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Energy constrained multi-robot sensor-based coverage path planning using capacitated arc routing approach

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ABSTRACT

Multi-robot sensor-based coverage path planning requires every point given in the workspace has to be covered at least by a sensor of a robot in the robot team. In this study, a novel algorithm was proposed for the sensor-based coverage of narrow environments by considering energy capacities of the robots. For this purpose, the environment was modeled by a Generalized Voronoi diagram-based graph to guarantee complete sensor-based coverage. Then, depending on the required arc set, a complete coverage route was created by using the Chinese Postman Problem or the Rural Postman Problem, and this route was partitioned among robots by considering energy capacities. Route partitioning was realized by modifying the Ulusoy partitioning algorithm which has polynomial complexity. This modification handles two different energy consumptions of mobile robots during sensor-based coverage, which was not considered before. The developed algorithm was coded in C + + and implemented on P3-DX mobile robots both in laboratory and in MobileSim simulation environments. It was shown that the convenient routes for energy constrained multi-robots could be generated by using the proposed algorithm in less than 1 s.

1. Introduction

Complete coverage path planning is the determination of a path such that every point in a given workspace is covered at least once [1]. It is required in a variety of applications such as vacuum cleaning robots [2] and lawn mowers [3]. In these applications robot apparatus is expected to move over all the points. In some other applications, such as patrolling and search–rescue operations [4], it is enough to move the robot so that sensors on the robot cover all the points of the environment. In these applications, robot has not to pass over all the points of the environment. This type of coverage is referred as sensor-based coverage [5].

In sensor-based coverage of narrow or cluttered spaces, where obstacles lie within the detector range, Generalized Voronoi Diagram (GVD) [6] can be used to model the environment. For complete sensor-based coverage of the given area, it is sufficient for the robot to follow the GVD [5]. Additionally, a representative graph of the environment could be constructed based on GVD. Then, a better time-effective coverage path can be obtained using this graph and some specialized algorithms [7]. Using multiple robots may reduce the time required to complete the coverage task and enhances robustness compared to the single robot. There are some approaches for multi-robot coverage path planning [8–10] in the literature. In [8], the cost was evaluated in terms of traveled distance by the robot. They used arcs of the configuration space and Voronoi diagram to compute the paths in the whole area. Firstly, a tour was generated for traversing all the paths, and then appropriate parts of the tour were assigned to each robot according to a distance-based cost evaluation. However, the method of partitioning the path among the robots considering their energy capacity was not considered. The approach in [9] presented an adaptation of the single-robot cellular decomposition approach to multiple robots. A robot team moves in formation to cover cells. As cells are created and/or completed, the team splits up into smaller teams, each of which continues coverage task. In that work also, the energy capacities of the robots were not considered. In another work [10], mobile robot deployment problem was considered for a specific type of coverage problem. The deployment problem was described as determination of the number of groups unloaded by a carrier, the number of robots in each group, and the initial locations of those robots. Both timing and energy constraints of robots were considered. This work only considers simple rectangular scanlines as the coverage routes, and solves the deployment problem using fewer robots in vast environments. However, the deployment was not considered for narrow-complex environments. So, to the best of the authors' knowledge, there is no work in the literature that considers efficient multi-robot sensor-based coverage of narrow environments considering robot energy capacities.

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In this study, multi-robot sensor-based coverage of narrow environments is achieved considering the robot energy capacities. Firstly, a GVD-based model of the environment is constructed, and then the sensor-based coverage problem is described as partitioning arcs of the GVD-based graph among the robots without exceeding their energy capacities [11]. This problem resembles the capacitated arc routing problem (CARP). The CARP is a problem that aims to construct tours for vehicles to minimize total traverse without exceeding energy capacity of the vehicles [12]. The vehicle capacity in the CARP correspond the energy capacity of a robot in the coverage problem. In the CARP, amount of the material to be collected (or distributed) on an arc is defined as the arc demand. However, in the coverage problem, two different arc demands based on the robot's energy consumption could be defined. The robot passes through an arc on the GVD with or without covering. These situations require different energy consumption for a given arc. This is the difference between the CARP and the coverage problem. Due to this difference, classical CARP solution techniques cannot be used directly for the coverage problem. Therefore, a new solution technique or modification of an existing method is required. In this study, the Ulusoy partitioning heuristic was modified and used to solve the multi-robot sensor-based coverage path planning problem (MRSBCP) considering robot energy capacities. The Ulusoy partitioning algorithm is chosen because of its flexible nature for modification and ability to reach a near optimal solution in a short time.

The rest of this paper is arranged as follows. In Section 2, the CARP and its relation with sensor-based coverage are explained. In Section 3, the proposed robot control architecture is given. Experimental results both using real robots and simulation environment are given in Section 4. Conclusions and discussions are given in the final section.

2. Capacitated arc routing problem and relation with sensor-based coverage

A graph can be modeled as $G(V, A)$ where V is the set of vertices and A is the set of arcs connecting the vertices. A graph is called undirected if all arcs have no direction. Otherwise, it is called directed. If it is possible to reach all of the vertices through existing arcs, the graph is called connected, otherwise disconnected [13]. In addition, if all the vertices have a connection with other vertices directly, the graph is called complete, otherwise sparse. A weighted graph is one where distance or cost is assigned to its arcs. The weight of the arc can be calculated as the Euclidian distance between each pair of vertices or traveling cost. The matrix of Euclidian distances is the distance matrix. In a sparse and connected graph, a shortest path algorithm should be used to form the distance matrix and there are numerous algorithms to find the shortest path between any two vertices such as the Floyd algorithm [13]. In a complete and planar graph there is no need to calculate the shortest distance.

A tour is defined as Eulerian if it is possible to return to the starting vertex by passing through each arc exactly once [14]. If an Euler tour does not exist, some arcs must be visited twice or more to return the starting point. In this case, it is important to determine the shortest tour and the Chinese Postman Problem (CPP) occurs. The CPP is defined as determination a tour of minimum cost or minimum length that visits each arc at least once. Since the CPP is not an NP-hard problem, both mathematical model and heuristics such as Edmonds and Johnson's Minimum Perfect Matching algorithm [14] and the Hierholzer algorithm [13] can be used to obtain the CPP tour. In this problem, if some arcs of the graph need to be visited, the CPP turns into the Rural Postman problem (RPP). Unlike the CPP, the RPP is an NP-hard problem [15]. In the RPP, the arcs are divided into two groups as requiring service (required arc set) and not requiring service (non-required arc set). If the graph of the required arc set is connected, the RPP tour can be obtained like finding the CPP tour by using the algorithms mentioned above with an optimal solution. However, the graph of the required arc set may be disconnected. In this case, the Frederickson heuristic can be used to determine the RPP tour. In addition, the RPP tour may be unnecessarily long when it is constructed by using only the required arcs. In this case, the tour may be improved by using the Shorten Algorithm [16].

If there are more than one vehicle having certain capacities and the aim is to obtain the minimum total distance without exceeding capacity constraints, the problem is called the capacitated arc routing problem (CARP). The CARP was originally proposed by Golden and Wong, and was proven to be NP-hard [17]. Exact solution methods were proposed for the CARP, such as hierarchical relaxations lower bound of Voß and Amberg [18], valid inequalities of Belenguer and Benavent [19], and cutting-plane-based algorithm [20]. Recently, Wøhlk has developed new lower bounds for the classical CARP [21]. Since obtaining the optimal solution is not easy due to the NP-hard nature of the problem, different heuristic algorithms have been developed in the literature such as simple constructive methods, and two-phase constructive methods [12]. Additionally, meta-heuristic algorithms were also developed such as tabu search-based algorithm [22].

Although there are many solution techniques to solve the CARP, these techniques cannot be directly applied to the MRSBCP. In this problem, there are more than one robot (vehicle) having certain capacities. Since arcs are defined as required and non-required, and the robots have limited energy capacity, this problem resembles the CARP. However, unlike the CARP, there are two types of arc demand which can be called traveling energy and task performing energy (coverage energy) in the MRSBCP. When the robot passes through a non-required arc, there is no need to consume coverage energy for this arc and the arc demand is determined by only the traveling energy which arises from motors, embedded computer, microcontroller card, and navigation sensors (sonar) [10]. On the other hand, for a required arc, the robot consumes energy for both traveling and performing its coverage task. Namely, robot consumes additional energy for covering the environment by its coverage sensor (for example camera, laser range finder, thermal sensor, etc.). Then, the arc demand is calculated by adding the traveling energy and the coverage energy. Defining two different demands for an arc is quite different from the classical CARP. Because of this critical difference, the CARP solution techniques (both exact methods and heuristics) cannot be used directly for the MRSBCP. Therefore, a new solution technique or modification of an existing method is required.

In this study, a well-known CARP heuristic, the Ulusoy partitioning algorithm [23], was modified and used to solve the MRSBCP. The Ulusoy partitioning algorithm is chosen due to following reasons. Firstly, it is a constructive heuristic and generates a feasible solution in a polynomial time. Secondly and more importantly, this algorithm is flexible to adapt to the MRSBCP. In the CARP literature, there are many heuristic algorithms to generate a feasible solution for the CARP. Most of these heuristics generate the tour by connecting the current location of the vehicle to the depot when the total load exceeds the capacity of the vehicle. However, this approach is not suitable for the MRSBCP, because the robot will consume traveling energy to return to the depot and addition of this energy may result consuming the whole energy of the robot before reaching the depot. The Ulusoy partitioning algorithm permits to control the total energy requirement of a constructed tour. Therefore, a modified version of the Ulusoy partitioning algorithm is used for the MRSBCP.