Swarm Based Coverage Using Multiple Informed Leaders
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Abstract:
Robotic exploration typically involves navigation through unknown terrains. In this paper, collaborative strategy for coverage is presented, in which the concept of informed agents as a leader in a swarm has been introduced for autonomous coverage. The small population of robots in large swarm act as informed leaders and help others to accomplish their tasks related to the exploration. These informed leaders receive information about the environment from external sources (e.g. humans, media etc.), and influence uninformed robots using their swarm behaviors. Multiple Swarm behaviors have been designed for swarm navigation, and dynamic selection of the informed leaders. This approach has been tested in simulation of homogeneous swarm, with and without informed leaders. The number of informed agents needed to guide the swarm effectively has been investigated as well. Experimental results showed that the introduction of informed agents improves the coverage task.

Keywords: Swarm Intelligence; Swarm robotics; Multi robotic exploration; leader selection.

1. Introduction
Autonomous robotic exploration and coverage has been a hot research topic in which a robot visits the environment, build the map, and localize itself within the map simultaneously. If an environment is dangerous, remote, or expensive for human access, a mobile robot may help to build a map of its surroundings and navigate based on the map [1]. Furthermore, robots are resource-constrained specially in multi-robotic environments (where robots collectively perform a task) in which coverage is one of the key issues to be addressed effectively. Coverage problem has applications in exploration, navigation, search and rescue operations, particularly at city scale. In a multi-robotic environment, coverage becomes an issue due to limited capabilities of the robots, in terms of memory and computation. Either this can be achieved in a completely distributed fashion, where robots can only sense each other and do not communicate [2] or it can be achieved where robots can sense as well as communicate with each other. The behavior based coverage and exploration using multi-robots presented in [2] has been extended for the swarm. We have focused on leader based swarm coverage. Dynamic Leader selection is one of the challenges that have been addressed in this research. In this regard, social science based leader selection mechanisms have been considered as a starting point [3]-[4]. We have refined the model presented in [4], so that it works for large scale coverage. In addition to mobility issues, such as target selection, obstacle and collision avoidance, and density-based speed, we have also focused on natural group-based mobility paradigm; the swarm robotics [5]. The informed leaders are guiding other robots in the swarm to maximize the coverage rate. We have examined the usability of swarm base mobility as compared to the individual decision making using GIS map based simulations.

2. Related Work
Rekleitis et.al [18] proposed an exploration algorithm, in which one robot explores environment, while two stationary robots observe it, making a triangle shaped group [6].

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The main disadvantage of this technique is a centralized control. In a later work, the same authors presented a technique in which a couple of robots track the environment to search each other, for better mutual localization [7]. Arkin et al. suggested a behavior-based exploration [8], where the “wander” behavior acts as communication actor, and “informed exploration” behavior helps to use map to explore the given arena. Powers et al. [9] suggested a motor-schemas behavior-based approach, where all robots agree on a direction, then they move toward that direction, they make decisions in a distributed way, but stay connected every time. Nguyen et al. [11] developed an actual real-world system using leader-follower approach. A similar leader-follower model has been designed by Howard and his team members [12] in which eighty robots were used to explore the building, and transmit all the acquired information to the remote operator. Yamauchi presented a revolutionary work in 1998 in which new exploration strategy using the concept of the “frontiers” [13] was introduced. In this technique, frontiers are the borders between visited area and unvisited area. In addition of Yamauchi’s frontier-based exploration, Simmons et al. proposed a technique in which robots used ‘bids’ based on estimates of the travelling cost to major locations, and information gain [14]. These bids were submitted to chief agent, which assesses and allocates tasks based on maximum utilization. Stachniss et al. used place labels to define structures of the environment that can be used instead of frontiers based approach [15]. Wurm et al.’s [16] work classifies unvisited area into segments, which are computed by Voronoi graph. Koenig et al. studied ant patterns and developed ant-like robot to explore [17]. Our approach is also inspired from nature and is using behavior-based approach. The swarm is steered toward the unexplored parts of the environment using multiple leaders.

3. Behavoir Based Swarm Design

3.1. Environment

To simulate this problem, a portion of Vienna city map is used, which contains parks, roads, streets, narrow streets. The shape files of this GIS maps are imported into NetLogo, and this map is segmented into the small grids called cells. Furthermore, walkable, and non-walk-able cells were defined. Fig. 1 shows the screenshot of the whole environment.

For ease and visibility, walkable portion is shown in yellow, buildings in brown and robots in red color. In this environment, obstacles can be placed at any part of the map, beside predefined buildings and other obstacles.

3.2. Behaviors

In this approach, it is assumed that robots have limited processing and memory. Therefore, behavioral-based architecture is used for collective mobility and control of the swarm. Many behaviors have been designed including obstacle avoidance, avoid visiting past locations, locating open area, leader selection, etc.

![Fig. 1. GIS based environment for Robotics Coverage Simulation.](image)

3.2.1. Obstacle Avoidance

It is the basic behavior in which robot detects the obstacle using local sensing capabilities and avoids these obstacles. This behavior is fused with other behaviors and it
avoids obstacles in such a manner that it could get largest free space to navigate.

3.2.2. Avoid Visited Locations
This behavior helps robots to navigate toward the newest locations. For this behavior, relatively long-range sensors are used as compared to the obstacle avoidance behavior. It keeps the track of previously visited locations. We have used efficient data structure to store and retrieve the information about the visited locations. Whenever robot coordinates are changed, it checks if cells ahead is already visited. If any of the cell up to predefined length is already visited, then it will rotate 45 degrees and check again for the patches ahead. It keeps on doing the same for all 8 possible angles until it returns to the same position. If all are visited, it moves to the patch ahead.

3.2.3. Locate Open Space
This behavior locates a wide area in which robot can search for targets, this may be an open room or hall. In our case, we have used this to locate open streets, roads, and open grounds like parks. It is a very useful behavior since it saves time going to closed type rooms and round shaped areas. In multi-robotic autonomous exploration, usually robots stuck in the corners and wasting time over there. This behavior also addresses this issue by gathering information of the largest fee space around the robot’s current location. Whenever this behavior is triggered then robots stops its movement and starts searching open space around itself.

3.2.4. Leader Selection
This is most important behavior regarding our contribution in this work. We have tested many leader selection algorithms to find which best fits in our case for search and rescue of large open space area. We studied motion and movement of ants and birds and their swarm principles then we suggested our strategy which is more near to the nature. Moreover, our strategy for leader selection (informed agent) is dynamic i.e. leader changes with the passage of time based on the shape of swarm. As the direction of swarm changes then leader is changed if it is necessary. Leader selection algorithm runs after every 30 ticks and elects for new leader if necessary. When leaders receive goals then they start moving toward their goal. Other agents observe the leader nearby them which helps swarm to move toward the goal. The algorithm of the leader selection is shown in Algorithm 1.

3.3. Inter-Agents Communication
In our approach, robots communicate the speed, previously visited locations, and other information with agents in their neighborhood. In this implementation, we are using Stigmergy, which is indirect communication mechanism. This technique is inspired from ant communication. Though in future, direct and explicit communication techniques can be used once this algorithm is extended to the real robots.

Algorithm 1. Leader Selection.

Procedure SETUP
if ticks > maximumTicks then
  set percent = 10;
  set ticks = 0;
  set isLeader = false;
  set neighbor_agents = φ;
  broadcast message “No leader”;
  SELECTLEADER(percent);
end if
end procedure

Procedure SELECTLEADER (int PERCENT)
  set neighbor_agents = ask all agents to broadcast their IDs, and no of other agents in radius of their vision;
  sort neighbor_agents;
  max_leaders = (total_agents * percent)/100;
  ask neighbor_agents[max_leaders] top entries to set isLeader = true;
  ask leaders to broadcast message “I am leader”;
  broadcast message “Follow new leaders”;
  set ticks=ticks + 1;
end procedure
3.4. Informed Agent and Swarm Control

Informed agents receive information about the unexplored region which is considered as the goal. All the leaders receive the goal information simultaneously, so that the swarm could be steered toward the goal. In real-world situation, the goal information about unexplored and important regions can be received from other sources, e.g., human operator, media, other robots like aerial robots. Besides the goal information, global heading and speed is computed for leaders. Other robots move based on the local control laws of the swarm. These local control laws include align, attract, and repel. These control laws are fused with other behaviors described earlier, including obstacle avoidance, avoid visited locations etc. Alignment and speed of the normal robots (robots other than leader) is the average of the other robots in the neighborhood, but if there is a leader in the neighborhood, the heading and speed of the leader is given higher weightage, which helps the robot to be aligned with the leader. This is how leaders influence the alignment and speed of the swarm. Robots avoid collisions and cohesion in swarm using repulsion and attraction behaviors. Attraction, repulsion, and alignment are fused with other behaviors, and normalized to compute the motion of the swarm. Leader in the swarm is selected dynamically based on leader selection algorithm.

3.5. Coverage Calculation

In this work our focus is to explore the whole area, we have used the formula derived for coverage as described by Schwager et.al. [19]. The coverage is the percentage of area explored by all the robots in a swarm. In our case, total walkable patches are counted, and the total patches visited by the swarm. So, we can easily estimate coverage in percentage using the equation defined below.

\[
Coverage = \frac{AreaCovered}{TotalTargetArea}
\]
3 Randomly distrusted strategy were used, while in experiment 4-7 group distributed strategy is used. Detailed information about these experiments can be seen in table 1. Each experiment is conducted 3 times.

**TABLE 1.** Experiments details.

| Strategy         | Experiment | Agents | Leader % |
|------------------|------------|--------|----------|
| Randomly Distributed | 1          | 100    | 0        |
|                  | 2          | 100    | 10       |
|                  | 3          | 100    | 10       |
| Group Distributed | 4          | 100    | 0        |
|                  | 5          | 100    | 10       |
|                  | 6          | 100    | 10       |
|                  | 7          | 100    | 20       |

**4.2. Experiment 1**

First experiment was conducted with total of 100 agents which were randomly distributed over the whole environment. Agents can re-visit the visited places. Table 2 shows average and Standard deviation of three combined runs. Figure 2 shows graph of exploration w.r.t time (in minutes).

**TABLE 2.** Average and SD for Experiment 1.

| Run | Average | Standard Deviation |
|-----|---------|--------------------|
| 3   | 565 min | 47.08 mins         |

Almost all the runs took around 10 hours. We can see a lot of flat zones (in Figure 2), because the exploration was conducted without any informed agents and also by avoid visited location behavior. This let the agents to visit the already visited locations. We simply call this a redundancy.

**4.3. Experiment 2**

Experiment 2 was conducted with the same configuration as for the previous experiment except now we have 10% informed agents. Average and Standard deviation of combined three runs can be seen in table 3. Figure 3 shows graph of three runs w.r.t time (in minutes).

**TABLE 2.** Average and SD for Experiment 2.

| Run | Average  | Standard Deviation |
|-----|----------|--------------------|
| 3   | 205.3 min| 25.23 min          |

In figure 3 we can see that our flat zones were reduced. This is because we used 10% of informed agents but still we are lacking avoid visited location behavior that still costs us redundancy. Informed agents know some places of the environment that are still unvisited so they take the group to those places which leads us a quality exploration in corresponding against previous experiment. It is clear that by introducing informed agents total time taken to explore the whole environment drops to almost a half.

**4.4. Experiment 3**

Third experiment was conducted with 10% informed agents and with avoid visited locations behavior. Average and Standard deviation is listed under table 4. Figure 4 shows graph of exploration w.r.t time.
TABLE 3. Average and SD for Experiment 3.

| Run | Average   | Standard Deviation |
|-----|-----------|--------------------|
| 3   | 205.3 min | 25.23 min          |

Fig. 3. Three Combined runs of Experiment 2.

By locking at average of this experiment we do not see any major progress by introducing informed agents but still we improve our standard deviation. Also, this strategy was randomly distributed so agents wasted most of the time in making swarm.

Avoid visited location saves us some time but still we need improvement in time. Figure 4 also shows that we have very low flat zones.

4.5. Experiment 4

Experiment 4 was conducted with group distributed strategy. In this experiment, we used single group with no informed agents. All the agent population was placed in a single group and were randomly assigned to some walkable portion. Table 5 shows average and standard deviation of all three runs. Figure 5 shows graph of exploration v/s time.

TABLE 4. Average and SD for Experiment 4.

| Runs | Average | Standard Deviation |
|------|---------|--------------------|
| 3    | 270 min | 12.5 min           |

Fig. 5. Three Combined runs of Experiment 4.

As the exploration started all the single group swarm stated to move in one direction but as the time passes it broke into several groups. As we are lacking informed agents and avoid visited location, behavior agents started to wander which led them to visit already visited location. By comparing it to previous experiment, total time taken to complete the exploration increased.
4.6. **Experiment 5**

Experiment 5 was the same as the experiment 4 but this time we used 10% leaders (informed agents) over the entire population. Average time and Standard deviation of combined three experiments can be seen in table 6. Figure 6 shows graph for all three runs of exploration v/s time.

**TABLE 6. Average and SD for Experiment 5.**

| Run | Average   | Standard Deviation |
|-----|-----------|--------------------|
| 3   | 132.3 min | 12.5 min           |

Fig. 6. Three Combined runs of Experiment 5.

It is clear to see in Table 6 that total average falls up to 50% if we compare it with experiment 4. By enabling informed agent behavior, the single group broke into several small groups. Informed agents took all the agents in their swarm to major location which led to a decent exploration.

4.7. **Experiment 6**

The only change made in current experiment was to enable avoid visited location behavior. Figure 7 shows graph of whole three exploration v/s time, and Table 7 shows average and Standard deviation of all three combined runs performed for this experiment.

**TABLE 7. Average and SD for experiment 6.**

| Run | Average | Standard Deviation |
|-----|---------|--------------------|
| 3   | 81.6 min| 2.0 min            |

4.8. **Experiment 7**

In this last experiment, we used 20% informed agent rather than 10%, in-order to see whether increasing informed agents will effect the overall performance or not. Rest of the configuration was the same as in the experiment 6. Table 8 shows average and standard deviation of all the three runs which were performed for above mentioned experiments.

Fig. 7. Three Combined runs of Experiment 6.
TABLE 5. Average and SD for Experiment 7.

| Run | Average  | Standard Deviation |
|-----|----------|--------------------|
| 3   | 100.6 min| 5.05 min           |

Fig. 8. Three Combined runs of Experiment 7.

In this last experiment, we used the same configuration as in the experiment 6. The only change was in the percentage of informed agents. In order to see influence of informed agent we used 20% instead of 10%. As discussed earlier, informed agent does not get whole map of the environment. They just get clues about major goals. As major goals are limited and not all informed agents got unique goals, a single goal was shared between more than one informed agent which led multiple groups(swarms) to a single location. Hence overall exploration effected.

5. Conclusion

In this paper, we have suggested a coverage technique for large scale environment. The basic implementation of this type is system is feasible in a disaster or search and rescue operation. As our results show that in large scale environment informed agents played key role in exploration of an unknown area. Also, it was a behavior based technique so agents decide which behavior to call in which type of situation.

REFERENCES

[1] S. Mac, et al. “From theory to practice: Distributed coverage control experiments with groups of robots,” Experimental Robotics. Springer, Berlin, Heidelberg, 2009.

[2] J. S. Cepeda, L. Chaimowicz, R. Soto, J. L. Gordillo, E. A. Alanís Reyes, and L. C. Carrillo-Arce, “A behavior-based strategy for single and multi-robot autonomous exploration,” Sensors, vol. 12, pp. 12772-12797, 2012.

[3] S. Wu and Q. Sun, “Computer simulation of leadership, consensus decision making and collective behaviour in humans,” PloS one, vol. 9, 2014.

[4] J. R. Dyer, A. Johansson, D. Helbing, I. D. Couzin, and J. Krause, “Leadership, consensus decision making and collective behaviour in humans,” Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 364, pp. 781-789, 2009.

[5] J. Berg and C. H. Karud, Swarm intelligence in bio-inspiredrobotics. Master's thesis, Norwegian University of Science and Technology, Norway, 2011.

[6] I. M. Rekleitis, G. Dudek, and E. E. Milios, “Multi-robot exploration of an unknown environment, efficiently reducing the odometry error,” in International Joint Conference on Artificial Intelligence, 1997, pp. 1340-1345.

[7] I. A. D. G. A. M. E. Rekleitis, “Multi-robot collaboration for robust exploration,” Annals of Mathematics and Artificial Intelligence, vol. 31, no. Springer, pp. 7-40, 2001.

[8] R. C. Arkin and J. Diaz, “Line-of-sight constrained exploration for reactive multiagent robotic teams,” 7th
Ahmad Din (et al.), Swarm Based Coverage Using Multiple Informed Leaders (pp. 61 - 69)

International Workshop on Advanced Motion Control, 2002, pp. 455--461.

[9] T. A. A. R. C. Balch, “Communication in reactive multiagent robotic systems,” Autonomous Robots, vol. 1, no. Springer, pp. 27-52, 1994.

[10] M. Powers and T. Balch, “Value-based communication preservation for mobile robots,” In Distributed Autonomous Robotic Systems 6, Springer Japan, 2007, pp. 327-336.

[11] Nguyen, Hoa G., et al., Maintaining communications link for a robot operating in a hazardous environment. Space And Naval Warfare Systems Command San Diego CA, 2004.

[12] Howard, Andrew, Lynne E. Parker, and Gaurav S. Sukhatme, “Experiments with a large heterogeneous mobile robot team: Exploration, mapping, deployment and detection,” The International Journal of Robotics Research, vol. 25, no. 5-6, 431-447, 2006.

[13] B. Yamauchi, “Frontier-based exploration using multiple robots,” in Proceedings of the second international conference on Autonomous agents, ACM, 1998, pp. 47--53.

[14] R. Simmons, D. Apfelbaum, W. Burgard, D. Fox, M. Moors, S. Thrun, and H. Younes, “Coordination for multi-robot exploration and mapping,” in Proceedings of the 17th National Conference on Artificial Intelligence and 12th Conference on Innovative Applications of Artificial Intelligence, 2000.

[15] C. Stachniss, M. Mozos, and W. Burgard, “Efficient exploration of unknown indoor environments using a team of mobile robots,” Annals of Mathematics and Artificial Intelligence, vol. 52, pp. 205--227, 2008.

[16] K. M. Wurm, C. Stachniss, and W. Burgard, “Coordinated multi-robot exploration using a segmentation of the environment,” IEEE/RSJ International Conference on Intelligent Robots and Systems, 2008.

[17] S. Koenig, B. Szymanski, and Y. Liu, “Efficient and inefficient ant coverage methods,” Annals of Mathematics and Artificial Intelligence, vol. 31, pp. 41-76, 2001.

[18] I. Rekleitis, G. Dudek, and E. Milios, “Multi-robot collaboration for robust exploration,” Annals of Mathematics and Artificial Intelligence, vol. 31, no. Springer, pp. 7-40, 2001.

[19] M. Schwager, B. Julian, and D. Rus, “Optimal coverage form multiple hovering robots with downward-facing cameras,” In International conference on Robotics and Automation, Japan, Kobe, 2009.

[20] Dyer, John RG, et al., “Leadership, consensus decision making and collective behaviour in humans,” Philosophical Transactions of the Royal Society B: Biological Sciences, pp. 781-789, 2009.