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Finding a risk-constrained shortest path for an unmanned combat vehicle

Kyung-Yeol Bae [a], Yeong-Dae Kim [b,*], Jun-Hee Han [b]

[a] Korea Army Training and Doctrine Command, Yuseong-gu, Daejeon 308-878, South Korea
[b] Department of Industrial Engineering, Korea Advanced Institute of Science and Technology, Yuseong-gu, Daejeon 305-701, South Korea

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ABSTRACT

We consider a problem of finding a reconnaissance route of an unmanned combat vehicle (UCV) in a terrain, which is modeled as a grid. It is assumed that the traverse time to pass through each cell in the grid and risk level associated with each cell are given and that the cells where the reconnaissance points to be visited by the UCV are located and the visiting sequence of such cells are given in advance as in real situation of military operation. We focus on the problem with the objective of minimizing the total travel time of the UCV for a given limit on the sum of risk level values associated with the cells on the path of the UCV. We develop an optimal solution algorithm based on a dynamic programming algorithm for multiple-choice knapsack problems. We also present a heuristic algorithm, which can be used for large-size problems. For evaluation of the performance of the proposed algorithms, computational experiments are performed on a number of problem instances, and results show that the proposed algorithms give optimal or good solutions within an acceptable time for real military operations.

1. Introduction

In this paper, we consider a problem of finding a route of an unmanned combat vehicle (UCV) in the military battlefield. The UCV is a remote-controlled vehicle with no person on board that carries out various missions, such as surveillance, reconnaissance, and mine detection. It is usually equipped with a telescope, mine detection device, and/or guns. To carry out a mission assigned to a UCV, it should visit a number of locations. In general, the sequence of the locations the UCV should visit is determined by the commanding unit (before determining the route of UCVs) with consideration of the probabilities that there are enemy's military units in certain regions, the aggressiveness and threats (on the friendly units) of those units, and the total length of the resulting route of the UCV by using the information send from satellites. The operator of the UCV has to determine the best route to minimize the time required to complete a given mission, considering the risk of being found and attacked by the enemy during the operation. In this study, we focus on a risk-constrained shortest path problem of minimizing the total travel time of a UCV for a given sequence of locations (reconnaissance points) to be visited while limiting the risk level associated with the path within a predetermined value.

The problem considered in this paper is similar to the travelling salesman problem (TSP) in that both problems are concerned with finding a shortest path to visit a given set of locations and return to the initial location. However, a path between each pair of locations (to be visited) is given in the typical TSP and hence there is at most one arc between each pair of nodes (locations) in the associated network, while in the problem considered in this study, there may be multiple paths between each pair of locations (to be visited), from which one is to be taken, although the sequence of locations to be visited is given. In addition, if risk is regarded as resource, our problem is closely related to the resource-constrained shortest path problem (RCSPP), which is to find a shortest route from the source node to the destination node under the constraint that resource(s) required by the arcs on the path should not exceed a given limit(s). The difference is that there are multiple destinations (locations to be visited) in our problem, while there is a single destination in the typical RCSPP.

There are a few studies on path planning of UCVs. Stentz (1994) suggests a two-step algorithm in which an initial path is determined based on known initial information and the path is modified by using updated information. Also, many metaheuristics have been developed for path planning of UCVs. Harder, Hill, and Moore (2004) and Shetty, Sudit, and Nagi (2008) suggest tabu search algorithm for unmanned combat aerial vehicles (UCAVs), and Edison and Shima (2011) develop a genetic algorithm based on graph theory. Moreover, Park, Kim, and Jeong (2012) suggest

* Corresponding author. Tel.: +82 42 350 3120; fax: +82 42 350 3110.
E-mail address: ydkim@kaist.ac.kr (Y.-D. Kim).

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two-phase heuristic algorithms, and Han, Kim, and Lee (2014) suggest a heuristic algorithm based on the label-correcting algorithm. On the other hand, Cunningham and Roberts (2001) develop an adaptive algorithm to generate paths for multiple UCAVs, and Rathbun, Kragelund, Pongpunwattana, and Capozzi (2002) presents a path planning algorithm for a UCAV considering uncertain obstacles in a dynamically changing environment. Another problem that is similar to our problem is the path planning problem for robots. For this problem, Rhee and Rhee (1996) develop an algorithm for finding a collision-free path using learning techniques, and Choi and Kim (1996) develop an algorithm based on graph theory for generating a road-map and finding collision-free paths. Also, Chakraborty, Akella, and Wen (2010) present a two-step approach for a multiple-robot path planning problem, assigning destinations to the robots and finding paths for the robots. Meanwhile, Besada-Portas, de la Torre, and de la Cruz (2010) present an algorithm based on evolutionary algorithms, and Darrah et al. (2013) and Sahingoz (2014) suggests a genetic algorithm for path planning for multiple unmanned aerial vehicles.

Although research on our problem is rare, if any, there are many research articles on TSPs and RCSPPs. For TSPs, Held and Karp (1970), Padberg and Rinaldi (1987), Fischetti and Toth (1997), and Bektas (2006), among many others, give optimal solution approaches, and many researchers develop various heuristic algorithms including those of Croes (1958), Lin and Kernighan (1973), Ozgur and Brown (1995), Russell (1977), Suh and Kim (2001), Samanlioglu, Ferrel, and Kurz (2008), Zhao, Li, Sun, and Mei (2009), and McWilliams (2010). The RCSPP, which is shown to be NP-complete (Handler & Zang, 1980), has been used as a model for various real-world problems in Mingozzi, Boschetti, Ricciardelli, and Bianco (1999), Holmberg and Yuan (2003), Wilhelm, Arambula, and Choudhry (2006), Wilhelm, Choudhry, and Damodaran (2007), and Shin, Yang, and Baek (2006) among others. There have been a variety of solution approaches to the RCSPP. For instance, a number of algorithms have been developed based on dynamic programming (Aneja, Aggarwal, & Nair, 1983; Desrochers & Soumis, 1988; Joksch, 1966), Lagrangean relaxation methods (Beasley & Christofides, 1989; Handler & Zang, 1980), and a column generation method (Chen & Shen, 2013). On the other hand, Wilhelm and Tarmy (2003) give a pseudo-polynomial-time two-phase algorithm for RCSPPs. Approximation algorithms have also been proposed for RCSPPs, including schemes by Henig (1986) and Warburton (1987) for multi-objective problems. Recently, Shi (2010) and Puglia Pugliese and Guerriero (2013) suggest approximation algorithms for shortest path problems with multiple constraints.

In this study, we develop an optimal solution method for finding a shortest route for a given sequence of locations to be visited within a pre-specified total risk level. We also present a heuristic that can be used for large instances, for which optimal solutions cannot be found in a reasonable amount of time. In both algorithms, a number of (promising) paths are generated for each pair of consecutive locations in the sequence, and then one path is selected for each pair using a dynamic programming algorithm.

The remainder of this paper is organized as follows. In Section 2, we describe the problem in detail, and we develop an optimal solution algorithm and a heuristic in Sections 3 and 4, respectively. These algorithms are evaluated through a series of computational experiments and results are reported in Section 5. Finally, Section 6 concludes the paper with a short summary and discussions on future research.

2. Problem description

We consider a shortest path problem for an unmanned combat vehicle (UCV) which reconnoiters a focused area at night time. As in actual military operations, the terrain, or the area of interest, is represented with a grid map. The grid and each cell of the grid are rectangular. Two types of information are known for each cell, traverse time and risk level. These are estimated for each cell from the configuration of the ground, i.e., topography, of the cell (given in military operations maps) and the locations of the enemy's units. (Such information is obtained by satellites and various intelligence assets of friendly units and updated frequently.) Note that a path from one point in the terrain to another can be represented by a sequence of cells through which the UCV passes, since there is no road (between the points in the terrain) on which the UCV can move, as is the case with the battlefield. Also, note that the probabilities that the UCV is detected and attacked by the enemy may differ in different cells. The problem is to find a path that requires the shortest traverse time for visiting a set of locations (reconnaissance points) according to a given sequence and returning to the base. The sum of risk levels associated with cells the UCV passes through should not exceed a given upper limit (U^R) on the cumulative risk level. As stated earlier, the problem can be considered as a resource-constrained shortest path problem (RCSPP) if the risk level is considered as resource, and it is denoted as RCSPP-UCV in this paper.

In this study, the terrain, which is represented on an $M \times N$ grid, is also represented by network $G = (V, A)$, where V and A are the index sets of nodes and arcs, respectively. The nodes represent cells in the grid and each arc represents a connection or path between two adjacent cells. From each cell except for the cells on the border of the grid map, the UCV can move to eight adjacent cells as shown in Fig. 1. Fig. 2 shows a simple example of paths between two cells in the grid. Reconnaissance points are also represented by nodes. In addition, it is assumed that in order to reconnoiter a point, the UCV must pass through the cell in which the reconnaissance point is located. This is the way paths are determined and moving times are estimated in the battlefield (since there are no well-defined roads between the reconnaissance points). That is, the moving time between two points through a path is estimated as the sum of traverse times of cells included in the path.

In this study, a path between two consecutive reconnaissance points in a given sequence is called a *partial route*. Each partial route can be defined by a sequence of nodes and/or arcs included in the route. A *complete route*, i.e., a path starting from the source (base), visiting all reconnaissance points according to a given sequence, and returning back to the source, is given as a concatenation of such partial routes. The sum of risk level values of the nodes (cells) included in a route is called the *cumulative risk level* of the route, and a route is called *feasible* if the cumulative risk of the route is not greater than a pre-specified limit (U^R) on the cumulative risk of a complete route.

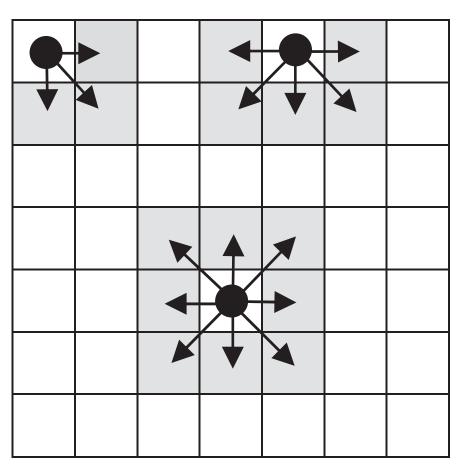

Fig. 1. Possible directions of movement from a cell.