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Sensor And Location Selection Problem For Tethered Surveillance Aerostats

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Abstract: *Today, Tethered Aerostats are one of the major Intelligence, Surveillance and Reconnaissance Systems which are used for fighting against smuggling, preventing illegal trade, monitoring terrorism and migration ways. The use of these surveillance systems should be evaluated by countries who suffer from potential border threats. But, due to high investment cost, a considerable planning period is required before implementation of these systems. In this study, we proposed an integrated approach that includes Geographical Information System and Set Covering Algorithm to determine the locations and sensor types of TAs that would be used for monitoring certain points on the southern boundary line of Turkey Repuplic. And, the viewshed analysis of GIS is used to examine the effectiveness of results. The study results provide remarkable contributions both to the research process that should be carried out before the establishment of these surveillance systems, and to the effectiveness control of these systems after installation.*
Keywords : *k-Center Covering, Sensor Selection, Set Covering, Unit Disk Covering, Viewshed Analysis.*

I. INTRODUCTION

Today, various political disputes in neighboring countries highlight the importance of border security. Many countries are investigating new technologies to establish an Intelligence, Surveillance and Reconnaissance (ISR) system. It is critical that countries should foresee and take measures to address threats from neighboring countries. Currently, developed countries use state-of-the-art technologies to protect their borders, such as Unmanned Aerial Vehicles (UAVs), satellite-based surveillance systems, sensors and also Tethered Aerostats (TAs).TA is basically a balloon in vertebrate structure hosting a beneficial payload for information processing. Although these big balloons are used for transportation, mapping, advertising etc., it has been used for military purposes for many years. Some developments like fiber optic cable connection to the ground, integration of the stabilized camera systems, replacement of the gas system with helium, provision of fireproof and airtight exterior coating, lifting/elevating easily with special cranes have made it possible for TAs to stay in air longer than other surveillance agents.

In case of using these systems for border security, it is important to determine where the TAs are deployed. Thus, a considerable planning period is required before using these systems. It is also important to consider the TA and sensor capabilities together, since the field of view of a TA is associated with the features of the camera sensor integrated on it. This problem can be described in "Site Selection Problem" which is frequently encountered in daily life.

In this study; to provide an effective ISR system with TAs on the south boundary line of Turkey Repuplic (TR), we aimed to determine the minimum number of TAs and sensor types needed. The remainder of this study is organized as follows. Relevant publications and military studies are examined in the second part. After defining the problem, an integrated approach that includes Geographical Information System (GIS) and Set Covering algorithm is proposed in third part. Then, the effectiveness of model results are discussed in the viewshed analysis of GIS using the real digital elevation data of the region. In the fourth part, suggestions for further studies are presented.

The motivation behind the work is to address the research and investigation process that need to be done prior to the establishment of these ISR systems. The difference from other works are focusing on a recent ISR system, integrating the geographical elevation values to lineer model, determining sensor types and TA settlements simultaneously and using viewshed analysis of GIS to test the model results.

II. LOCATION SELECTION PROBLEM

The theory of location selection is one of the topics that has been studied since 1900s. The issue was firstly addressed by Alfred Weber who focuses on how one depot should be placed closest to customers in different positions. Hakimi [1], called the problem of placing the facilities at minimum distance to the customers as "*P-Median Problem*". Church and Revelle [2], White and Case [3] concentrated their work on minimizing the number of installed facilities. Gary and Johnson [4] showed that the problem can be solved in a certain time by integer programming, but intuitive techniques are needed for large node*(N)* and possible point*(P)* values. The *"Greedy Adding with Substitution Algorithm"* used by Church and Revelle [2] seems to be the first intuitive study in the literature. In the following periods; they have theoretically pointed out the relation between the *P-Median Model* of Hakimi [1] and the *Maximum Covering Model* (MCM). Schilling [5], Boeffey and Narula [6] used Multi-Criteria Decision Making techniques in location selection problems, Megiddo et al. [7] developed a network theory based algorithm for MCM.

In general, site selection problems deal with covering maximum number of demand centers with minimum number of facilities under the constraints of time, cost, distance etc. Due to the structure of objective function, the problem is also referred as "*Min-Max Problems*". According to Mehrez and Stulman [8], there are often a set of infinite solutions for such problems rather than a single one.

Schilling et al. [9] reviewed site selection literature from 1900 to 1991 and classified models which use the concept of covering in two categories: (1) *Set Covering*(SC) where coverage is required and (2) *Maximal Covering*(MC) where coverage is optimized. A general linear model of SC can be represented as follows:

Indices:
c_j*= the fixed cost of setting up a facility at node "j".*
S= maximum service distance or service time.
N_i*= "j" facilities serving the demand node "i";* $N_i=\{ j \mid d_{ij} \leq S \}$
Decision variable:
x_i*= if the facility is located at node "i"; "1", otherwise "0".*

$$Min\ Z = \sum_{i=1}^{n} C_{\mathrm{i}} * X_{\mathrm{i}} \tag{1}$$

st.

$$\sum_{i \in N_i}^{n} X_{\mathrm{i}} \geq 1 \tag{2}$$

$$X_{\mathrm{i}} \in (0,1) \tag{3}$$

In the model; equation (1) aims to locate facility with a minimum cost, equation (2) ensures that all demand points must be associated with a facility within the prescribed distance, equation (3) refers that the decision variable can get a value of {0,1}.

Assuming that "*S*" is a set of "p_i" points defined in the space and "*k*" is an integer where "$k \leq n$", determination of the minimum set of "*k*" that covers "*S*" is called as "*k-Center Problems*". This problem seeks solutions to satisfy demands at "*n*" points fully or partially with the minimum number of service centers at "*k*" points. According to Gary and Johnson [4]; another type of this problem is *Unit Disc Covering* (UDC) which is known as a geometric version of covering problems. As stated in equation (4) and (5); UDC models search solutions for covering "p_i" points where $P=\{p_1, p_2, p_3, \ldots, p_n\}$, with the minimum number of "D_i" disks where $D =\{d_1, d_2, d_3, \ldots, d_m\}$.

$$D^* \subseteq D \tag{4}$$

$$P \subseteq \bigcup_{d_i \in D^*} d_i \tag{5}$$

Fowler et al. [10], Hochbaum and Maas [11] claimed that this kind of problems have an NP-hard structure. In the relevant literature; it is seen that usually heuristic algorithms are used when iterative-combinational searches are conducted in multi-dimensional site selection problems. According to Xiao B. [12], Feder and Greene [13]; if the $K=\{k_1,k_2,k_3,\ldots,k_m\}$ points representing candidate locations of discs become unlimited, the level of complexity of the problem is further increased.

More detailed review can be found in [14]. Numerous studies have been conducted for the real-living conditions so far [15]. It is also possible to see the location selection applications in military and defense science.Some recent works are as follows: Sarıkaya [16] to determine the position of the gendarmerie stations, Tanergüçlü [17] to determine the positions of the air defense systems, Gencer and Açıkgöz [18] to determine the locations of search and rescue teams, Ayöperken [19] to select the bases of a heterogeneous UAV fleet, Carlıoğlu [20] to determine the locations of coastal radars in the Aegean region. At their study on scanning a field with short-range UAVs, Kress ve Royset [21] used a two-stage model which searches for the locations of the UAV control stations at first stage and tries to determine UAV flight routes at second stage. Kurban [22] used Expected MC algorithm to determine the locations of control station of a mini UAV fleet under various service probability conditions.In addition, it is seen that GIS have been used in multi dimensional location selection problems. Gunhak Lee [23] calculated signal spread distances of candidate points with line of view analysis of GIS in their work related to inhouse wireless network setup. Murray et al. [24] used viewshed analysis of GISfor a security system installation of a closed are.

However many studies related to military issues can be found in the literature, studies on ISR systems with TAs seem as limited.

III. LOCATION SELECTION PROBLEM OF TETHERED AEROSTATS ON SOUTHERN TURKEY

Turkey Republic has a total border of 2573 km with two European (Bulgaria and Greece) and six Asian (Azerbaijan, Armenia, Georgia, Iraq, Iran and Syria) countries. Due to its geostrategic position, especially in Iraq, Iran and Syria, security problems such as terrorism and illegal immigration have been experienced so far. Therefore, constant surveillance of borderline is important for national defense. For this purpose; a number of critical locations on southern border region of Turkey are identified based on the views of the military experts and the statements issued by the Turkish Armed Forces. The image of the candidate points is given in Fig. 1.

Figure 1: The candidate points.

The purpose of the problem is to determine the minimum number and locations of TAs for continuous monitoring of the critical points at the border region. Considering that the field of view of a TA is related to the geographical nature of the area and the capability of camera sensor, the problem becomes more complicated.

III.I The Role of GIS

GIS is frequently used for geographical analysis and digital map processing. Visibility analysis in GIS searches for whether a location is visible form another location. The inputs of visibility analysis are the properties of natural or man-made layers. Using the Digital Elevation Model (DEM) data, an imaginary line is created between the target cell and the viewpoint. If both cells are located on this imaginary line, it is understood that there is visibility and then the result is plotted on the map [25]. An example for surface imaging analysis of a particular point can be found in Fig. 2. Here; the visible cells for are colored in green, and the unvisible cells are colored in red.

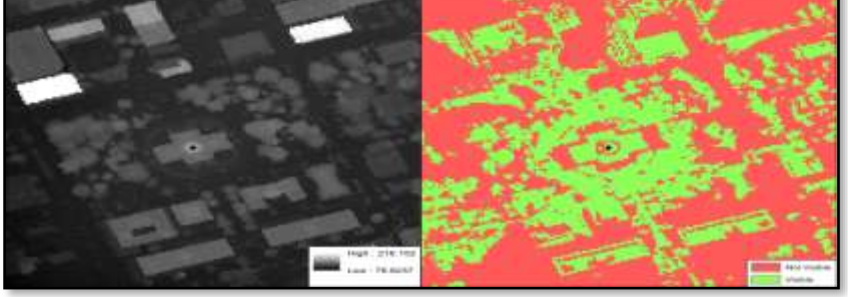


Figure 2: An example for surface imaging analysis of a particular point.

GIS is frequently used in military and defense applications, especially in the examination of geographical features, the movement planning of military units [26]. ArcGIS Viewshed Analysis module is used for geographical analysis in this study. The DEM data is obtained from the reference [27].

III.II Mathematical Model and Results

In application process, same structured TAs are used in clear weather conditions and the ground connection cable is determined as 1 km length. The integration costs and the view ranges of the camera sensors are given in Table 1.

Table 1. Maximum viewing ranges and installation costs for TA/sensortypes.

Sensor Types	Max. Viewing Ranges	Integration Costs
s1	20 km	$100
s2	40 km	$200
s3	60 km	$300
s4	80 km	$400
Installation cost of TA: $10000		

The linear model developed for the scenario is as follows;

Sensor Type and Location Selection with Minimum Cost, SC Model:

İndices:
İ = candidate TA settlement points, $i := \{ i_1, i_2, ..., j, ..., i_{107\,;\,(i_x, i_y, i_z)} \}$
$d(i,j)$*= the imaginary line segment that connects point "i" and "j".*
$s_{(k)}$ *= sensor types,* $s_{(k)} = \{s_1, s_2, s_3, s_4\}$
c_B*= installation cost for TA.*
$c_{s_{(k)}}$ *= integration costs for sensor types.*
$N_{s_{(k)}}$ *= inventory amounts for sensor types.*
$f_{is_{(k)}}(g)$ *= the visible points set for the sensor "$s_{(k)}$", that integrated to TA located at point "i".*
$s_{(k)}(i,j)$*= if the imaginary line segment "$d(i,j)$" is covered by the sensor "$s_{(k)}$", that integrated to TA located at point "i"; "1", otherwise "0".*

Decision Variables:
x_i *= if the TA is located at node "i"; "1", otherwise "0".*
$f_{is_{(k)}}$ *= if the sensor $s_{(k)}$ is integrated to TA located at point "i"; "1", otherwise "0".*

Model:

$$Min\ Z = \sum_{s}^{s4} \sum_{i}^{i_{107}} x_i * (c_B + f_{is_{(k)}} * c_{s_{(k)}}) \tag{6}$$

$st.$

$$\forall s \quad s_{(k)}(i,j) = \begin{cases} 1, & d(i,j) \in f_{is_{(k)}}(g) \\ 0, & dd. \end{cases} \tag{7}$$

$$\forall j \quad \sum_{s}^{s4} \sum_{i}^{i_{107}} (x_i * f_{is_{(k)}} * s_k(i,j)) \geq 1 \tag{8}$$

$$\forall s \quad \sum_{i}^{i_{107}} x_i * f_{is_{(k)}} \leq N_{s(k)} \tag{9}$$

$$\forall i \quad \sum_{s}^{s_4} x_i * f_{is_{(k)}} \leq 1 \tag{10}$$

$$\forall i \quad x_i = \begin{cases} 1, & if\ the\ TA\ is\ located\ at\ node\ \text{"}i\text{"} \\ 0, & otherwise \end{cases} \tag{11}$$

$$\forall i \quad f_{is_{(k)}} = \begin{cases} 1, & if\ the\ sensor\ s_{(k)}\ is\ integrated\ to\ TA\ located\ at\ point\ \text{"}i\text{"}, \\ 0, & otherwise \end{cases} \tag{12}$$

$$x_i \in \{0,1\} \ ; \quad f_{is_{(k)}} \in \{0,1\} \tag{13}$$

In the linear model; equation (6) implies that covering all points with minimum cost is targeted. Equation (7) tests whether the imaginary line segment "*d(i,j)*" formed between points "i" and "j" is visible, from the sensor $s_{(k)}$ integrated on TA placed at point "*i*". Equation (8) indicates that all points must be covered. Equation (9) represents the inventory constraint for sensor $s_{(k)}$. Equation (10) suggests that only one sensor type can be integrated on a TA. Equations between (11) and (13) refer that the decision variables can take “1” or “0” values.

Various cases are developed to examine different situations. The conditions where TAs use 20, 40, 60 and 80 km sensors are tested respectively and finally all sensor types are considered together. The model is executed in GAMS 24.7.1 optimization software package. Model results are given in Table 2.

Table 2. The Solution Results of Mathematical Models

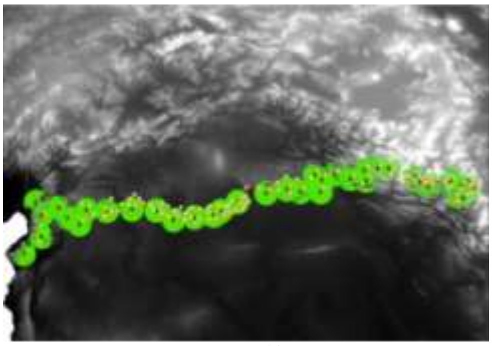
TA Settlement Points and Sensor Type Used (x_i-s_k)							Total cost (Z_{min})
Case 1: *(Using 20 km sensors)*							
x_1-s_1	x_4-s_1	x_5-s_1	x_6-s_1	x_8-s_1	x_9-s_1	x_{10}-s_1	
x_{13}-s_1	x_{21}-s_1	x_{23}-s_1	x_{29}-s_1	x_{35}-s_1	x_{40}-s_4	x_{47}-s_1	
x_{50}-s_1	x_{58}-s_1	x_{64}-s_1	x_{68}-s_1	x_{71}-s_1	x_{73}-s_1	x_{74}-s_1	$393 900
x_{75}-s_1	x_{76}-s_1	x_{78}-s_1	x_{79}-s_1	x_{80}-s_1	x_{81}-s_1	x_{83}-s_1	
x_{87}-s_1	x_{88}-s_1	x_{91}-s_1	x_{95}-s_1	x_{97}-s_1	x_{100}-s_1	x_{101}-s_1	
x_{103}-s_1	x_{104}-s_1	x_{106}-s_1	x_{107}-s_1				
Case 2: *(Using 40 km sensors)*							
x_2-s_2	x_5-s_2	x_7-s_2	x_8-s_2	x_{10}-s_2	x_{13}-s_2	x_{18}-s_2	
x_{29}-s_2	x_{43}-s_2	x_{55}-s_2	x_{66}-s_2	x_{69}-s_2	x_{72}-s_2	x_{74}-s_2	$306 000
x_{75}-s_2	x_{76}-s_2	x_{79}-s_2	x_{80}-s_2	x_{81}-s_2	x_{83}-s_2	x_{87}-s_2	
x_{88}-s_2	x_{89}-s_2	x_{95}-s_2	x_{97}-s_2	x_{100}-s_2	x_{101}-s_2	x_{103}-s_2	
x_{106}-s_2	x_{107}-s_2						
Case 3: *(Using 60 km sensors)*							
x_2-s_4	x_5-s_4	x_{11}-s_4	x_{24}-s_4	x_{32}-s_4	x_{55}-s_4	x_{70}-s_4	
x_{75}-s_4	x_{77}-s_4	x_{78}-s_4	x_{80}-s_4	x_{81}-s_4	x_{84}-s_4	x_{85}-s_4	$216 300
x_{86}-s_4	x_{94}-s_4	x_{96}-s_4	x_{97}-s_4	x_{100}-s_4	x_{102}-s_4	x_{105}-s_4	
Case 4: *(Using 80 km sensors)*							
x_3-s_4	x_{23}-s_4	x_{52}-s_4	x_{73}-s_4	x_{85}-s_4	x_{103}-s_4		$62 400
Case 5: *(Considering sensor types together)*							
x_1-s_1	x_8-s_4	x_{30}-s_4	x_{62}-s_4	x_{75}-s_4	x_{91}-s_4		$62 100

According to the results, to observe all points; 39 TAs are needed for the 1th Case where 20 km sensors used, 30 TAs are needed for the 2th Case where 40 km sensors used, 21 TAs are needed for the 3th Case where 60 km sensors used, 6 TAs are needed for the 4th Case where 80 km sensors used. A total of 6 TAs located at points 1, 8, 30, 62, 75 ve 93 and using one unit of 20 km - five units of 80 km sensors are needed for the 5th Case.

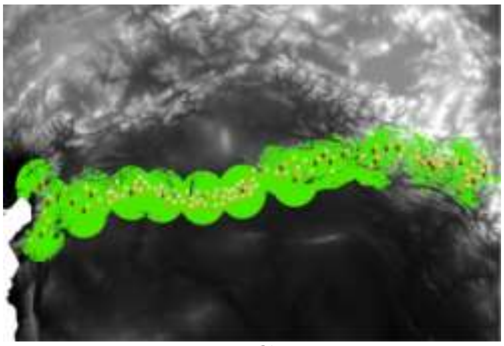
Altough the number of TAs needed for the Cases 4th and 5th are equal, in terms of investment cost the solution of 5th Case appears to be more advantageous.

III.III Viewshed Analysis of Cases

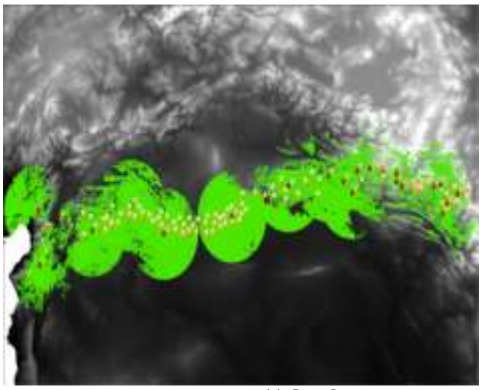
The field of view provided by TAs should be examined because of the different layouts in Cases. The relevant analysis is performed with viewshed analysis module of ArcGIS, as seen in Fig.3.



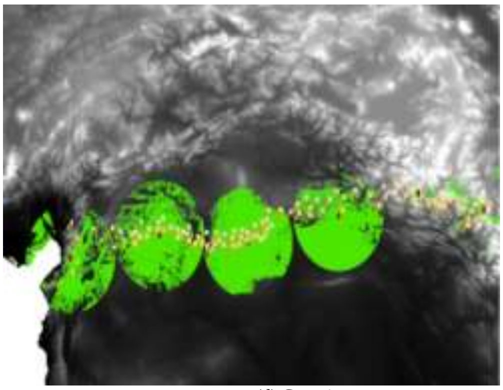
(a) Case 1.



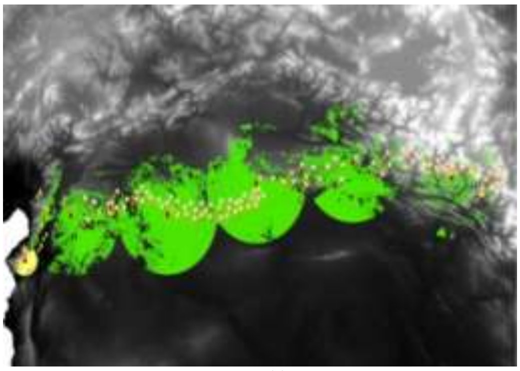
(b) Case 2.



(c) Case 3.



(d) Case 4.



(e) Case 5.

Figure 3: Images of Viewshed Analysis for Cases.

The green fields in the images refer to the visible areas for TAs. It is seen that all the points expected to be seen, are covered by the TAs placed in the given locations at Table 2. Especially in the 4th and 5th Cases, although the points at the southeast region can be seen by TAs, the layout provides a less viewing on total southeast region.

IV. CONCLUSIONS AND FUTURE WORKS

Today, TAs are one of the major (ISR) systems which are used for fighting against smuggling, preventing illegal trade, monitoring terrorism and migration ways. The use of these surveillance systems should be evaluated by countries who suffer from potential border threats. Where these TAs would be deployed and how surface viewings will they provide, are crucial issues that must be addressed before implementing these systems.

In this study, we proposed an integrated approach that includes GIS and SC model. The proposed approach is used in the location and sensor type selection problem of TAs that will observe the southern borderline of Turkey where intense terror and immigration incidents happen. In the cases developed for the problem, the conditions where TAs use 20, 40, 60 and 80 km sensors are tested respectively and finally all sensor types are considered together. In the lineer SC model, we aimed to find the combinations of TA locations and sensor types which would provide maximum point observation with minimum set up cost. Surface viewings provided by TAs located at the points determined with the SC model are examined using GIS.

According to the model results; covering all points with minimum cost is achieved when all sensor types considered together, as seen in the 5th Case. The relevant solution recommends to locate TAs at the 1th, 8th, 30th, 62th, 75th and 91th positions, and to use one unit of 20 km and five units of 80 km sensors. Although, the observation of all points is provided by six TAs according to the result of 4th Case where only 80 km sensors used, the result of 5th Case appears to be more advantageous in terms of investment costs.

According to the results of the viewshed analysis; however all the points expected to be observed are covered; it is not possible to monitor the entire border area due to the rugged terrain structure. The results of the study emphasize the use of a hybrid ISR system for the countries that have bad geographical structure. This hybrid system may include the use of TAs for visible areas and UAVs for unvisible regions. For further studies, it will be benefical to focus on hybrid systems, especially on examining the dynamic scanning of unvisible areas with UAVs.

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