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Drone-Aided Border Surveillance with an Electrification Line Battery Charging System

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Abstract
This paper proposes to develop a drone-aided border surveillance system with electrification line battery charging systems (DABS-E). Currently, mobile and fixed border surveillance systems such as truck-mounted video recording units, agent portable surveillance units, aerostats, and fixed towers are often used to enhance the comprehensive situational awareness along the U.S. border lines. However, a few drawbacks of the existing systems include limited operating capability, blind spots, physical fatigue of field agents, and lack of fast-responding situational awareness capability. The use of drones and mobile technologies are an ideal way to overcome these issues in border patrol activities. Even though drones bring numerous technical advantages (i.e., short response time, being able to access dangerous areas, and no on-board pilot required) for the border patrol mission, a relatively short flight duration is the main concern for the full implementation for patrol at this time. Therefore, this paper proposes a new concept that is built on electrification line (*E*-line) systems to wirelessly charge drones during the flight to extend flight duration. As a result, extra power can be provided for drones without the need of landing, stopping or returning back to ground control centers. To accomplish our goal, this paper proposes an optimization model and algorithm to schedule drone flights for a DABS-E. Through a numerical example, this paper shows the feasibility of our proposed method and corresponding economic benefits.

Keywords Border patrol · Drone · Wireless power transfer · Remote surveillance system · Battery charging

1 Introduction

Four U.S. states share borders with Mexico, and the U.S.-Canada border is the longest international border in the world between two countries [1]. The border region serves as a conduit and source of commerce, tourism, and other forms of trade. The U.S. Customs and Border Protection (CBP) plays an important part in securing and protecting the United States. However, it is impossible for CBP to detect, secure, monitor, and patrol tens of thousands of miles of land borders and shorelines by law enforcement agents, due to harsh environments along the border areas coupled with insufficient budgets [2, 3]. According to released data, about 56% of the southern border of the U.S. is controlled and monitored by agents and/or surveillance technologies [4]. Some border areas have tough terrain and environmental factors, which may not allow easy access for patrol agents. This necessitates the need for remote surveillance systems to minimize blind spots and secure the safety of the field agents.

Recently, the U.S. Department of Homeland Security (DHS) has tried to deploy drones for border patrol operations [5, 6]. Small-sized drones (also known as unmanned aerial vehicles: UAVs) have emerged as an ideal alternative remote sensor for stationary surveillance systems or field agents. They have attractive features such as quick response time, no need for pilots on board, and the capability to access dangerous sites/areas, to name a few. Even though drones have many advantages as mentioned above, short flight duration is one of major concerns to overcome, and it requires a high precision service schedule to determine the number of drones to operate, their flight paths, operating costs, and the number of crew members [7–9]. Some attempts were made to cope with the relatively short flight duration of drones such as stationary pole

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type charging and fuel cells [10, 11]. However, significant limitations still remain, such as needing to land/stop on stationary poles and the flight back to control centers to exchange fuel cells. These limitations make it difficult to carry out incessant surveillance missions and also reduce real-time situational awareness.

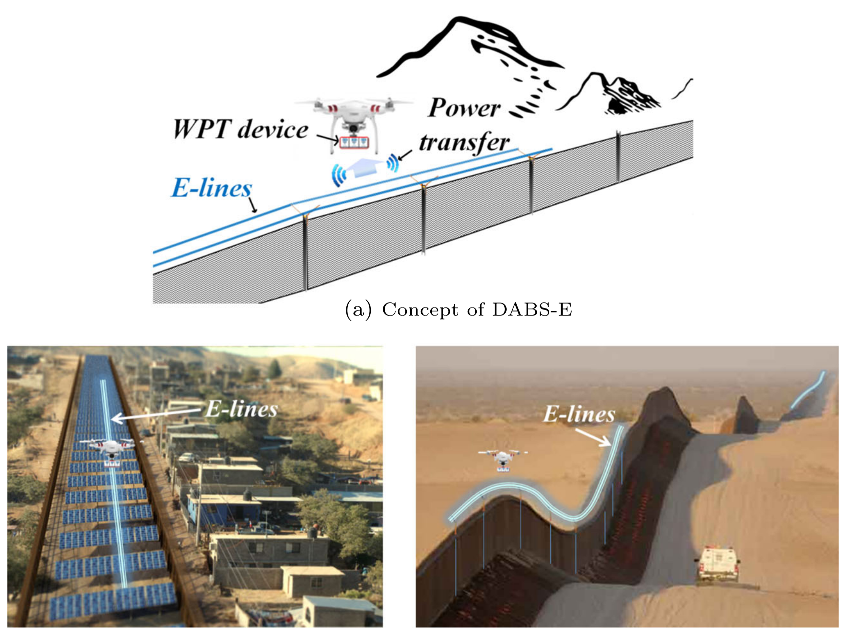
To overcome the short flight duration issue, we propose to develop a drone-aided border surveillance system with electrification line battery charging systems (DABS-E). The electrification lines consist of multiple coiled lines, which transmit power to batteries on drones wirelessly by electromagnetic methods (called wireless power transfer (WPT) [12]) installed on border walls (Fig. 1a).

Thus, extended flight duration of drones will help achieve a real-time and continuous surveillance and enhance situational awareness in routine and emergency events. Furthermore, successful outcomes of this proposed research will lead to an enhanced ability to secure and facilitate transnational flows, increase safety of ground patrol teams, and prevent unauthorized transnational flows in real-time. For vulnerable and/or isolated (uncontrolled and unmonitored by agents and/or surveillance technologies) areas, DABS-E can be alternative to patrol those areas and help enhance situational awareness in surveillance missions by reducing blind spots and extending the remote surveillance system's operating time (Fig. 1b). By utilizing the drones, it is possible to cultivate surveillance and reconnaissance capabilities in these vulnerable areas, and by utilizing the *E*-line systems, the operating duration of the drones can be prolonged to perform seamless surveillance missions.

The primary goal of this paper is to propose DABS-E to enhance the capability of border patrol mission in real time. Since there have been no studies of the DABS-E so far, this work focuses on the development of the DABS-E deploying method and optimal scheduling method. To accomplish the goal of this work, first, an algorithm is developed to provide a procedure describing how to deploy our proposed concept DABS-E in reality. Then, a new mathematical model for DABS-E is developed to help decide where the *E*-line systems are installed and how many drones are needed. In this model, we seek to find the optimal use of resources (drones and *E*-line systems) in DABS-E for seamless surveillance missions. As the resulting model is expected to be highly complex and nonlinear, a computationally efficient method is developed to obtain near optimal solutions with less burden on solving the mathematical model. By conducting cost analysis with different unit lengths of the *E*-line systems, we will show the feasibility of DABS-E with minimum cost.

This work contributes to the existing body of literature as follows:

- To propose a new method to recharge drone batteries using *E*-line systems for extending flight duration of drones during border surveillance missions (DABS-E). The proposed method is to charge a drone battery without the need of stopping. In turn, this DABS-E may enhance the ability to secure and facilitate a seamless situational awareness of border agents.
- To develop a mathematical formulation model to describe the DABS-E. The model is to obtain the optimal locations of *E*-line systems and the optimal number of required drones for border line surveillance missions.



(a) Concept of DABS-E

(b) Future of border patrols [13, 14]

Fig. 1 *E*-line systems on border walls

– To propose a solution approach for real-time decision making. The solution approach is to reduce computational effort to provide decision makers with the optimal surveillance flight paths of drones under *E*-line systems.

The rest of this paper is organized as follows. A review of literature relevant to this problem is presented in Section 2. Section 3 describes the problem in detail and presents a procedure to solve the problem. A mathematical optimization model to illustrate DABS-E is described in Section 4, in which a solution approach is also proposed to improve the computational performance of our proposed DABS-E mathematical model. In Section 5, a case study is used to illustrate the feasibility of the proposed model in practice, and an analysis of the results of the case study is described. Finally, Section 6 concludes with a discussion of the contribution and the potential extension of this work.

2 Literature Review

As the technology advances and the size of economic trades increases, the role of the U.S. Border Patrol is being highlighted to secure our nation's border regions. Combining with (or instead of) in-person patrol, the remote systems are used along the border lines to enhance situational awareness [2, 3]. The illegal and unauthorized flows of people and goods over the border lines frequently occur where the agency cannot easily access, monitor, and chase without remote border surveillance systems (BSS) due to harsh environments.

Under those circumstances, the quick and sustainable situational awareness ability of the border agency is vital to successfully carrying out their patrol mission. In many cases, the agency's ability is significantly enhanced using the BSS, which primarily depends on the use of modern technologies. There are two types of the BSS: 1) fixed BSS such as fixed towers, aerostats and remote surveillance video cameras, and 2) mobile BSS such as truck-mounted video units, aircraft and agent portable surveillance units [15]. With these enhanced surveillance assets, the situational awareness ability can be enhanced remotely.

However, there are several challenges in using the current BSS. The major challenge of the remote BSS is to secure a reliable power source [16]. The fixed systems usually collect data and monitor from dedicated locations. If the installed location does not provide an electrical power source for the system, it creates a black hole in border surveillance. This problem necessitates the need for alternative power sources to extend the continuous operation of the remote BSS.

Another challenge is the lower mobility of the remote BSS. The existing mobile BSS has a significant level of mobility compared with the fixed (stationary) BSS; specially since the unmanned aircraft systems (UAS) have made significant contributions to fill gaps in border surveillance systems [2, 3]. However, it is desirable to utilize small UAS to achieve a quicker response time, reduced landing areas, and decreased noise [6].

Flight time and duration of UAS is a big concern for them to be practical in border surveillance [17]. Some studies have shown how to extend the UAS's flight duration with solar power, fuel cells, and stationary wireless charging poles [18–23]. Solar power can be stored and converted into electrical power by solar panels attached to the top of UAS wings, but it cannot provide a reliable power that is sufficient to operate UAS. The solar power may not be a stable source because it is affected by time of the day, locations and weather conditions. Fuel cells can provide longer flight duration compared with generic batteries, but they have a low power density [24]. The weight of fuel cells could also be a crucial issue for small UAS, as a heavier battery consumes more energy. A stationary wireless charging pole is a method of WPT, but this method requires landing/stopping of UAS on the stationary pole. These methods do not provide the real-time and continuous mobile surveillance capability of UAS for the border patrol missions.

A dynamic battery charging method has been studied for electric ground vehicles (EVs) using WPT [25–28]. By driving on the electrified roadway (charging lanes on roadway: E-lane), the EV can recharge its batteries and extends its driving range. The dynamic method is to eliminate the need to stop EVs to charge batteries. The batteries of EV are wirelessly charged while driving at a relatively slower speed than the normal driving speed. Some other attempts of using a dynamic battery charging method can be found in [26, 29].

3 Problem Description

This work proposes DABS-E to enhance the ability to secure and improve the situational awareness of border agents. The *E*-line systems, which provide additional power sources in a way that WPT, is a new method to extend the flight duration of drones as a remote surveillance system for border line patrols.

The purpose of this work is to develop a model to determine optimal locations to install *E*-line systems and drone surveillance schedules. The objective of this model is to find the minimum overall cost including drone operating cost and *E*-line systems installation and operating costs. *E*-line systems installation costs occur once, and the other costs incur whenever drones and *E*-lines are utilized. This model focuses on the regular surveillance flight mission of drones over the vulnerable area, in which the drone takes off from a control center (depot) and returns to the initial launch control center (initial depot) after finishing a surveillance mission. The drone can directly fly to a waypoint from a control center or return to the initial launch control center from a waypoint taking into account flight environments. The surveillance mission of a drone is to visit a part or the entire distance of a border line. Once the drone returns to the control center, they are re-utilized to conduct the following surveillance mission over the same area after replacing their batteries.

We propose the mathematical model for DABS-E by making the following assumptions using rotor wing drones that are equipped with WPT devices.

- The efficiency of WPT is expressed as a constant value regardless of drone type. In this study, we assume that all drones are equipped with a same performance WPT device. The device charges the drone battery with the same efficiency. If a drone flies over *E*-line systems, the drone, regardless of type, gets an additional flight duration.
- The *E*-line systems are only installed on border walls and designed as shown in Fig. 2. Using a renewable source of energy, batteries connected along *E*-lines will be charged to produce and store electricity, which will be wirelessly transferred to a drone's battery through *E*-lines' inverter device, coiled lines, and drone's rectifier device consecutively. The proposed WPT method shown in Fig. 2 is possible considering current developed dynamic WPT technologies [25].
- The remaining battery duration of a drone does not exceed the battery capacity. If the capacity of a battery is 35 min, the remaining duration of the battery, after recharged by *E*-line systems, is up to 35 min. Even though a drone with a battery duration of 34 min flies over *E*-line systems, the remaining duration of the battery is up to 35 min after finishing wireless charging.

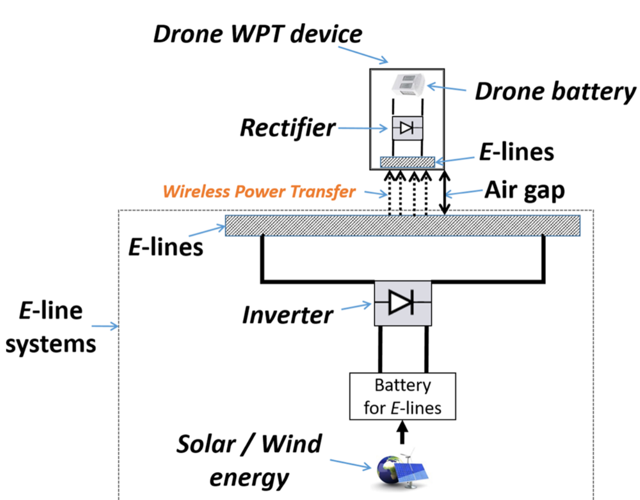


Fig. 2 Design of *E*-line systems

- The air gap, which is a distance between the WPT device of a drone and *E*-line systems installed on border lines as shown in Fig. 2, is kept constant during flights over *E*-line systems.
- The WPT process is not affected by environmental factors such as rain, snow, or wind.
- The flight speed of the drones, regardless of type, is constant for all surveillance flights.

This paper follows Algorithm 1 to solve the problem.

Algorithm 1 Procedure

Inputs:

Surveillance mission information: locations, patrol period
Flight environments: no flying zones, obstacles, border line shapes
Drone information: initial flight duration at launching point (depot), operating cost,
E-lines information: unit length (l), installment cost (per unit length), operating cost.

Step 1 - Constructing flight network

Section the whole border line (D) by the unit length (l) of *E*-line systems:
$\lceil \frac{D}{l} \rceil = n$ (i.e., n flight segments)
Construct a flight segment table (See Table 1) to configure the maximum number of flight between waypoints

Step 2 - Defining a flight times table and a charging efficiency table of *E*-lines

Flight time table: on a flight segment
Charging efficiency table: when *E*-lines are installed on a flight segment

Step 3 - Solving problem

Develop a mathematical optimization model to illustrate the DABS-E
Run the model to get the optimal value and solution of the problem
Analyze results and conduct sensitivity analysis

Algorithm 1 consists of three steps. Step 1 is to construct a flight network including flight waypoints and flight configuration, which is to define the flight possibility between two waypoints based on flight environments and surveillance mission. The flight network is constructed based on initial input data including center location, patrol locations, drone specifications, and *E*-line specifications. The whole border line needing drone-aided surveillance is divided into waypoints by an unit length (km or $mile$) of *E*-line systems. There is a minimum length of dynamic WPT systems to get an efficient power transfer [27]. If the whole length of a border line is D and the unit installation length of *E*-line systems is l, then we can get

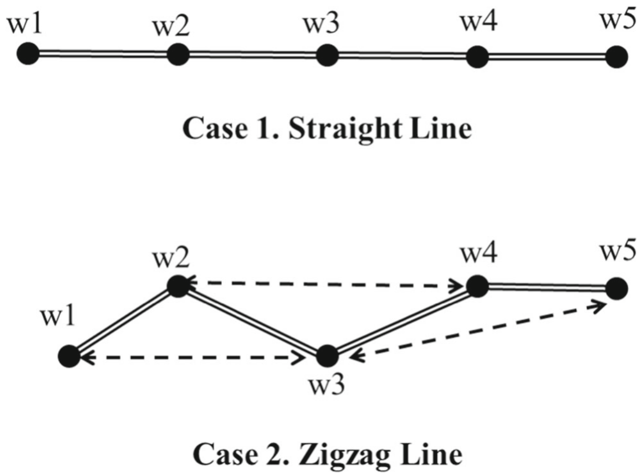


Fig. 3 Different cases of border line shapes

the number of flight segments (n) and waypoints ($n+1$) by $\lceil \frac{D}{l} \rceil = n$. Next, a flight configuration table is made with these waypoints. The table includes the number of possible flights for each segment, in which the number is determined by surrounding harsh flight environments (such as prohibited flying zones and border line shapes) and surveillance mission. For example, if the shape of a border line is a zigzag type (Case 2 as shown in Fig. 3), then there are three additional possible flight segments (i.e., $w1-w3$, $w2-w4$ and $w3-w5$) compared with Case 1 in Fig. 3. The corresponding configuration to each case is shown in Table 1. If some segments need to be visited more than once due to geographical vulnerability, this can be reflected in Table 1. Moreover, using the flight network, we can define the availability of segment between i and j for E-line installation considering the surveillance mission and the surrounding environments. For example, a particular area such as lakes, rivers, or basin may have geographical features that make it impossible to install the system [30].

Step 2 is to define parameter values including flight times between waypoints and the charging efficiency of WPT. In this study, we consider asymmetric flight times between waypoints i and j, in which the flight time from waypoint i to waypoint j may not be same as the flight time from waypoint j to waypoint i, due to real flight conditions such as weather interference. The efficiency of WPT is referred from ground electric vehicles data under dynamic WPT methods, because there is no data related to our proposed concept (Fig. 2).

Table 1 Flight configuration for Case 1 in Fig. 3

Waypoint	w1	w2	w3	w4	w5
w1	0	1	0 (1)	0	0
w2	1	0	1	0 (1)	0
w3	0 (1)	1	0	1	0 (1)
w4	0	0 (1)	1	0	1
w5	0	0	0 (1)	1	0

( ): for Case 2

Lastly, Step 3 is to solve the problem with a DABS-E mathematical optimization model. The details of the DABS-E mathematical model are described in Section 4.1. In Step 3, we get the optimal locations to install E-line systems and surveillance flight schedules of drones. In addition, a sensitivity analysis is conducted to show how different values of l (i.e., unit length of E-line systems installation) impact the optimal values (the overall cost of DABS-E).

4 Formulation and Solution Approach

This section includes the DABS-E mathematical model and a solution approach. Based on the problem description (Section 3), we propose a mathematical optimization model for the DABS-E in Section 4.1. This proposed model includes non-linearities in constraints, which usually cause the difficulties in solving the problem [31]. Hence, we propose a solution approach to linearize the non-linearities in Section 4.2.

4.1 Formulation

The following notation is introduced to be used in the DABS-E mathematical optimization formulation.

Indices

- I Set of waypoints ($i, j, u \in I$)
- K Set of drones ($k \in K$)
- R Set of centers (depots) ($r \in R$): $R \cap I = \emptyset$

Parameters

- m The number of flights for border patrol mission per given period
- M Sufficiently large number estimated from other parameter values
- B_k Maximum flight duration (battery capacity) of drone k
- P_k Operating cost of drone k
- E_{ij} Availability of segment between i and j for E-line installation
- EO_{ij} Operating cost of E-lines between i and j
- EI_{ij} Installment cost of E-lines between i and j
- FT_{ij} Flight time for flight segment ($i \rightarrow j$)
- CF_{ijk} Charging flight duration when drone k flies over E-line installed between i and j
- FD_{ij} The number of possible flights between waypoints i and j ($= FD_{ji}$)

Decision Variables

Our aim is to determine where E-line systems are installed, and which drone should be assigned for surveillance flights while minimizing the overall cost of DABS-E. Accordingly, we define decision variables as:

[Binary variables]

x_{ijk} 1 if drone k flies from waypoint i to j (i.e., segment ($i \rightarrow j$)), 0 otherwise

h_{ij} 1 if E-lines are installed between i and j, 0 otherwise

g_k 1 if drone k is utilized to fly, 0 otherwise

[Integer variables]

rf_{ik} Remaining flight duration when drone k arrives at waypoint i

μ_i The order of sequence of visiting waypoint i in a flight path

The mathematical optimization model of DABS-E is expressed below:

$$\text{Minimize} \quad z = m \times \sum_{k \in K} P_k \times g_k + \sum_{i \in I \cup R} \sum_{j \in I \cup R} \times (EI_{ij} + m \times EO_{ij}) \times h_{ij} \tag{1}$$

$$\text{Subject to:} \quad \sum_{i \in (I \cup R)} \sum_{k \in K} x_{ijk} \geq 1, \qquad \forall j \in I \tag{2}$$

$$\sum_{j \in (I \cup R)} \sum_{k \in K} x_{ijk} \geq 1, \qquad \forall i \in I \tag{3}$$

$$x_{iik} = 0, \qquad \forall i \in (I \cup R), k \in K \tag{4}$$

$$\sum_{i \in I \cup R} x_{iuk} - \sum_{j \in I \cup R} x_{ujk} = 0, \qquad \forall u \in I, k \in K \tag{5}$$

$$\sum_{j \in I} x_{rjk} - \sum_{i \in I} x_{irk} = 0, \qquad \forall r \in R, k \in K \tag{6}$$

$$\sum_{r \in R} \sum_{j \in I} x_{rjk} = g_k, \qquad \forall k \in K \tag{7}$$

$$\sum_{i \in I} \sum_{r \in R} x_{irk} = g_k, \qquad \forall k \in K \tag{8}$$

$$\sum_{k \in K} x_{rjk} \leq FD_{rj}, \qquad \forall r \in R, j \in I \tag{9}$$

$$\sum_{k \in K} x_{irk} \leq FD_{ir}, \qquad \forall i \in I, r \in R \tag{10}$$

$$\sum_{k \in K} x_{ijk} + x_{jik} = FD_{ij}, \qquad \forall i, j \in I \tag{11}$$

$$h_{ij} \leq \sum_{k \in K} x_{ijk} + x_{jik}, \qquad \forall i, j \in I \cup R \tag{12}$$

$$h_{ij} \leq E_{ij}, \qquad \forall i, j \in I \cup R \tag{13}$$

$$rf_{ik} \leq B_k \times g_k, \qquad \forall i \in I, k \in K \tag{14}$$

$$\sum_{i \in I \cup R} \sum_{j \in I \cup R} (FT_{ij} - CF_{ijk} \times h_{ij}) \times x_{ijk} \leq B_k, \qquad \forall k \in K \tag{15}$$

$$B_k - (FT_{rj} - CF_{rjk} \times h_{rj}) \times x_{rjk} - M \times (1 - x_{rjk}) \leq rf_{jk}, \qquad \forall r \in R, j \in I, k \in K \tag{16}$$

$$rf_{jk} \leq B_k - (FT_{rj} - CF_{rjk} \times h_{rj}) \times x_{rjk} + M \times (1 - x_{rjk}), \qquad \forall r \in R, j \in I, k \in K \tag{17}$$

$$B_k - (FT_{ij} - CF_{ijk} \times h_{ij}) \times x_{ijk} - M \times (1 - x_{ijk}) \leq rf_{jk}, \qquad \forall i, j \in I, k \in K \tag{18}$$

$$rf_{jk} \leq B_k - (FT_{ij} - CF_{ijk} \times h_{ij}) \times x_{ijk} + M \times (1 - x_{ijk}), \qquad \forall i, j \in I, k \in K \tag{19}$$

$$\mu_i - \mu_j + n \times x_{ijk} \leq n - 1, \qquad \forall i, j \in I, k \in K \tag{20}$$

$$x_{ijk}, h_{ij}, g_k \in \{0, 1\}, \mu_i \geq 0, n = |I|.$$

The objective function (1) is to minimize the overall operating cost of DABS-E during a patrol period, which includes the total drone operating cost ($m \times \sum_{k \in K} P_k \times g_k$) and the total E-line systems installation and operating costs ($\sum_{i \in I \cup R} \sum_{j \in I \cup R} (EI_{ij} + m \times EO_{ij}) \times h_{ij}$). Constraints (2) and (3) ensure that each waypoint is visited at least once by drones. If more than one drone is needed for a surveillance mission, the drones overlap at some waypoints to visit each segment. Constraint (4) is to prevent a drone from revisiting the same waypoint. Constraint (5) is to conserve the flight flow of a drone at intermediate waypoints, and Constraint (6) is to guarantee a drone return to the initial launch control center (initial depot). Constraints (7) and (8) are to define which drone is utilized. As described in Section 3, the flight configuration between waypoints is described by constraints (9)–(11). Constraints (9) and (10) are to define the flight configuration between a depot and a waypoint (i.e., the number of possible flights between r and i). The two inequalities allow drones to directly fly to a waypoint from a depot or directly return to a depot from a waypoint depending on the values of FD_{ir}. Constraint (11) ensures how many times a segment ($i \rightarrow j$ or $j \rightarrow i$) on a border line should be visited by drones during a patrol mission. Some areas may need to be visited more often or be prohibited from flying drones compared to other areas by the surrounding flight environments. Constraints (12) and (13) are to define the installation of E-line systems on a segment ($i \rightarrow j$ or $j \rightarrow i$) of the border line. Regardless of the flight direction of drones, the E-line systems are installed only once on some of the border line (Constraint (12)), and the availability of the E-line systems installation (E_{ij}) is defined by considering the surveillance mission and surrounding border environments as described in Section 3 (Constraint (13)). Constraint (14) describes the aforementioned assumption on the recharging process, in which the remaining duration of a drone after being recharged (rf_{ik}) cannot exceed the maximum capacity of a battery. As a specification of a drone, Constraint (15) considers the maximum flight duration of the drone in a flight path, and constraints (16)–(19) describe varying remaining battery duration of the drone at each waypoint. If a drone flies over the segment where the E-line systems are installed ($h_{ij} = 1$), then the charging performance of the systems for the drone (CF_{ijk}) should be considered when calculating the remaining battery duration. Constraints (16) and (17) are set for visiting an initial waypoint from a depot while constraints (18) and (19) are for visiting the next intermediate waypoints. The parameter M in constraints (16)–(19) is to ensure equality only when a drone flies over a segment (a depot to a waypoint or a waypoint to another waypoint, i.e., $x_{rjk} = 1$ or $x_{ijk} = 1$). If there is no flight over a segment, then we let rf_{ik} open. By ensuring the equality, we can get the remaining flight duration at each waypoint (rf_{ik}). The value of parameter M is estimated from other parameter values. Constraint (20) prevents the solution from containing sub-tours (disconnected from depot r) [32, 33].

4.2 Solution Approach

The DABS-E model is a mixed integer non-linear programming (MINLP) model , which can be difficult to solve and requires more computational efforts [34]. In constraints (15)–(19), two decision variables, h_{ij} and x_{ijk}, are formulated in non-linear formation ($h_{ij} \times x_{ijk}$) to describe whether E-line systems are installed on segment ($i \rightarrow j$) of drone k's flight path. Therefore, Proposition 1 is proposed to linearize the MINLP model of the DABS-E.

Proposition 1 [34] *Assuming α and β are binary variables, then $\alpha \times \beta$ can be linearized by introducing new binary variable γ that is equal to $\alpha \times \beta$. The following inequalities hold true:*

$$\alpha + \beta - 1 \leq \gamma \leq \beta, \tag{21}$$

$$0 \leq \gamma \leq \alpha. \tag{22}$$

Let us introduce a new binary variable ω_{ijk} ($= h_{ij} \times x_{ijk}$ for each $i, j \in I \cup R$ and $k \in K$). By using Proposition 1, constraints (15)–(19) can be replaced by following linearized constraints:

$$x_{ijk} + h_{ij} - 1 \leq \omega_{ijk} \leq h_{ij}, \qquad \forall i, j \in I \cup R, k \in K \tag{23}$$

$$0 \leq \omega_{ijk} \leq x_{ijk}, \qquad \forall i, j \in I \cup R, k \in K \tag{24}$$

$$\sum_{i \in I \cup R} \sum_{j \in I \cup R} (FT_{ij} \times x_{ijk} - CF_{ijk} \times \omega_{ijk}) \leq B_k, \qquad \forall k \in K \tag{25}$$

$$B_k - (FT_{rj} \times x_{rjk} - CF_{rjk} \times \omega_{rjk}) - M \times (1 - x_{rjk}) \leq rf_{jk}, \qquad \forall r \in R, j \in I, k \in K \tag{26}$$

$$rf_{jk} \leq B_k - (FT_{rj} \times x_{rjk} - CF_{rjk} \times \omega_{rjk}) + M \times (1 - x_{rjk}), \qquad \forall r \in R, j \in I, k \in K \tag{27}$$

$$B_k - (FT_{ij} \times x_{ijk} - CF_{ijk} \times \omega_{ijk}) - M \times (1 - x_{ijk}) \leq rf_{jk}, \qquad \forall i, j \in I, k \in K \tag{28}$$

$$rf_{jk} \leq B_k - (FT_{ij} \times x_{ijk} - CF_{ijk} \times \omega_{ijk}) + M \times (1 - x_{ijk}). \qquad \forall i, j \in I, k \in K \tag{29}$$

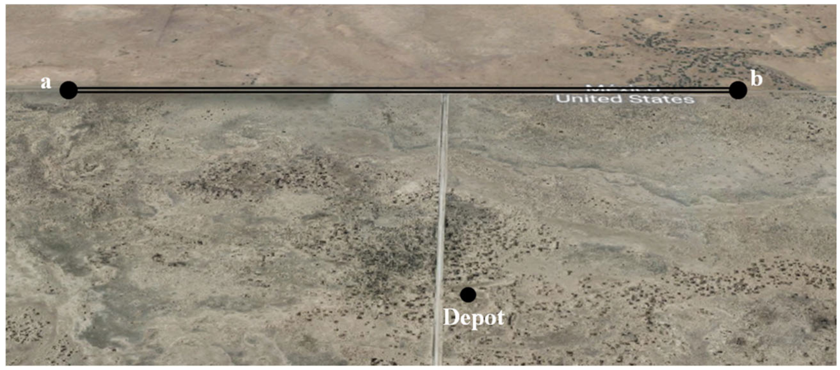


Fig. 4 A numerical example: U.S.- Mexico border patrols

5 Numerical Experiments

This section consists of four parts. In the first part, we describe a case study and how the steps 1 and 2 in Algorithm 1 work on the case network. Then we test the proposed DABS-E model on the case network in the second part. The third part is to analyze how the unit length change of the *E*-line systems affect overall DABS-E operation. In the last part, computational performance of our proposed linearized model is discussed to show the efficiency for real-time decision making. All models are implemented in GAMS [35] and solved by CPLEX 12.6.2 [36], and all experiments are performed on a server running RedHat Linux 64-bit with an Intel Xeon processor and 16GB of RAM.

5.1 Case Study

As a sample network for the case study, a part of the U.S.—Mexico border line in Columbus, New Mexico, U.S. is selected as shown in Fig. 4. The length of the border line for our case study is 6 km (between a and b), and there is one depot as a control center (Depot).

By using the proposed procedure (Algorithm 1), first, we construct the flight network as shown in Fig. 5. Based on the minimum unit length of *E*-line systems installation, line a-b is divided into six segments, in which the minimum unit length is assumed as 1 km [25]. Consequently, seven waypoints are assigned as shown in Fig. 5 ($w1$-$w7$).

For the second step in Algorithm 1, we consider three types of drones as shown in Table 2. Each cost regarding to drone operating and *E*-line systems installation/operating are also shown in Table 2. We assume that the charging efficiency of the *E*-line systems is 5 min per km regardless of drone type (described in Section 3), the number of flights for surveillance missions per given period is 30 times ($m = 30$), and the *E*-line systems are installed within the border line (a-b).

Based on the shape of border line a-b in Fig. 5, we define the flight configuration for this case study as shown in Table 3. The shape is a straight line, in which we assume that each flight segment is covered only once by a drone (i.e., the value between two waypoints is 1). A drone can directly visit any waypoint and return to the initial depot from any waypoint (i.e., the value between the depot and a waypoint is 2).

5.2 Numerical Results

The DABS-E model is solved to identify the locations of *E*-line systems and the specific surveillance routes of drones. The results are shown in Table 4.

The resulting cost of our proposed DABS-E is \$5,190, in which only one Type II drone is needed to conduct the surveillance flight over border line a-b, and *E*-line systems are installed from waypoint 2 ($w2$) to waypoint 5 ($w5$) via waypoints 3 and 4. The total length of the *E*-line systems is 3 km. Compared to DABS without *E*-line

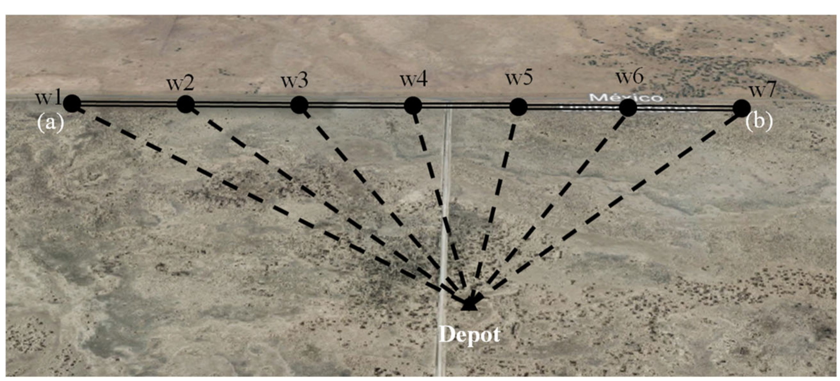


Fig. 5 Topology of the case study

Table 2 Parameters for case study

Parameter		Value	Unit
Drone	Flight duration (B)	Type I = 42	Minute
		Type II = 35	Minute
		Type III = 30	Minute
	Operating cost (P)	Type I = 80	U.S. Dollar ($)
		Type II = 70	U.S. Dollar ($)
		Type III = 40	U.S. Dollar ($)
E-lines	Installment cost (EI)	1,000	U.S. Dollar ($) per km
	Operating cost (EO)	1	U.S. Dollar ($)
	Charging efficiency (CF)	5	Minutes/km
No. of border patrol mission per given period (m)		30	

systems, the number of required drones for surveillance mission is reduced in the DABS-E (3 drones → 1 drone). In terms of the overall cost, the DABS-E ($5,190) incurs less overall cost than the DABS without E-line systems ($5,700). Although the overall cost of DABS without E-line systems only includes drone operating costs compared with the DABS-E, which includes two additional costs (installation and operating costs of E-line systems) as well as the total drone operating cost, it seems to be increasing as a proportion of the number of required drones in a sufficient number of flights. In this case study, the number of flights for a surveillance mission is considered as 30 ($m = 30$). As shown in Fig. 6, if the value of m is less than 26, the overall cost of the proposed DABS-E (the solid line in Fig. 6) is more than that of the DABS without E-line systems (the dashed line in Fig. 6).

Even though the total installation cost of E-line systems is very high, the cost occurs only once. The operating cost of drones, on the other hand, incurs whenever the drones are utilized. Therefore, the E-line systems contribute to decreasing in the number of required drones and thus reducing the overall operating cost in this case study with our parameter values in the sufficient flights per given period.

The specific flight paths under DABS without E-line systems and DABS-E are shown in Fig. 7a and b, respectively. Under DABS without E-line systems as shown in Fig. 7a, three drones (one from each type) are required to conduct the surveillance mission, where each drone visits three waypoints. The Type III drone with the shortest flight duration (30 min) covers three waypoints $w3$, $w4$, and $w5$, which are relatively close to the depot. Under DABS-E as shown in Fig. 7b, the whole border line from $w1$ to $w7$ is covered by only one Type II drone with flight duration 35 min.

As shown in Fig. 8, the remaining flight duration of the Type II drone decreases to 10 min until the drone arrives at $w2$ via $w1$. However, the duration increases when the drone flies the following waypoints $w2$, $w3$, $w4$, and $w5$, in which E-line systems are installed to recharge the drone battery through WPT. The drone accomplishes the surveillance mission by visiting the remaining waypoints ($w6$ and $w7$) with recharged battery power (updated remaining flight duration at $w5$: 25 min) in 65 min. The proposed E-line systems provide drones with extra power without the need of landing or stopping during flight.

5.3 Analysis on the Unit Length of *E*-line Systems

To show the sensitivity of the minimum unit length of E-line systems installation (l) to the objective function value (the overall cost of DABS-E), four different unit lengths are considered as input scenarios: 1 km, 0.75 km, 0.5 km, and 0.25 km. The WPT efficiency is assumed to be proportional to the unit length. Table 5 shows the results from four

Table 3 Flight configuration for the case study

	Depot	w1	w2	w3	w4	w5	w6	w7
Depot	0	2	2	2	2	2	2	2
w1	2	0	1	0	0	0	0	0
w2	2	1	0	1	0	0	0	0
w3	2	0	1	0	1	0	0	0
w4	2	0	0	1	0	1	0	0
w5	2	0	0	0	1	0	1	0
w6	2	0	0	0	0	1	0	1
w7	2	0	0	0	0	0	1	0

Table 4 Results from case study

	Overall cost ($)	Drone type	Optimal flight path
DABS-E	5,190	Type II	Depot $\rightarrow w1 \rightarrow w2 \rightarrow w3 \rightarrow w4 \rightarrow w5 \rightarrow w6 \rightarrow w7 \rightarrow$ Depot
			$*E$-line installation: $w2 \leftrightarrow w3 \leftrightarrow w4 \leftrightarrow w5$
DABS (without E-line)	5,700	Type I	Depot $\rightarrow w1 \rightarrow w2 \rightarrow w3 \rightarrow$ Depot
		Type II	Depot $\rightarrow w5 \rightarrow w6 \rightarrow w7 \rightarrow$ Depot
		Type III	Depot $\rightarrow w5 \rightarrow w4 \rightarrow w3 \rightarrow$ Depot

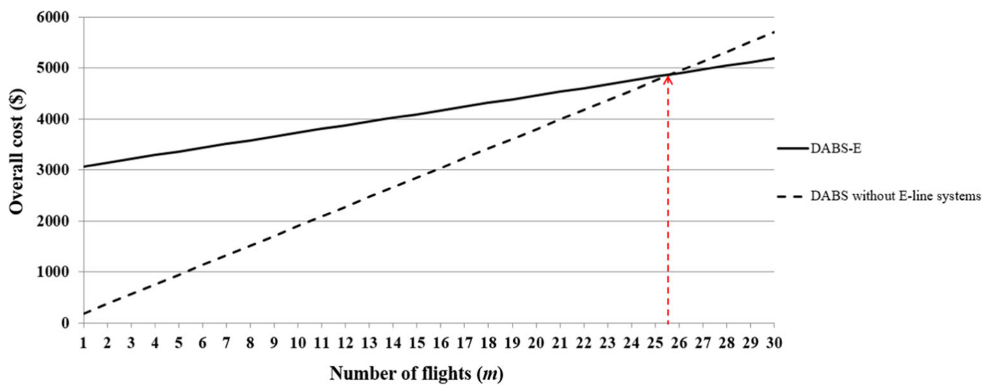


Fig. 6 Overall cost with varying the number of flights

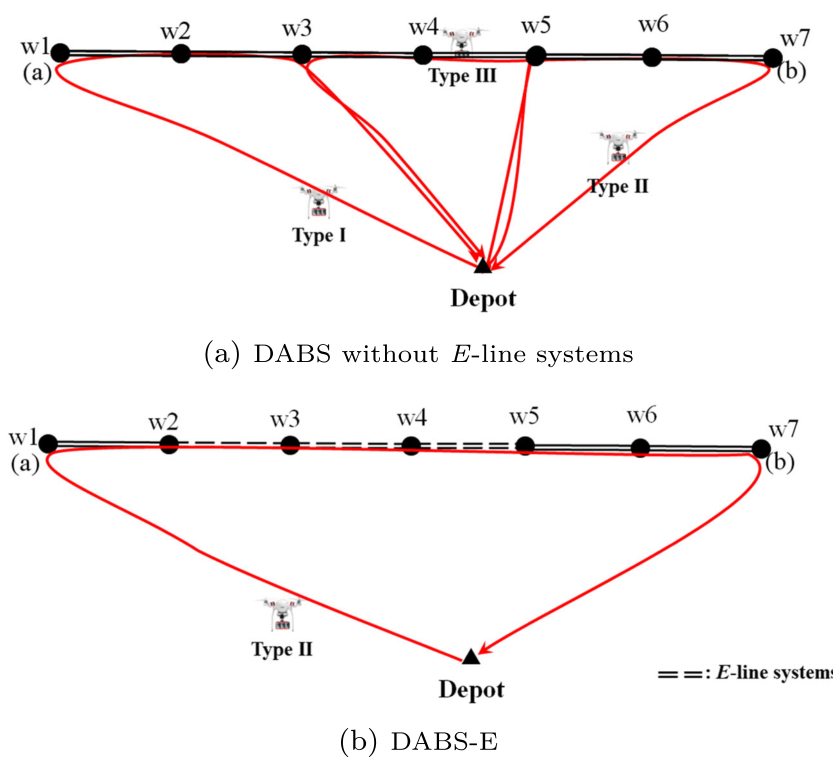


Fig. 7 Optimal flight paths under DABS and DABS-E

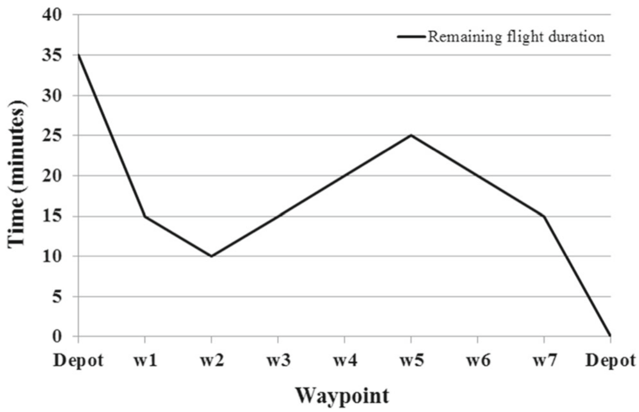


Fig. 8 Remaining flight duration at each waypoint under DABS-E

different scenarios. The initial value of the unit length is 1 km, in which the total cost is \$5,190. When the unit length is shortened by 25% (1 km → 0.75 km: Scenario #2), the corresponding cost is \$5,062.5, which decreases by 2.46% from the initial total cost (\$5,190) as shown in Table 5. In Scenario #3 (shortened the initial unit length by 50%), the corresponding cost to this scenario decreases by 14.07%. The last scenario ($l = 0.25$ km: Scenario #4) shows that the corresponding cost to this scenario decreases by 15.75%, while the unit length decreases by 75%. The overall cost in the last scenario does not decrease considerably despite the large reduction in the unit length. Although it is difficult to find the exact relation between the change of the detailed costs (drone operating, *E*-line installation, and *E*-line operating) and the change of the minimum unit length l, the overall cost for deploying the DABS-E tends to increase as the minimum unit length of *E*-line systems installation increases as shown in Fig. 9.

In Table 5, scenarios #1 and #2 show that one drone is needed for each, whereas scenarios #3 and #4 need two drones each. The specific flight paths of each scenario are shown in Fig. 10. As described in Section 3, the drones start the following surveillance flight schedule after returning to the Depot for preparation of the next schedule. Let us look at the interval in visiting time for a specific waypoint. In scenarios #1 and #2, the interval between the current visiting and the next visiting for a specific waypoint is 65 min, because each waypoint under these scenarios has to wait until the same drone that just passed comes back, after visiting the whole border line as shown in Fig. 10a and b. The interval time under scenarios #3 and #4, however, is between 34.5 and 44.5 min. The waypoints 1 through 7 in Scenario #3 (waypoints 1 through 14 in Scenario #4) have to wait for the Type III drone (Type I drone in Scenario #4), in which the interval time is 44.5 min. It takes 44.5 min to patrol 3.5 km on the left side of the whole border line as shown in Fig. 10c and d. The remaining waypoints (the right side of the border line), meanwhile, have to wait for the Type III drone with 34.5 min. The above interval times do not include a time spending on preparing the next flight at the Depot. The interval time describes the uncovered and/or uncontrolled time over waypoints if border agents repeatedly conduct the border surveillance mission only with the given drone(s) without any additional drones. Hence, Scenario #4 could be the best scenario achieving the minimum uncontrolled time over the border line and the minimum overall cost of DABS-E.

5.4 Computational Performance

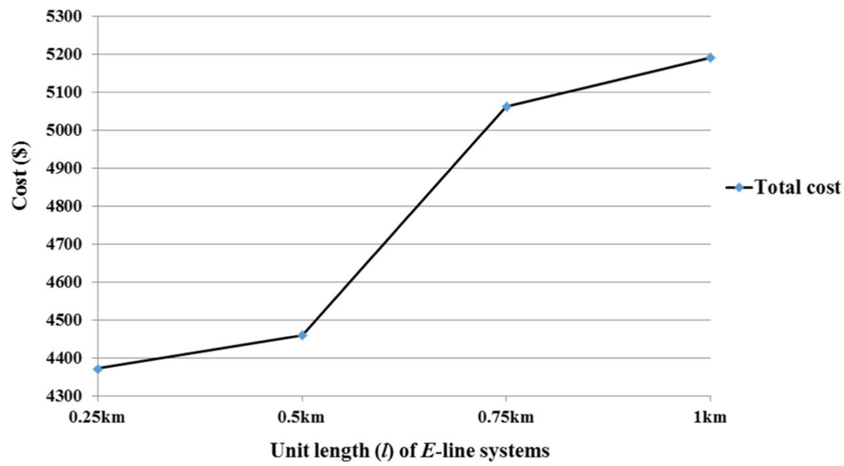
This section presents the computational performance of the proposed solution approach. For the comparison between two models, the initial non-linear model (Model 1) and the linearized model (Model 2), two different sizes of the problem are considered. Case 1 contains 8 nodes (1 depot and 7 waypoints) while Case 2 contains 14 nodes (1 depot and 13 waypoints). The two models are executed with a stopping criterion of 1% gap, which is calculated as $100 \times \frac{Upper\ bound - Lower\ bound}{Upper\ bound}$. The resulting performance is shown in Table 6, which shows that Model 2 obviously outperforms Model 1.

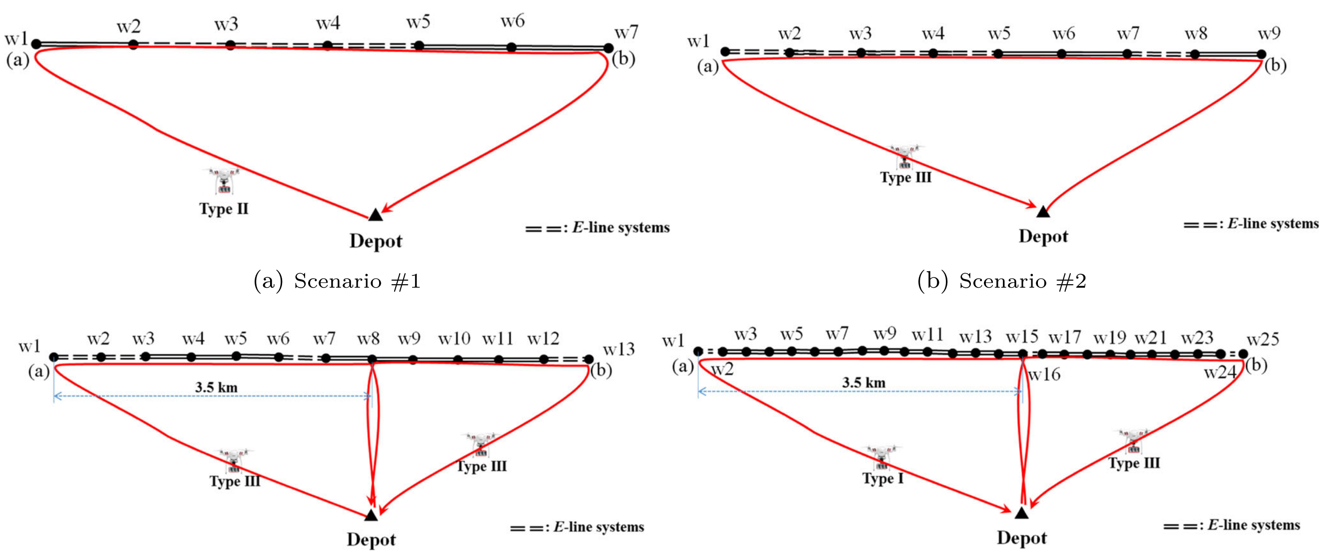
In Case 1, the two models have the same objective function value of \$5,190, but Model 2 generates the value with 0% gap in less than 3 s, whereas Model 1 gets the value with 0.983% gap in 25.413 s. The efficiency of the solution approach is even greater in a large size problem. In Case

Table 5 Cost comparison with different unit lengths of the *E*-line systems

Scenario	Overall cost (\$)					Total length of installing *E*-line systems	The number of required drones
	Drone operating	*E*-line systems		Total	Difference from #1		
		Installation	Operating				
#1 (1 km)	2,100	3,000	90	5,190	0%	3 km	1
#2 (0.75 km)	1,200	3,750	112.5	5,062.5	−2.46%	3.75 km	1
#3 (0.5 km)	2,400	2,000	60	4,460	−14.07%	2 km	2
#4 (0.25 km)	3,600	750	22.5	4,372.5	−15.75%	0.75 km	2

Fig. 9 Cost analysis for the DABS-E: total cost versus unit length of *E*-line systems





(a) Scenario #1

(b) Scenario #2

(c) Scenario #3

(d) Scenario #4

Fig. 10 Optimal flight paths under different scenarios

Table 6 Computational performance comparison between non-linear and linear models

	Performance	Model 1	Model 2
Case 1	Computational time (seconds)	25.413	2.531
	Objective function value ($)	5,190 (gap: 0.983%)	5,190 (gap: 0%)
Case 2	Computational time (seconds)	84.225	9.731
	Objective function value ($)	4,460 (gap: 0.987%)	4,460 (gap: 0.807%)

2, the two models get the same objective function value of \$4,460. However, Model 2 solves Case 2 in 9.731 s, whereas Model 1 solves Case 2 in 84.225 s. Moreover, the quality of the objective function value from Model 2 is better than that from Model 1. Even though the solution approach (Proposition 1) increased the number of variables (additional binary variable: ω_{ijk}) and constraints (additional constraints (23) and (24)) compared to Model 1, the proposed solution approach shows the outstanding computational performances.

6 Conclusion

This paper proposed a new concept for the border line surveillance missions to surveil the vulnerable and/or isolated border lines using drones with electrification line battery charging systems (DABS-E). The DABS-E was used for minimizing blind spots, securing the safety of the field agents, overcoming the short flight duration issue of drones, thus enhancing situational awareness, and achieving seamless and real-time border line surveillance missions. The *E*-line systems were introduced to overcome the short flight duration issue of drones by referring to the dynamic WPT technologies for ground electric vehicles. A problem solving algorithm was developed to construct a flight network over the border line and define initial data sets. The optimization mathematical model of DABS-E was developed to find the optimal installation locations of *E*-line systems and the specific flight path of drones. Since the optimization model was the MINLP model, a solution approach to linearize the original model was used to enhance the computational performance. A case area was selected to test the proposed DABS-E, in which the DABS-E showed the feasibility on the actual network of U.S.-Mexico border lines in the New Mexico area. The DABS-E model was compared with the DABS model without *E*-line systems in terms of the overall cost for deploying each model. As a sensitivity analysis, the minimum installation unit length of *E*-line systems was selected as different scenarios. These analysis results showed that the overall cost for deploying DABS-E increases as the unit length increases. Moreover, the linearized model was compared with the original non-linear model, in which the linearized model showed the outstanding performances in terms of the computational time and the quality of the objective function value.

As an extension of this paper, one can include an uncertain charging efficiency of *E*-line systems according to different drone flight speeds and air gaps. The continuous flights without returning to an initial launching center can be also considered in optimization model for DABS-E.

References

1. Wikipedia, Canada-United States border. http://en.wikipedia.org/wiki/ (Last accessed on 15 June 2017)
2. Patrol, U.B.: 2016 border patrol strategic plan (2012)
3. CBP Vision and Strategy 2020. https://www.cbp.gov/ (Last accessed on 15 June 2017)
4. Gehrke, J.: Border patrol has situational awareness of 56 percent of the border. http://www.washingtonexaminer.com/ (Last accessed on 9 August 2017)
5. Haddal, C.C., Gertler, J.: Homeland security: unmanned aerial vehicles and border surveillance. Library of Congress Washington DC Congressional Research Service (2010)
6. Small Unmanned Aircraft System (sUAS) Federal Project: https://govtribe.com/project/small-unmanned-aircraft-system-suas-1 (Last accessed on 15 June 2017) (2017)
7. Kim, S.J., Lim, G.J., Cho, J., Côté, M.J.: Drone-aided healthcare services for patients with chronic diseases in rural areas. J. Intell. Robot. Syst. **88**(1), 163–180 (2017)
8. Lim, G.J., Kim S. J., Cho J., Gong, Y., Khodaei A.: Multi-UAV pre-positioning and routing for power network damage assessment. IEEE Trans. Smart Grid https://doi.org/10.1109/TSG.2016.2637408
9. Carrivick, J.L., Smith, M.W., Quincey, D.J., Carver, S.J.: Developments in budget remote sensing for the geosciences. Geol. Today **29**(4), 138–143 (2013)
10. Kim, K., Kim, T., Lee, K., Kwon, S.: Fuel cell system with sodium borohydride as hydrogen source for unmanned aerial vehicles. J. Power Sources **196**(21), 9069–9075 (2011)
11. Wang, C., Ma, Z.: Design of wireless power transfer device for uav. In: 2016 IEEE International Conference on Mechatronics and Automation (ICMA), pp. 2449–2454. IEEE (2016)
12. Xie, L., Shi, Y., Hou, Y.T., Lou, A.: Wireless power transfer and applications to sensor networks. IEEE Wirel. Commun. **20**(4), 140–145 (2013)
13. Border Wall as Infrastructure. http://www.rael-sanfratello.com/?p=19 (Last accessed on 15 June 2017)
14. Finoki, B.: Floating Fences 1 (Imperial County). http://subtopia.blogspot.com/2009/03/ (Last accessed on 15 June 2017) (2009)
15. Harrison, D.: DHS-CBP-PIA-022 Border Surveillance Systems 2014. https://www.dhs.gov/sites/default/files/publications/privacy-pia-CBP-BSS-August2014.pdf. (Last accessed on 15 June 2017)
16. Pratap, P., Kallberg, J.M., Thomas, L.A.: Challenges of remote border monitoring. In: 2010 IEEE International Conference on Technologies for Homeland Security (HST), pp. 303–307. IEEE (2010)
17. Wong, K.V.: Research and development of drones for peace—high power high energy supply required. J. Energy Resour. Technol. **137**(3), 034702 (2015)
18. Klesh, A.T., Kabamba, P.T.: Solar-powered aircraft: energy-optimal path planning and perpetual endurance. J. Guid. Control. Dyn. **32**(4), 1320 (2009)
19. Sachs, G., Lenz, J., Holzapfel, F.: Unlimited endurance performance of solar uavs with minimal or zero electric energy storage. In: AIAA Guidance, Navigation, and Control Conference, pp. 10–13 (2009)
20. Soban, D.S., Upton, E.: Design of a uav to optimize use of fuel cell propulsion technology. In: AIAA Infotech@ Aerospace 2005 Conference and Exhibit, AIAA Paper, vol. 7135 (2005)
21. Sharaf, O.Z., Orhan, M.F.: An overview of fuel cell technology: fundamentals and applications. Renew. Sust. Energ. Rev. **32**, 810–853 (2014)
22. Junaid, A.B., Lee, Y., Kim, Y.: Design and implementation of autonomous wireless charging station for rotary-wing uavs. Aerosp. Sci. Technol. **54**, 253–266 (2016)

23. Simic, M., Bil, C., Vojisavljevic, V., Perilla, J.P.A.: Design of a recharge station for uavs using non-contact wireless power transfer. In: 54th AIAA Aerospace Sciences Meeting, pp. 12710–12720. American Institute of Aeronautics and Astronautics (2016)
24. Belmonte, N., Luetto, C., Staulo, S., Rizzi, P., Baricco, M.: Case studies of energy storage with fuel cells and batteries for stationary and mobile applications. Challenges **8**(1), 9 (2017)
25. Choi, S.Y., Gu, B.W., Jeong, S.Y., Rim, C.T.: Advances in wireless power transfer systems for roadway-powered electric vehicles. IEEE J. Emerg. Sel. Top. Power Electron. **3**(1), 18–36 (2015)
26. Miller, J.M., Onar, O.C., White, C., Campbell, S., Coomer, C., Seiber, L., Sepe, R., Steyerl, A.: Demonstrating dynamic wireless charging of an electric vehicle: the benefit of electrochemical capacitor smoothing. IEEE Power Electron. Mag. **1**(1), 12–24 (2014)
27. Gil, A., Taiber, J.: A literature review in dynamic wireless power transfer for electric vehicles: technology and infrastructure integration challenges. In: Sustainable Automotive Technologies 2013, pp. 289–298. Springer, Berlin (2014)
28. Bi, Z., Kan, T., Mi, C.C., Zhang, Y., Zhao, Z., Keoleian, G.A.: A review of wireless power transfer for electric vehicles: prospects to enhance sustainable mobility. Appl. Energy **179**, 413–425 (2016)
29. Song, K., Koh, K.E., Zhu, C., Jiang, J., Wang, C., Huang, X.: A review of dynamic wireless power transfer for in-motion electric vehicles. In: Wireless Power Transfer-Fundamentals and Technologies. InTech (2016)
30. Fischhendler, I., Feitelson, E.: Spatial adjustment as a mechanism for resolving river basin conflicts: the US–Mexico case. Polit. Geogr. **22**(5), 557–583 (2003)
31. Bussieck, M.R., Pruessner, A.: Mixed-integer nonlinear programming. SIAG/OPT Newsletter: Views & News **14**(1), 19–22 (2003)
32. Wu, T.-H., Low, C., Bai, J.-W.: Heuristic solutions to multi-depot location-routing problems. Comput. Oper. Res. **29**(10), 1393–1415 (2002)
33. Kulkarni, R., Bhave, P.R.: Integer programming formulations of vehicle routing problems. Eur. J. Oper. Res. **20**(1), 58–67 (1985)
34. Glover, F.: Improved linear integer programming formulations of nonlinear integer problems. Manag. Sci. **22**(4), 455–460 (1975)
35. C. GAMS Development, General Algebraic Modeling System (GAMS) Release 24.5.6, Washington, DC, USA. http://www.gams.com/ (2015)
36. IBM, CPLEX Optimizer. http://www.ibm.com/

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