performance metric, the average of D_{SA}^k over all grids and mission in Eq.(4) is called the Mean SA Delay: D_{MSA}.

$$D_{MSA} = \frac{1}{T \cdot K} \sum_{t}^{T} \sum_{k}^{K} D_{SA}^k \qquad (4)$$

3.5 Compared strategy

Conscientious Reactive (CR) [10] as a traditional and high-performance strategy is also introduced to compare to the proposed strategy. All robots other than the BS acts as an explorer. Each robot r_n selects a grid with the highest assumed idleness in G_n, from the adjacent grids to the grid where it is currently located without any consciousness of the connectivity. Since traditional CR does not consider the BS, this paper added the scheme to share the assumptions between each robot and the BS when connected. Each robot connects to the BS when the distance between them is smaller than d_s, and disconnects when the distance is larger than d_c. The assumption-sharing scheme is identical to Algorithm 1.

4. SIMULATIONS

Simulated patrol missions evaluated the proposed strategy and compared it to the existing strategy.

4.1 Configurations

A swarm R with $N = 10, 15, 20$ patrols a grid map G with a total size of 600 * 600 [m] and a grid size of 30 * 30 [m] (i.e., $K = 400$) for $T = 20000$ [timestep], ten trials per condition. The simulator locates the origin to the left bottom of the map and a robot r_1 as the BS to the origin. The other robots: $r_2 \sim r_N$ are randomly distributed in the fan-shaped area: $\|x_n\| \leq 2\sqrt{N}$. The robot closest to the origin acts as an initial group leader, and the others act as explorers.

The swarm starts patrolling under the algorithms in section 3.3. The explorers select their target grids in the range of $\delta = 20\sqrt{N}$ [m]. The range includes two grids each in the upper, lower, left, and right directions, one grid in the diagonal directions when $N = 10$, for instance. Patrolling of a grid completes when a robot moves in 3 [m] or closer to the centroid of the grid. The robot subsequently selects the next patrol target grid. Other schemes: repeaters deployment, robot motions, propagation of $\boldsymbol{x}_L$ and $\boldsymbol{u}_L$ among the robots, network formation, and disconnection recovery follow the methods in [12]. The other parameters are set as follows: $d_s = 90$ [m], $d_c = 150$ [m], the maximum linear and angular velocity of robots $\boldsymbol{v} = (1.5[m/timestep], 1.0[rad/timestep])$.

For each metric, the simulations logged normalized values in Eq.(5) [10] as well as the absolute values of the metrics.

$$value_{normalizeed} = value_{absolute} * N / K \qquad (5)$$

The normalized values include the quality of coordination among the robots. The higher normalized values indicate the poor quality of coordination among robots, or in other words, less scalability with less performance improvement despite more robots or smaller mission areas. When the robots coordinate ideally, the normalized value keeps constant to the size of swarms and areas.

As for absolute metrics, the simulations except the data in the transition phase. At the beginning of missions, the idlenesses of all grids and all robots' assumed idleness are initialized as zero. Thus, the metrics tend to be low during the early phase of the missions. In order to offset this transitory phase, the results show metrics in the stable phase, $10001 \leq t \leq 20000$, determined through the preliminary simulations.

4.2 Results

The proposed strategy successfully conducted the simulated patrol. Fig. 3 shows the typical mission progress by a swarm with ten robots. In this figure, the darker the color of grids, the higher idleness, indicating that such grids have not been monitored for a long time.

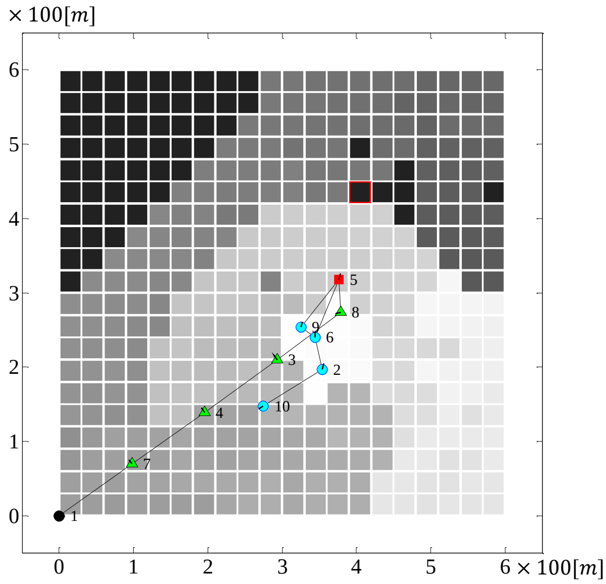
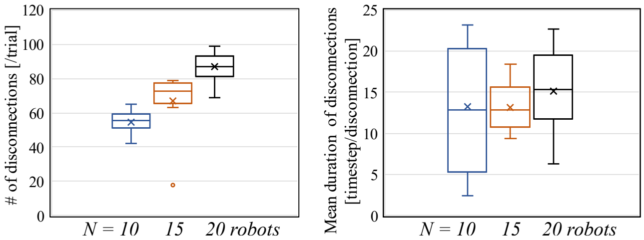


Fig. 3 A screenshot of mission progress by a swarm with *N=10*

The swarm successfully patrolled the grid map with continuous connectivity. The repeaters shown in green triangles maintained the communication connection between the group leader r_5 shown in red rectangle and the BS r_1 shown in the black circle. The group leader r_5 selected the grid with high assumed idleness and close in the distance, shown with a red edge in the figure, located at $(405, 435)$ in this case. In Fig. 3, the robots shown in cyan circles are explorers with local patrolling around r_5.

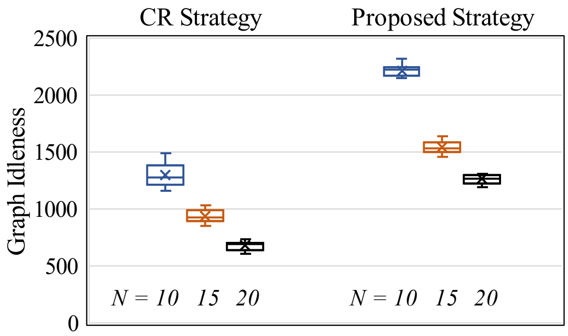
Fig. 4 shows the performance of the proposed strategy in



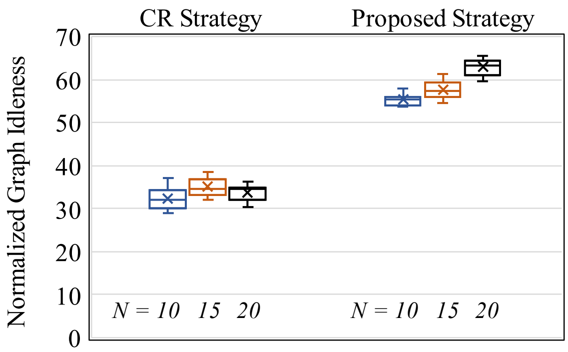
(a) The number of disconnections per trial (b) Mean duration of disconnections per trial

Fig. 4 Communication link disconnections during the patrolling missions by the proposed strategy

terms of connectivity. In this context, connectivity is regarded as *maintained* when an undirected graph composed of the network is connected. Figs. 4(a) and (b) show the frequency and the mean duration of disconnections per trial, respectively. While Fig. 4(a) shows there were disconnections, the strategy recovered the disconnections in a few dozen seconds at most, maintaining connectivity throughout the missions (Fig. 4(b)). The frequency of disconnections tended to increase as the swarm size N increased. This trend may due to the lower density of explorer robots since the search range δ in the local patrolling increases with the swarm size.



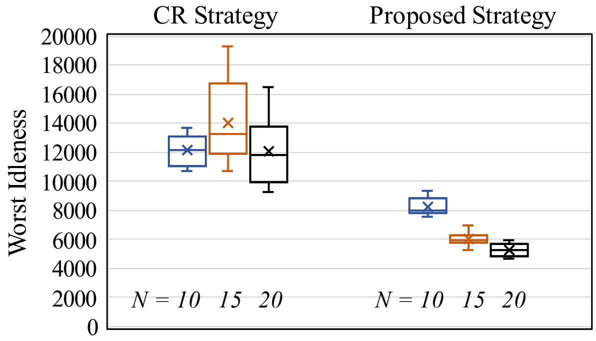
(a) Graph idleness with different swarm size



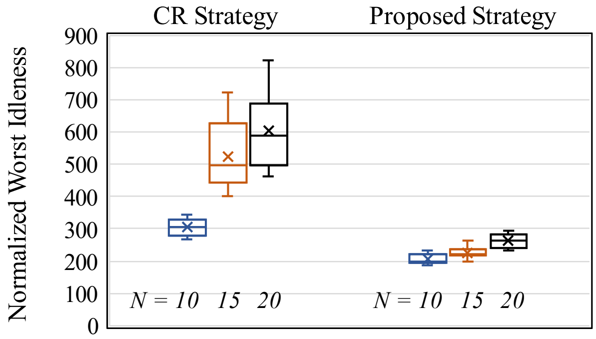
(b) Normalized graph idleness with different swarm size

Fig. 5 Patrol performance in terms of Graph idleness

Fig. 5 and Fig. 6 show the patrol performance in terms of idleness, in which a lower value indicates higher performance. Fig. 5(a) indicates that graph idleness I_G decreases as the swarm size increases, and the CR strategy



(a) Worst idleness with different swarm size



(b) Normalized worst idleness with different swarm size

Fig. 6 Patrol performance in terms of Worst idleness

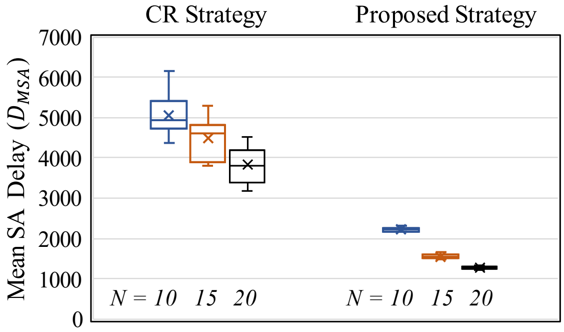
performed better than the proposed strategy. Accordingly, the normalized graph idleness also shows the same trend in Fig. 5(b). Fig. 6(a) shows the worst idleness, in which the proposed strategy performed better than CR. In Fig. 6(b), the normalized worst idleness by CR increases as the swarm size increase, while the value by the proposed strategy remains approximately constant.

Finally, Fig. 7 shows the mission performance in terms of the SA of the BS. While the metric decreased as the swarm size increased, the proposed algorithm performed better than the CR (Fig. 7 (a)). This trend is more significant in the normalized metric (Fig. 7 (b)). The proposed algorithm maintained the normalized Mean SA Delay constant, though the metric increased by CR.

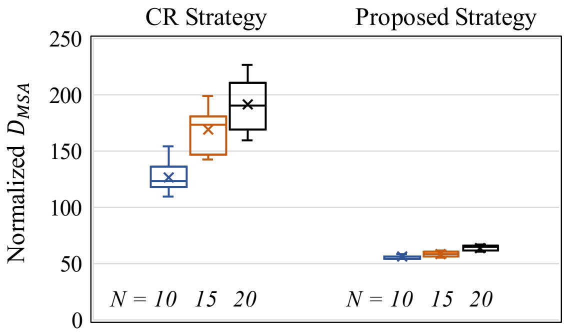
4.3 Discussion

The proposed strategy successfully conducted the simulated patrol mission with continuous connectivity to the fixed BS. All parts of the strategy were distributed; the robots locally managed their communication connections and determined the location to patrol without directions from the BS. Though there were moments when the communication links were disconnected, all disconnections were intermittent and recovered in a few dozen seconds at most (Fig. 4). It depends on the mission whether these temporary disconnections are acceptable. However, many types of missions may accept the disconnections since the proposed strategy works with the remaining robots other than disconnected robots. The swarm can also wait for the connection recoveries if it detects disconnections.

As Fig. 5 shows, the proposed strategy showed inferior performance in graph idleness compared to CR with up to t-



(a) Mean SA Delay with different swarm size



(b) Normalized Mean SA Delay with different swarm size

Fig. 7 Degree of the SA (D_{MSA} and its normalized value) by the BS

wice the metric value. On the other hand, it performed better in terms of worst idleness (Fig. 6), patrolling the area widely without leaving some grids not been patrolled for a long time. Because the robots under CR select the patrol target only from the adjacent grids, they fall into the local optima and leave some grids with high idleness for a long time. Furthermore, the proposed strategy also performed better in terms of SA of the BS, indicated by the Mean SA Delay in Fig. 7. The BS updated its assumption on the field status faster and also with a scalably to the swarm size.

It is worth noting that the performance in graph idleness and Mean SA Delay may also be positively correlated, though the simulations showed the trade-off relation. For instance, when all robots patrol only nearby grids around the BS, they can communicate with the BS frequently to update the BS's assumption. However, since the robots do not patrol grids far from the BS, they would not update the assumption on those grids, leading to the higher Mean SA Delay. Future studies will improve the proposed algorithm in both idleness and SA.

5. CONCLUSIONS

This paper proposed a hierarchical and distributed strategy for patrolling by robotic swarms. The robotic swarms under the proposed strategy patrol and maintain connectivity through hierarchized algorithms and role-switching. The strategy was evaluated in terms of the degree of SA: Mean SA Delay, which is newly introduced in this paper, as well as a traditional patrol performance metric: idleness. Simulation studies demonstrated that the proposed strategy improves the BS's SA without local optima.

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