Aerospace Science and Technology 76 (2018) 112–125

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Cooperative multiple task assignment problem with stochastic velocities and time windows for heterogeneous unmanned aerial vehicles using a genetic algorithm

Zhenyue Jia, Jianqiao Yu *, Xiaolin Ai, Xuan Xu, Di Yang

School of Aerospace Engineering, Beijing Institute of Technology, 5 South Zhongguancun Street, Haidian District, Beijing, 100081, China

ARTICLE INFO

Article history:
Received 17 January 2017
Received in revised form 1 June 2017
Accepted 31 January 2018
Available online 6 February 2018

Keywords:
Stochastic programming
Task assignment problem
Heterogeneous unmanned aerial vehicles
Genetic algorithm
Path coordination

ABSTRACT

In this paper, a combinatorial optimization problem, formulated as a cooperative multiple task assignment problem with stochastic velocities and time windows for heterogeneous unmanned aerial vehicles, is studied in the form of a two-stage stochastic programming model. To create a more realistic mission scenario, we involve several types of constraints in this problem, such as kinematic constraints, resource constraints (both boarded weapons and fuels), and time constraints (both task sequences and time windows). Due to the prohibitive computational complexity of the problem, a novel meta-heuristic based on a modified genetic algorithm is proposed to improve the solution of this stochastic task assignment problem. After a feasible solution is obtained, a set of actual flight paths will be created by a path coordination process according to the requirements of the task precedence. In the simulation part, the effect of the proposed algorithm, both on searching capability and convergence speed, is demonstrated by comparison with the random search algorithm. Moreover, the stochastic nature of this problem caused by the stochastic flight velocities is also illustrated by comparison with a deterministic model. Additionally, actual flight trajectories meeting all time constraints are displayed for this stochastic task assignment problem.

1. Introduction

A task assignment problem is a combinatorial optimization problem that minimizes a predefined objective function by allocating one agent (or several agents) to multiple tasks, such as the traveling salesman problem (TSP) [1], generalized assignment problem (GAP) [2], and vehicle routing problem (VRP) [3]. In recent decades, the cooperative task assignment problem for unmanned aerial vehicles (UAVs) has been an emerging issue with application to sophisticated military missions, such as Wide Area Search Munitions (WASM) [4,5], Suppression of Enemy Air Defense (SEAD) [6,7] and combat Intelligence, Surveillance, and Reconnaissance (ISR) [8]. Among these military applications, the cooperative multiple task assignment problem (CMTAP) [9] has been studied as a typical situation in which multiple unmanned vehicles perform multiple consecutive tasks, such as classification, attack, and verification on stationary targets known *a priori*.

Compared with the TSP and VRP, CMTAP for UAVs involves two main characteristics: the cooperation and kinematics of UAVs. CMTAP is concerned with the selection of conflict-free matchings of tasks to vehicles. In other words, a higher-level component of a mission planner provides a list of tasks to the task assignment component, deciding which of the available UAVs should perform each task based on information about the tasks and the capabilities of the UAVs. In this paper, by means of introducing heterogeneous UAVs with special capabilities and resource limitations, the characteristics of cooperation are considered in this stochastic task assignment problem. Additionally, the constraint of the kinematics of UAVs must be taken into account in the process of path generation. Thus, the Dubins Car model is adopted to generate a set of elementary flight paths for UAVs. Furthermore, due to the constraint of the task sequence described below, we propose two extra maneuvering flights to coordinate the flight paths of UAVs and to finally create the actual flight paths for each UAV.

In the scenarios of some special military missions, time constraints such as time windows and task sequences are always involved in the task assignment problem. In this paper, we assume that the time windows are soft constraints which mean that the assignment is penalized if the task performance time exceeds the predefined time intervals. In contrast, a solution of the task assignment is infeasible if the task precedence constraints are broken on any target. Moreover, an unacceptable phenomenon called dead-

* Corresponding author.
E-mail address: jianqiao@bit.edu.cn (J. Yu).

https://doi.org/10.1016/j.ast.2018.01.025
1270-9638/

lock may also be involved in the task allocation due to the task precedence constraints. Thus, an approach based on graph theory [10] is adopted to solve this problem.

The aforementioned constraints of the task assignment problem are comprehensive, but the common disadvantage is that all problem elements are deterministic. In real-life applications, the quality of task execution may become quite poor if uncertainties are disregarded. In [11,12], the authors discussed a chance constrained path planning problem. For robust execution, uncertain factors, such as uncertain localization, modeling errors and disturbances, are considered. Different from the studies mentioned above, this paper takes into account the stochastic elements in the process of task assignment at the mission level. The described problem extends the classical task assignment problem by introducing negative stochastic flight velocities based on a known probability distribution for each UAV in each flight segment, leading to a stochastic task performance time. Thus, a two-stage stochastic programming model is adopted to solve this stochastic task assignment problem in a more reliable and effective manner.

From a mathematical perspective, the task assignment problem is one of the fundamental combinatorial optimization problems in the branch of operations research. Hence, the cooperative multiple task assignment problem with stochastic velocities and time windows (CMTAPSVTW) proposed in this paper belongs to the class of NP-hard (non-deterministic polynomial hard) [13] combinatorial optimization problems as well. Complexity is one of the main challenges of CMTAP involving the size of the problem and the types of constraints. Because the deterministic search methods are not suitable for dealing with problems with prohibitive computational complexity, it is practical and reasonable to design heuristic and meta-heuristic algorithms to obtain a good feasible solution in an expected runtime. In this paper, a novel meta-heuristics modified genetic algorithm (GA) is proposed to obtain a more efficient solution in a reasonable number of generations.

The main contribution of this paper is the incorporation of these constraints together with the uncertainties to create a more realistic mission scenario and the proposal of a novel modified GA combined with a path elongation algorithm to make the results more convincing and practical. The remainder of this paper is organized as follows. Section 2 provides a literature review on both the classical task assignment problem and the stochastic task assignment problem. In section 3, a theoretical model of CMTAPSVTW is established and cast within the framework of a two-stage stochastic programming model. In section 4, a novel GA with modified encoding and genetic operators is described; additionally, a type of infeasible state called deadlock is introduced and solved in this section. In section 5, a set of elementary flight paths for each UAV are generated according to the Dubins Car model, and two types of extra maneuvering flights are introduced to coordinate the flight paths and create the actual flight paths for each UAV. In section 6, numerical simulations are carried out to demonstrate the superiority of our algorithm and to evaluate the performance of the two-stage stochastic programming model for this stochastic task assignment problem. Sample trajectories of selected UAVs are also shown in this section. Various major conclusions are drawn in section 7.

2. Literature review

2.1. Classical task assignment problem

Generally, classical task assignment problem solutions can be classified into the following two categories according to the search algorithms:

- ***Deterministic algorithms***: methods that attempt to obtain the optimal solution for a given objective.
- ***Heuristic algorithms***: methods that aim to provide an effective means of obtaining sub-optimal solutions.

The deterministic algorithms including the family of branch and X algorithms (such as the branch and bound algorithm, branch and cut algorithm, and branch and price algorithm), linear programming and dynamic programming, have been introduced in many published papers. As far as we know, a mixed integer linear programming (MILP) formulation for UAV task assignment problem was first presented in [14]. Three tasks were required to be completed for each target in the MILP model. Due to the complexity of the resulting MILP, only small-sized problems could be solved quickly. Therefore, the authors proposed another work [5] in which classification and attack were grouped into a single task allowing real-time solutions to be obtained for problems of practical size. However, there existed the following limitations: 1) the vehicles in the mission were homogeneous; and 2) the existence of a solution was guaranteed only when the air vehicles had sufficient endurance. Although both previous literatures referred to the continuous time variable, [8] presented a task assignment problem in a combat ISR mission by modifying the vehicle routing problem with time windows (VRPTW) to further discuss the time constraints. The common disadvantages in the MILP formulation are that the kinematics of UAVs are not considered and that computational complexity cannot be avoided as the dimension of the problem increases. In recent studies, a search tree model combined with a branch and bound search algorithm was developed [15,16]. In the proposed branch and bound search algorithm, an upper bound on the cost of the cooperative assignment was initialized by a candidate optimal solution obtained from the BFS algorithm. In contrast, a lower bound on the cost of the same target being serviced by a different UAV was obtained using Euclidean distances. The optimal solution to the assignment problem was found by applying these upper and lower bounding procedures iteratively. The search was terminated when all nodes had either been evaluated or pruned. [17] proposed a dynamic programming framework to solve the UAV task assignment problem and introduced two approximation algorithms that significantly reduced the computational complexity for larger problems.

Regarding the second category, heuristics and meta-heuristics approaches, such as Tabu Search (TS) [18], Simulated Annealing (SA) [19], Particle Swarm Optimization (PSO) [20] and Genetic Algorithms (GA) [7,9,21–23] have been studied more extensively than exact methods. These algorithms have been considered to avoid the computational complexity of the combinatorial optimization problems and have been demonstrated to provide an effective basis upon which sub-optimal solutions can be achieved. As a population-based meta-heuristics approach, GA is one of the most useful methods when the search space is not extremely rugged [24] in the presence of many types of constraints. In [21], the authors preliminarily proposed a genetic algorithm for the combinatorial optimization problem, taking the special requirements into account, such as task precedence and flyable trajectories. Subsequently, by introducing a finite set of approach angle, the CMTAP coupled with path planning was posed in the form of a digraph and a more comprehensive encoding with genetic operators was presented for both homogeneous and heterogeneous flight vehicles in [22]. Additionally, limited onboard resources (e.g., weapons), time-sensitive targets (e.g., simultaneous attacks) and deadlock situations were considered in [23]. Analogously, the applications of GA to classical combinatorial optimization problems such as TSP, GAP, and VRP have been widely studied in [25–28].

Furthermore, there have been various excellent works that discuss the dynamic environment. [4] addressed the problem of task