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Safety and security management with Unmanned Aerial Vehicle (UAV) in oil and gas industry

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Abstract

We describe a mathematical model for UAV aided security operations in the oil and gas industry. Operating UAVs can provide seamless awareness on possible emergency situations such as oil spills, shipping incidents, industrial accidents, acts of terrorism, and so on. The primary goal of this model is to generate an optimal UAV operational schedule to meet surveillance needs in the areas of interest in each time period. The performance of these UAVs depends on the risk assessment on spatio-and-temporal characteristics of threats, specifications of available UAVs, and decision makers' critical information requirements. The models are designed to provide insights into issues associated with designing and operating UAVs for strengthened maritime and port security.

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Keywords: Unmanned Aerial Vehicle (UAV); Maritime security; Vehicle routing problem

1. Introduction

The oil and gas infrastructure needs to maintain a high level of security conditions to deter any threats and risks. However, these have been often exposed to various risky situations because oil and gas products are extracted and stored on open ground facilities and transported long distances by pipelines or cargo ships with minimum security protection measures [1]. In 2013, natural gas facilities at Yemen and Algeria were attacked by Al Qaeda terrorists. In

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2012, an LNG cargo vessel also became a target of pirate attack off the cost of Oman [2,3]. Therefore having early warning and detection capabilities to against these threats are very important [4]. To enhance security conditions in oil and gas industry, we can consider utilizing a fleet of UAVs to monitor areas of interest.

Traditionally UAVs have conducted many military operations including surveillance and reconnaissance, standoff attacks and special operations [5]. Especially, UAVs have significantly contributed in the combat against terrorist attacks by providing 'sensor to shooter' capabilities without deploying ground troops [6]. As the UAV acquisition and operating costs get lower and the related regulations are relaxed, we can utilize UAV capabilities for security enhancement in the oil and gas sectors. We formulate the problem as an inventory routing problem (IRP) to optimize multiple UAVs' paths and battery charging conditions.

The remaining sections of this paper are organized as follows. Section 2 describes the proposed UAV path generation problem for multiple UAVs, Section 3 presents the proposed mathematical formulations in an IRP form, Section 4 discusses computational results and we conclude the paper with discussions of opportunities for extensions of our work in Section 5.

2. Problem statement

This problem aims to optimize multiple UAVs routing decisions and the battery charging schedule for security operations in a given time period. The target facilities to be monitored by security UAVs are composed of multiple sub-facilities including LNG terminals, offshore facilities, berth areas, mooring areas, storage tanks, and operating center. Each facility has to be inspected by a UAV within a given flying time. We consider a fleet of multiple heterogeneous UAVs. Every UAV has its own specific maximum operable distance and time to maneuver and conduct surveillance operations in the areas of interests. Maximum operable time and distance of a UAV is subject to a minutely battery charging rate and maximum battery charging limit. In this problem, there are four major decision variable groups. First, the battery charging level of a UAV must be determined. Second, a UAV with a proper operable capability has to be assigned to a path. Third and fourth, battery charging rate and charged level have to be planned.

3. Mathematical formulation

The problem can be formulated on a directed network $G(V,A)$. A UAV $k \in K$ at an operations center $i_0 \in K$ initiates surveillance operations over a single or multiple security check points $j \in V \setminus \{i_0\}$ through the traverse arc $(i,j) \in A$ within a designated time period $TM_j^{tot} + \beta$. An assigned UAV $k \in K$ to a path a_n can maneuver within a given operating time limit CG_k^{uav}. Total operating time of a UAV is subject to the minutely charging rate x_t^{mch} and total battery level x_t^{acc} considering a maximum minutely charging capacity $\overline{\psi}$ and maximum battery charging capacity $\overline{\rho}$. When a UAV flies through the traverse arc $(i,j) \in A$, the UAV's departure time x_j^{dep} and arrival time x_j^{tot} is subject to flying time $TR_{i,j}$ and inspection time D_j. The UAV surveillance scheduling model is presented in this section as a full formulation. We use the following notations:

3.1. Indices and Sets

K	Set of UAVs;
$G(V,A)$	Directed graph nodes V as the set of security check points and $A = \{(i,j) : i, j \in V, i \neq j\}$ as the set of arcs;
$i_0 \in V$	Index of the origin (operations center);

3.2. Data

$TR_{i,j}$	Estimated travel time of a UAV through the traverse arc $\left(i,j\right)\in A$;
C_k^{uav}	Fixed operating cost of a UAV *k*;
D_j	Surveillance time at *j*;
TM_j^{tot}	Expected time on check point *j*;
CG_k^{uav}	Maximum operating time of a UAV *k*;
C^{mch}	Unit minutely charging cost;
γ	Maximum number of security check points that can be monitored in a path;
M	Big-M;
β	Surveillance time window (number of minutes) from TM_j^{tot};
$\bar{\rho}$	Maximum battery charging capacity (level);
$\bar{\psi}$	Maximum minutely charging capacity (level).

3.3. Decision Variables

$x_{i,j}^{btr}$	Battery charging level of a UAV fly through the traverse arc $\left(i,j\right)\in A$;
$x_{i,j,k}^{uav}$	$= \begin{cases} 1, & \text{If a drone } k \text{ is assigned to the traverse arc;} \\ 0, & \text{Otherwise;} \end{cases}$
x_t^{mch}	Minutely charging rate on *t*;
x_t^{acc}	Minutely battery charged level on *t*;
x_j^{tot}	Arrival time of a UAV to a security check point j;
x_j^{dep}	Departure time of a UAV heading to a security check point *j*;
u_i	A flow in a UAV after it visits point *i*.

3.4. Objective Function

minimize

$$\sum_{t\in T} C^{mch} x_t^{mch} + \sum_{k\in K} C_k^{uav} x_{i,j,k}^{uav} \tag{1}$$

subject to

$$x_{i,j,k}^{uav} \le \sum_{l\in V} x_{j,l,k}^{uav} \le \left|V\right| - \left(\left|V\right|-1\right) x_{i,j,k}^{uav}, \qquad \forall\left(i,j\right)\in A, k\in K, \tag{2}$$

$$x_{i,j}^{uav} \le \sum_{k\in K} CG_k^{uav} x_{i,j,k}^{uav}, \qquad \forall\left(i,j\right)\in A, \tag{3}$$

$$\sum_{(i,j)\in A} x_{i,j,k}^{uav} \le \left|K\right|, \qquad \forall k\in K, \tag{4}$$

$$\sum_{j\in V}\sum_{k\in K} x^{uav}_{i_0,j,k} = \sum_{i\in V}\sum_{k\in K} x^{uav}_{i,i_0,k}, \qquad \forall i_0 \in V, \qquad (5)$$

$$\sum_{j\in V}\sum_{k\in K} x^{uav}_{i,j,k} \le 1, \qquad \forall i \in V \setminus \{i_0\}, \qquad (6)$$

$$\sum_{i\in V}\sum_{k\in K} x^{uav}_{i,j,k} \le 1, \qquad \forall j \in V \setminus \{i_0\}, \qquad (7)$$

$$u_i - u_j + \gamma \sum_{k\in K} x^{uav}_{i,j,k} \le \gamma - 1, \qquad \forall (i,j) \in A, \qquad (8)$$

$$\sum_{i\in V} x^{btr}_{i,j} - \sum_{t\in T}(D_j + \sum_{k\in K}\sum_{i\in V} TR_{i,j} x^{uav}_{i,j,k}), = \sum_{l\in V} x^{btr}_{j,l}, \qquad \forall j \in V \setminus \{i_0\}, \qquad (9)$$

$$x^{btr}_{j,i_0} = 0, \qquad \forall j \in V \setminus \{i_0\}, \qquad (10)$$

$$x^{tot}_j \ge x^{tot}_i + TR_{i,j} - M\left(1 - x^{uav}_{i,j,k}\right), \qquad \forall (i,j) \in A, k \in K, \qquad (11)$$

$$x^{dep}_j \ge x^{tot}_i + TR_{i,j} - M\left(1 - x^{uav}_{i,i_0,k}\right), \qquad \forall (i,j) \in A, k \in K, \qquad (12)$$

$$x^{tot}_j \le TM^{tot}_j + \beta, \qquad \forall j \in V, \qquad (13)$$

$$x^{mch}_t - x^{acc}_t + x^{acc}_{t-1} = \sum_{j\in V} D_j, \qquad \forall t \in T, \qquad (14)$$

$$x^{acc}_t \le \bar{\rho}, \qquad \forall t \in T, \qquad (15)$$

$$x^{mch}_t \le \bar{\psi}, \qquad \forall t \in T. \qquad (16)$$

The objective function in (1) minimizes overall operating cost for UAV operations in an hour. The first term is battery charging cost and the second one is a fixed cost for a single UAV assignment to a path. Constraint (2) controls the flow of an assigned UAV following a path to make a complete tour without being substituted by other type of UAVs. Constraint (3) aims to exclude any infeasible routing options which exceed UAV's maximum operating capacity. Constraint (4) counts the number of operating UAVs should be less than or equal to the number available in a fleet. Constraint (5), (6) and (7) denotes flow conservation conditions that all incoming and outgoing UAVs from an origin or every security check point must be the same number. Constraint (8) is Miller-Tucker-Zemlin (MTZ) sub-tour elimination constraint which filters any possible sub-tours in a path. Constraints (9) measures battery discharge time considering a route maneuver time and surveillance time at a security check point. The calculated discharge time may reflect to the next routing decisions. Constraints (10) set a condition that a battery life is zero when a UAV returns to an origin. Constraints (11) and (12) counts departure and arrival time of a UAV at each location through a path within a designated time window expressed in constraint (13). Battery charging schedule is determined in constraint (14) subject to the maximum battery charging limit in constraint (15) and minutely battery charging rate in constraint (16).

4. Computational results

For computational experiments, we set relative termination tolerance as 3% and time limit as 3 hours running on CPLEX 12.6. All following experiments were conducted on a 3.00 GHz Intel Xeon machine with 400 GB of memory. Based on the settings, we solved a small scale security UAV operations model within 60 minutes of time horizon.

As seen in Fig. 1 (a), LNG facilities are composed of three LNG trains, five storage tanks, two offshore facilities, two berths, a mooring area and an operating center. In accordance with a threat and risk assessment, we designated 18 security check points which require hourly surveillance. A UAV can inspect each facility during a given flying time. For the experiment, we consider that a fleet is composed of 15 heterogeneous UAVs. Every UAV has different maximum operating capabilities. For experiments, we made a coordinated LNG facilities map in Fig.1. (b).

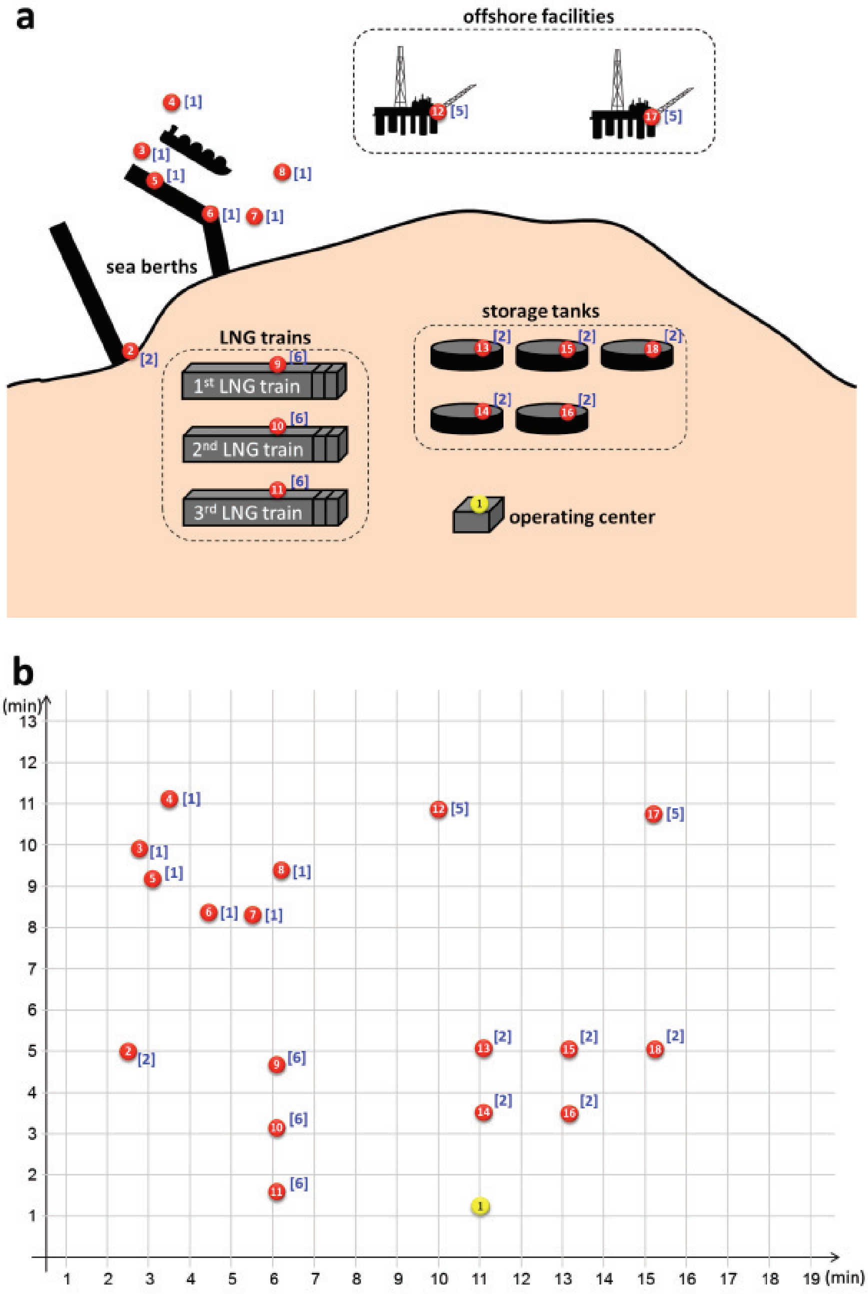

Fig. 1. (a) LNG facilities map with security vulnerable points; (b) coordinated LNG facilities map.

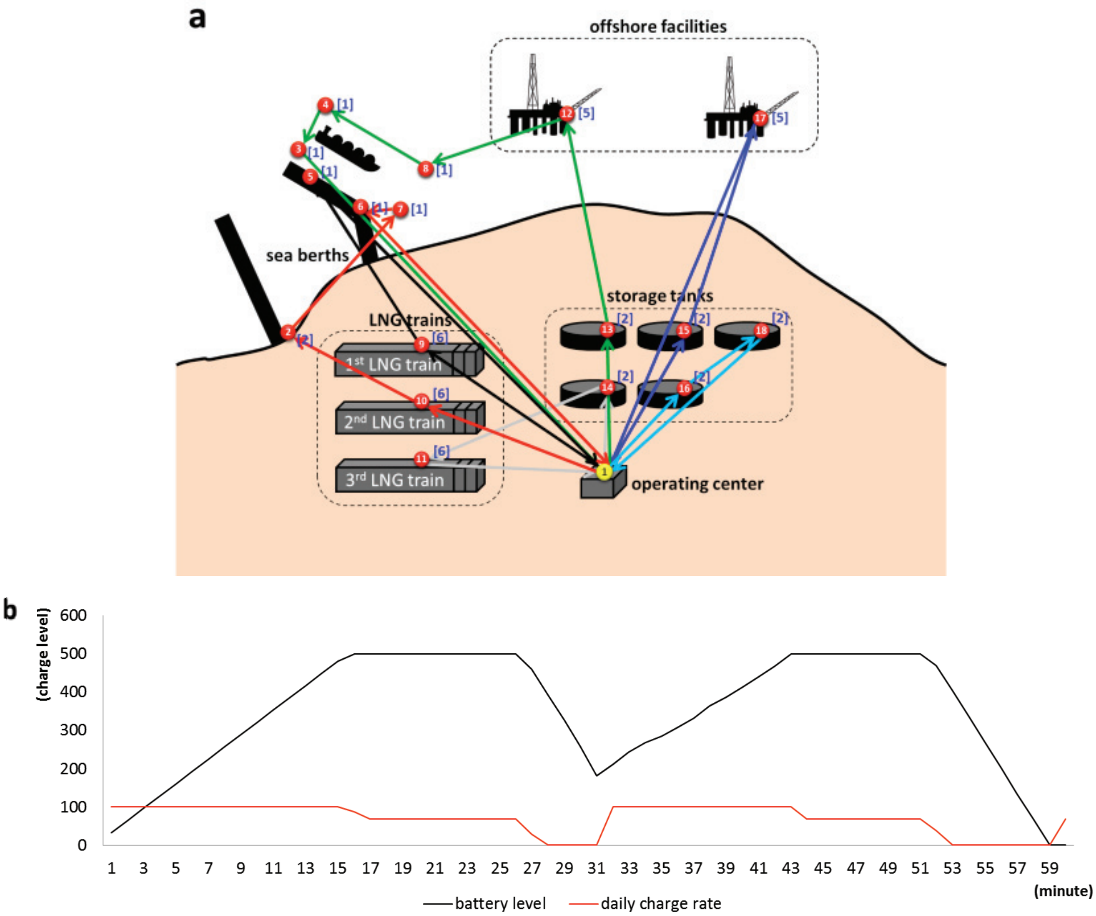

Fig. 2. (a) optimal UAV surveillance routes and paths; (b) battery charging schedule.

There are two sets of solutions in this model. As seen in Fig. 2. (a), optimal UAV surveillance paths are generated to cover all given security check points by using multiple heterogeneous UAVs. In the second solution set in Fig. 2. (b), we can see a minutely battery charging schedule within 60 minutes of time horizon. Both solutions sets are generated while minimizing hourly operating cost of multiple drones.

5. Summary and conclusions

In this paper, we proposed a paths generation model for multiple UAVs considering battery charging conditions. The model minimizes the hourly cost for multiple UAV operations. The numerical experiment verified that the model can monitor all vulnerable security check points with a minimum number of UAVs within a given time horizon. Additionally, this model also generates a battery charging schedule while minimizing electricity costs.

As this optimization model is an early stage of research on security UAV utilization into the oil and gas industry, it can extend in various ways to reflect many practical real world situations.

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