Research Article

A Method of UAVs Route Optimization Based on the Structure of the Highway Network

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It is essential for transportation management centers to establish a network of fixed and mobile sensors to collect traffic information of highway network, especially for very important links with frequent traffic events. Emerging Unmanned Aerial Vehicles (UAVs), it is introduced as a mobile sensor to collect road traffic information and its cruise route planning problem is researched based on the highway network physical structure. First, according to existing traffic data, a method used to calculate the link importance degree index is proposed, and the index is used to evaluate the link’s information. Second, a multiobjective optimization model is proposed, its aim is to minimize the total cruise time under detecting as many important links as possible and minimize the information value undetected by UAVs, and the fuzzy operator is introduced to the constraint conditions. Finally, a case study is used to demonstrate the feasibility and effectiveness of proposed model about UAVs’ route planning.

1. Introduction

Traffic information is the foundation of the traffic management and control. Traffic sensors are considered as an important way to collect traffic information. Most of commonly used traffic sensors are installed in fixed location, such as loop detector, microwave detector, video camera, and Automatic Vehicle Identification (AVI) readers. The biggest advantage of this kind of traffic sensors is that they can capture the traffic dynamic characteristics of the specific location for a long time horizon. While the disadvantage of fixed traffic sensor is also obvious, it cannot be installed on everywhere in a network because of the budget constraint. The movable traffic sensors are developed as a complementary tool for traffic information collecting. Due to the weakness of the fixed traffic sensor, more movable traffic sensors are invented for network surveillance. Unmanned Aerial Vehicle (UAV) is considered as a novelty tool, which can conduct different tasks by loading various sensors, such as high-resolution camera, radar, and infrared camera.

UAVs, well known for their wide field of view, easy operating, and outstanding flexibility, are promised to be a great aerial sensor for transportation applications. UAVs can be launched quickly and exchange data with control center in real time. According to the sensors on the UAVs, they can provide the entire image of the investigation area or a special location and also provide continuous traffic state evolution. Therefore, UAVs are considered as an effective traffic surveillance system compared with traditional fixed traffic sensors.

The maximum flight distance or flight time of UAV is limited by the fuel volume and battery volume that they can carry. If the number of monitored roads and available UAVs are determined, it is important and meaningful to investigate the optimal cruise route of UAVs in order to cruise more target roads under the UAVs’ capacity constraints or cruise all target roads with most efficient route.

In recent years, some researchers focused on the UAVs route planning problems. Ryan et al. [1] considered this problem as a multiple travel salesman problem with the objective of maximizing expected target coverage and solved it by applying a Reactive Tabu Search. In 2002, the UAVs route planning problem was studied by Hutchison. The monitored roads were divided into several subareas firstly, and all the target road in each subarea was inspected by one UAV. In his study, the UAVs route planning problem
was solved by simulated annealing algorithm [2]. Yan et al. [3] also considered the UAVs routing problem as a TSP and introduced a generic algorithm to find out the nearly optimal route. This paper creatively considered the different fly routes between two target roads into their model. They verified their method by a case study of sparse network in western part of China.

Ousingsawat and Campbell [4] considered this problem as two parts. First is to find the shortest path between two points, and the possible path combinations are listed for all UAVs; then the task assignment problem was used to give the results. Tian et al. [5] introduced the time window requirement of reconnaissance mission for each target road. They presented a mathematical model for cooperative reconnaissance mission planning problem which takes the reconnaissance resolution demands and time windows of the targets into account and with the constraints of maximum travel time of each UAV.

Wang et al. [6] presented a multiobjective ant colony system algorithm for UVA route planning in military application. Two components are taken into account in their cost function which are route length and danger exposure. Liu et al. [7] proposed a multiobjective optimization model for UAVs route planning. Two objectives are listed: minimize the total distance and maximize the total number of monitored points. The available amount of UAV and maximum cruise distance are considered as constraints. Liu et al. [8] introduced time window constraint in the optimization model. One of the main weakness of their study is that they did not consider the length of road links. Liu et al. [9] introduced UAV route planning method without and with flight distance constraints. K-means clustering algorithm was used to divide the UAV cruise area into subarea and simulated annealing algorithm was applied to solve this problem. The multiobjective optimization model proposed by Liu et al. [10] aimed to minimize UAV cruise distance and minimize the number of UAVs being used. Zhang et al. [11] presented a space-time network-based modeling framework for integrated fixed and mobile sensor networks, in order to provide a rapid and systematic road traffic monitoring mechanism. A Lagrangian relaxation solution framework is developed to decompose the original complex problem into a series of computationally efficient time-dependent and least cost path finding subproblems. A recent study by Zhu et al. [12] specifically considered the mobility constraints of traffic sensors, and a measure of traffic information acquisition benefits was used to evaluate the surveillance performance. Their proposed hybrid two-stage heuristic algorithms include both particle swarm optimization and ant colony optimization components.

Additionally, in military area, UAVs have already dominated the investigative equipment. While in the general aviation field, UAVs are facing some barriers in China, for instance, strict airspace and complicated route application. These barriers obstruct the UAVs’ application in transportation field. The China air traffic control center will open the low altitude space (lower than 1000 m) management in the following years. This is a great opportunity for the transportation department to explore the application of UAVs in road traffic network surveillance and traffic incident observation.

Based on above, this paper proposed a novel model of UAVs route planning under the assumption of UAVs’ flying space constraint where UAVs could only fly above the physical road network. Multiobjectives are considered in this model which minimize flying cost and maximize the collected information value or minimize the undetected information value.

The remainder of this paper is organized as follows. The problem statements and assumptions are first presented in the next section. In Section 3, a structure of the highway network based UAV routing planning model is developed to integrate with existing fixed traffic detectors to minimize flying time and maximize the detect information value. In Section 4 an illustrative example is given to demonstrate the effectiveness of the proposed models. The conclusion is summarized in Section 5.

2. Problem Statement and Assumptions

2.1. Problem Assumptions. At present, UAV flight facing a more practical problem in China is affected by the traffic management requirements and low-flying privileges, as well as inhabitant distribution, so the UAVs cannot be arbitrary flying in the sky. For the highway network, airspace along the road does not involve in residential and military no-fly zone and other restrictions; therefore UAVs flying along the physical road are more feasible.

In recent years, researchers proposed different kinds of UAVs route optimization methods. Someone used dual method and the links which are needed to be monitored were transformed into nodes; someone assumed UAVs fly along the road when they cruise road links. Figure 1 shows the main abstract methods of UAVs route optimization problem.

In [7–9], the authors abstracted the links which are needed to be detected into nodes, and it is assumed that arcs exist between both arbitrary nodes and UAVs can fly along them, but it is very difficult to carry out in reality. Reference [10] assumed UAVs fly along the road when they cruise road links which are needed to be detected, but the other path is along the straight line between two nodes. Reference [11] assumed UAVs fly along the road from beginning to end.

In this paper, stipulate UAV cruising routine based on topology network of road network. And the cruise targets are nondetector links. When the UAVs cannot cruise all nondetector links, the links with higher important degree will be selected to cruise prior to finally get maximum detection information. When the information value of links are equal, the low cost route will be selected prior.

2.2. The Link Importance Degree Calculation. We choose the links by the important degree of the links without fixed sensors as cruising targets. The information of the link will be increased with the important degree increasing. Thus, the cruising route of UAVs are determined by the important degree of links. The important degree assessment is equivalent to vulnerability analysis problem in some degree.
3. The UAVs Route Optimization Model

The intersection of highways, interchanges, and toll stations are abstracted as nodes and the original topology of highway network structure is extracted. Then, the adjacency matrix and incidence matrix between link and node of highway network topology can be obtained easily, denoted by \( M \) and \( B \), respectively. Furthermore, the flight time matrix \( D \) between any two nodes of UAV by using the highway mileage data and the UAVs’ speed is nonmonitoring links.

Let \( S \) be the set of all links in highway network, let \( S_0 \) be the set of links which are not installed fixed sensors, and let \( S_1 \) be the set of links which are installed fixed sensors; then \( S_0 \cap S_1 = \emptyset \), \( S_0 \cup S_1 = S \). The monitoring targets are the links which are not installed fixed sensors.

3.1. Preparation. Here, the calculation method of UAV’s flying time between two detected links is introduced.

The flight time contains two parts: (I) the cruise time of target links and (II) the flight time between two adjacent target links. Part (I) is obtained by link length and the speed of UAV on the link. Part (II) is calculated by formula (2) in [6] as follows.

As in Figure 2, links \( m \) and \( n \) are needed to be detected, and the link \( m \) connects the node \( a_i(m) \) and node \( b_i(m) \) and the link \( n \) connects the node \( a_i(n) \) and node \( b_i(n) \). When the UAV flies from link \( m \) to link \( n \), it has four possible route options as shown in dashed arrows: \( a_i(m) \rightarrow b_i(n), a_i(m) \rightarrow a_i(n), b_i(m) \rightarrow a_i(n), \) and \( b_i(m) \rightarrow b_i(n) \). Then the flight
time from link $m$ to link $n$ of UAV is obtained by following formula:

$$L'(m, n) = \alpha [\beta D_{mn}^1 + (1 - \beta) D_{mn}^2]$$

$$+ (1 - \alpha) [\beta D_{mn}^3 + (1 - \beta) D_{mn}^4] ,$$

where

$$\alpha = \begin{cases} 1 & \text{when } a_1(m) \rightarrow a_2(n) \text{ or } a_2(m) \rightarrow b_1(n) \\ 0 & \text{when } b_2(m) \rightarrow a_1(n) \text{ or } b_2(m) \rightarrow b_3(n) \end{cases}$$

$$\beta = \begin{cases} 1 & \text{when } a_1(m) \rightarrow a_2(n) \text{ or } b_2(m) \rightarrow a_3(n) \\ 0 & \text{when } a_1(m) \rightarrow b_2(n) \text{ or } b_2(m) \rightarrow b_3(n) \end{cases}$$

$D_{mn}^1$ represents the UAV's flight time from node $a_1(m)$ to node $a_2(n)$, and $D_{mn}^2 = d(a_1(m), a_2(n))$; $D_{mn}^3$ represents the UAV’s flight time from node $b_2(m)$ to node $a_1(n)$, and $D_{mn}^4 = d(b_2(m), a_3(n))$. Here, $D_{mn}^1$, $D_{mn}^2$, $D_{mn}^3$, and $D_{mn}^4$ can be obtained from matrix $D$. If link $n$ is the UAVs bases, that is, link $n$ becomes a node, then $D_{mn}^1 = D_{mn}^2$ and $D_{mn}^3 = D_{mn}^4$; formula (2) transforms into following formula:

$$L'(m, n) = \alpha D_{mn}^1 + (1 - \alpha) D_{mn}^3.$$  

Let

$$L(m, n) = L'(m, n) + h(m, n),$$

where $h(m, n)$ is the flight time on the monitored link and

$$h(m, n) = \begin{cases} l(m) & \text{when the first link in cruise route belongs to } S_o, \\ l(n) & \text{when the first link in cruise route belongs to } S_i. \end{cases}$$

$l(m), l(n)$ represent the flight time on links $m$ and $n$, respectively. $L(m, n)$ is the sum of flight time monitored link and the flight time from link $m$ to link $n$.

For UAV $k$, the total flight time of one patrolling mission $L_k^t$ is calculated by the equation as bellow

$$L_k^t = \sum_{m,n \in S, m \neq n} L_k(m, n) W_{mn,k},$$

in which $L_k(m, n)$ is the sum of flight time monitored link and the flight time from link $m$ to link $n$ for UAV $k$. $W_{mn,k}$ is a binary variable; if UAV $k$ flies from link $m$ to link $n$, then $W_{mn,k} = 1$; otherwise, it equals 0.

3.2. Model Established. In this paper, the optimization objectives are to minimize sum of uncollected information and minimize the total UAV’s flight time. The optimization model is listed as follows.

The objective functions:

$$\min \sum_{m \in S} C^F(m) x^F(m)$$

$$\min \sum_{k \in N_k} \sum_{m, n \in S, m \neq n} L_k(m, n) W_{mn,k}.$$  

The constraints:

$$\bigvee_{k \in N_k} x_{mk} \leq \sum_{k \in N_k} \sum_{n \in S, n \neq m} W_{mn,k}, \quad \forall m \in S_0,$$  

$$\bigvee_{k \in N_k} x_{mk} + x^F(m) = 1, \quad \forall m \in S_0,$$  

$$\sum_{n \in S_n, m \neq n} W_{mn,k} = \sum_{n \in S_0, n \neq m} W_{mn,k} = \begin{cases} 1 & \text{if } m \text{ is the start point of UAV } k, \\ 0 & \text{otherwise,} \end{cases}$$

$$\sum_{k \in N_k, m \in S} W_{mn,k} \leq N_u,$$  

$$\sum_{m,n \in S, m \neq n} L_k(m, n) W_{mn,k} \leq L_k,$$

in which $\bigvee$ is the fuzzy operator and represents taking the maximum value among all the elements; $C^F(m)$ represents the cost if link $m$ cannot be detected by all UAVs, $m \in S_0$; here the cost is uncollected information value; $x_{mk}$ is a binary variable; if link $m$ is detected by UAV $k$, then $x_{mk} = 1$; otherwise, it is equal to 0; $x^F(m)$ is a binary variable; if $\bigvee_{k \in N_k} x_{mk} = 0$, then $x^F(m) = 1$; otherwise, it is equal to 0; namely, if link $m$ cannot be detected by all UAVs, then $x^F = 1$; if link $m$ can be detected by someone’s UAV, then $x^F = 0$; $N_u$ is the number of UAVs; $k$ is the subscript of UAV; $L_k$ is the longest flight time of UAV $k$.

Formula (10) is the UAVs detected constraint and $\bigvee_{k \in N_k} x_{mk}$ is a variable to represent whether the link $m$ is
Table 1: The flying time and information value of links.

| Link number | A | B | C | D | E | F | G | H |
|-------------|---|---|---|---|---|---|---|---|
| Flying time (min) | 20 | 26 | 18 | 22 | 49 | 15 | 33 | 40 |
| Information value | 20 | 25 | 35 | 32 | 25 | 20 | 40 | 20 |

detected by an UAV. If $\sqrt{\text{det}_m} x_{mk} = 1$, then the link $m$ is detected by an UAV; that is, it exists in $k$ such that $W_{m,n,k} = 1$. Otherwise, $\sqrt{\text{det}_m} x_{mk} = 0$ indicates $W_{m,n,k} = 0$, for all $k$. Formula (11) represents that link $m$ must be detected or virtually detected exactly once. Formula (12) is a set of flow balance constraints, and each UAV departs and arrives airbase only once, when the depot of UAVs is located in link $m$; then for arbitrary $k \in N_u$, formula (12) holds. Formula (13) is the constraint of maximum number of available UAVs. Formula (14) is the UAVs duration time constraint.

The traditional method of solving multiojective optimization problem is to give weights to different objective functions, and then multiojective problem was converted into single-objective problem by linear combination. This approach is more intuitive and easier to operate for traffic managers, in order to obtain the satisfied program by which they can adjust the weights according to their needs directly. Thus, the proposed model is solved by introducing average weighting factors, and two objectives are normalized before the algorithm by using the following formulas:

\[
s_1 = \frac{p_1}{\sum_{m \in S} C^2 (m)} \times 100%,
\]
\[
s_2 = \frac{p_2}{\sum_{k=1}^{N_u} L_k} \times 100%,
\]

where $s_1$ and $s_2$ are the normalized values for objective 1 (formula (8)) and objective 2 (formula (9)), respectively. $p_1$ and $p_2$ are the values for objective 1 and objective 2, respectively.

The values of the final objective function $P$ are calculated as follows:

\[
P = \omega_1 s_1 + \omega_2 s_2,
\]

where $\omega_1$ and $\omega_2$ are the weight and $\omega_1 + \omega_2 = 1$. $P$ is smaller, and the solution is better.

4. Verification

The validity of proposed model is proofed through following small network. Here the beam search algorithm is used to solve the proposed model and realized by GAMS.

For simplicity, assume that the speed of UAVs is a constant; that is, the flight speed is the same value for all links.

In Figure 3, the network includes 6 nodes and 9 links. The flying time and information value of each link are listed in Table 1. Cruising complete network requires at least 247 minutes.

Top four information value links had been installed fixed detectors, which are link $\vartheta$, link $\varpi$, link $\varphi$, and link $\varrho$. Other links do not have fixed sensors which are shown by red line in Figure 4. These links should be detected by UAVs and the total information of undetected links is 110.

In the example, the UAVs airbase is located at node 3 which means the UAVs should start their tasks at node 3 and return to node 3, finally; $C^2 (1) = 20$, $C^2 (2) = 25$, $C^2 (5) = 25$, $C^2 (6) = 20$, and $C^2 (8) = 20$.

When the maximum duration time of UAVs $L_k$ is very large and $N_u = 1$, then one of the optimal cruising route is link $\varpi \rightarrow$ link $\varphi \rightarrow$ link $\varphi \rightarrow$ link $\varphi \rightarrow$ link $\varphi \rightarrow$ link $\varphi \rightarrow$ link $\varphi$. The minimum flying time is 189 minutes and minimum undetected information value is 0.

The following let the maximum duration time of UAVs $L_k$ be 150 minutes for all $k$; then the proposed model is verified by two scenarios: $N_u = 1$ and $N_u = 2$.

(i) $N_u = 1$. As can be found from above results, cruising all undetected routine, one UAV at least needs to fly 189 min; under constraint condition of UAV maximum endurance flight time is 150 min; cruising all undetected links needs at least two UAVs. Therefore, when only one UAV is available, through solving biobjective optimal model of minimum information amount of nondetect road and minimum flying time in this paper, obtain UAV optimize cruising route, as in Figure 5.

Route 1 is link $\varpi \rightarrow$ link $\varphi \rightarrow$ link $\varphi \rightarrow$ link $\varphi \rightarrow$ link $\varphi \rightarrow$ link $\varphi$, the total flying time is 79 minutes, and the uncollected information is 45.
As above, \( \omega_1 = \omega_2 = 0.5 \), then the values of the final objective function \( P \) is calculated as follows:

\[
P = 0.5 \times \frac{0}{110} + 0.5 \times \frac{227}{150 + 150} = 0.38.
\]

(18)

The above numerical examples show that the UAVs route optimization method is feasibility and effectiveness.

5. Conclusions

The fixed sensor-oriented traffic sensor network design problem has been widely studied. With UAVs as a special type of mobile sensors, this paper aims to propose a practically useful and computationally efficient UAVs routing model for daily traffic information collected. In this paper, cruise route planning problem of UAVs is developed based on the highway network physical structure. A multiobjective optimization model is proposed to minimize the total cruise time and minimize the information value nondetected by UAVs. Finally, a case study is used to demonstrate the results of proposed model in UAVs’ route planning.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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