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# A Multi-robot Balanced Coverage Path Planning Strategy for Patrol Missions

SeungHwan Lee

[1] School of Electronic Engineering, Kumoh National Institute of Technology,
Gumi, 39177, Korea (leesh@kumoh.ac.kr)

**Abstract:** This paper presents a multi-robot balanced coverage path planning (MCPP) strategy for patrol missions. In the entire path-based multi-robot path assignment problem, conventional studies allow path redundancy and divide the path itself according to the number of robots. However, more collisions between robots can happen due to path redundancy. Therefore, a strategy of equally assigning a path to each robot is proposed without path redundancy. First, given a map, a graph for robot movement is constructed. A problem similar to the traveling salesman problem is solved in the graph. As a result, an entire path is generated. Subsequently, unique paths are extracted from the whole path and combined according to the number of robots. Since the combined paths are not evenly divided, the paths are compensated in a way that minimizes the maximum length of ones. Simulations were performed by varying the number of robots. Through performance comparison, it showed that the paths were divided well using the proposed approach.

**Keywords:** Coverage Path Planning, Patrol Mission, Genetic Algorithm, Multi-robot System.

## 1. INTRODUCTION

For future unmanned surveillance systems, multi-robot coverage path planning (MCPP) techniques have been required to generate feasible patrol paths in the complex map and assign the paths to robots for recursive patrol. The MCPP techniques are normally classified into viewpoints generation and multi-robot path assignment and planning [1-4]. Especially, the multi-robot path assignment is crucial to save energy and patrol time. In addition, according to the assigned path, the collision between robots can be significantly reduced.

In this study, the multi-robot path assignment is considered, and its strategy is described. The contribution of the study is described as follows:

- The total path, including overlapping paths, is divided into several unique paths.
- The unique paths are clustered for *M* robots.
- *M* paths corresponding to the robots are compensated by solving the min-max problem.
- Finally, patrol paths are appropriately assigned to multiple robots without path redundancy.

## 2. PROBLEM DESCRIPTION

### 2.1 Basic Framework for MCPP

Fazli et al. [5-6] generate an entire path through a cyclic coverage algorithm. It distributes the robots equidistantly around the tour and moves. The tour that means the total path is computed by solving the given the traveling salesman problem (TSP) like problem. The definition of the TSP-like problem is that a final result includes overlapping nodes or paths. The path is divided equally for *M* robots, which are assigned to each robot. The abovementioned process is shown in Fig. 1.

### 2.2 Problem Description

In the conventional approaches for MCPP, the entire path is divided according to the number of robots after solving the TSP-like problem. However, after solving the TSP-like problem, the whole path contains duplicate paths (path redundancy). The 'T' and 'H' are the types of those paths. In this case, some paths overlap. If it is divided by *M* robots, their path length may be the same, but the possibility of robot collision increases due to the overlapping paths.

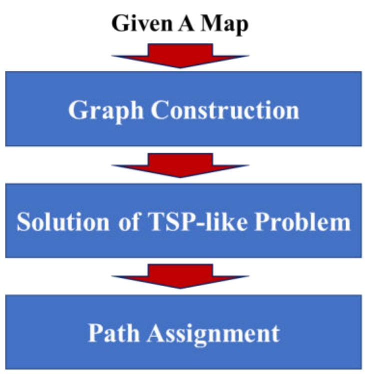


Fig. 1. The fundamental framework of MCPP

## 3. PROPOSED APPROACH

In this study, to solve this problem, first, after solving the TSP-like problem, the entire path $P_T$ is described as the sum of a set of unique paths as follows.

$$P_T = \cup_{i=1}^{K} UP_i, \tag{1}$$

where $UP_i$ is the *i*-th unique path. In addition, a condition, $UP_i \cap UP_j = \emptyset, \forall i \neq \forall j$, is satisfied. *K* is the number of unique paths.

Given the number of operatable robots *M*, the unique

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paths are combined to satisfy the number. However, since the lengths of the combined paths are not balanced, it is necessary to balance them. Balancing paths works in a way that minimizes the maximum patrol path as follows.

$$\min\left(\max_{i} CP_i\right), \tag{2}$$

where $CP_i$ is the patrol path of the $i$-th robot. In addition, a condition, $P_T = \bigcup_{i=1}^{M} CP_i$, is also satisfied.

## 4. SIMULATIONS

### 4.1 Environment

The simulation environment is shown in Fig. 2. The left figure is the top view of the robot operating space. The right figure is a corresponding SLAM map. The pixel size of the map is 4704 × 3968. In the white area of the map, the robot can move. The gray area denotes non-movable areas. The black line is the boundary line.

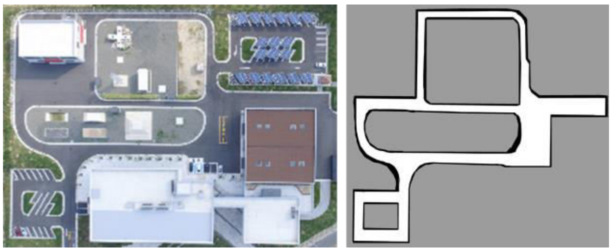


Fig. 2. Simulation environment

For the performance evaluation of the proposed approach, a balancing factor $\beta$ is suggested and calculated as follows.

$$\beta = \frac{\sum_i |L_i - \bar{L}|}{M}, \tag{3}$$

where $M$ is the number of operatable robots. $L_i$ and $\bar{L}$ are the path length of the $i$-th robot and the mean length of assigned paths, respectively. In the evaluation, a smaller $\beta$ means that an almost equal path is assigned to each robot.

### 4.2 Simulation Results

Fig. 3 shows generated nodes using the sensing range of the robot in the simulation environment. Based on the nodes, the entire path is created by solving the TSP-like problem, and the path is divided and assigned as many as the number of individual robots. The numbers of robots used in each simulation are 3 and 5, respectively. Table 1 shows the comparison of $\beta$ calculated using the proposed approach and the conventional one that does not consider the balanced path. In both two simulations, the values of $\beta$ are significantly reduced. Fig. 4 shows the area to which the proposed method is applied, and each robot performs repeated patrols according to its assigned path.

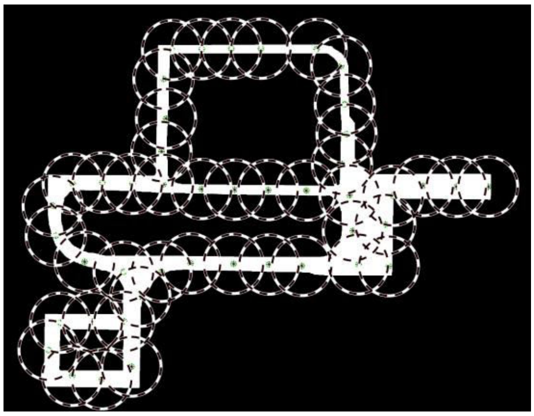
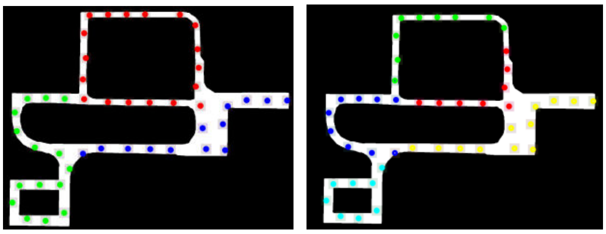


Fig. 3. Construction of graph based on sensing range of the robot. Green '*' denotes the generated nodes that should be visited.



(a) Paths for 3 robots (b) Paths for 5 robots

Fig. 4. The results of the proposed approach. The path of each robot is expressed in different colors.

Table 1. The performance of the proposed approach

| | Non-Balancing | Proposed |
|---|---|---|
| $\beta$ for 3 robots | 33.34 | 1.78 |
| $\beta$ for 5 robots | 24.8 | 1.12 |

## 5. CONCLUSION

This paper presents a multi-robot balanced coverage path planning strategy for patrol missions. A graph on a given map is constructed. The TSP-like problem that allows duplicate nodes is solved by generating a total path that visits all nodes. Since there are identical nodes in the path, we split it into a set of unique paths with no duplicates. The divided paths are combined according to the given number of robots. Since the combined path is not balanced, nodes involved in a robot with a relatively large path length are re-assigned to a robot with the most petite path length so that the maximum path length can be reduced. The simulations were conducted with different numbers of robots, and it was found that each robot had a similar path length through balancing the path.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