



An Integer Programming Model for the Heterogeneous UAV Fleet Routing Problems

Cihan ERCAN¹ Cevriye GENCER²

Abstract

With the recent developments in wireless communication and computer processing, more unmanned aerial vehicles (UAVs) are used in the military field. As the numbers of UAVs and their varied capabilities have increased dramatically, new approaches for the planning of a heterogeneous fleet have become an ongoing area of research for the operations research community. In this paper, an integer programming solution for the heterogeneous UAV static vehicle routing problem (VRP) is presented. Explanations of UAVs with a VRP and their importance for military operations are also provided. In addition, differences between homogeneous and heterogeneous definitions for UAVs are detailed. We extend a previous study and conclude with a comparison of the model with the literature.

Keywords: Static Vehicle Routing, Unmanned Aerial Vehicle, Integer Programming

Heterojen İHA Filosu Rotalama Problemi için Tam Sayılı Programlama Modeli

Öz

Son zamanlarda, kablosuz haberleşme ve bilgisayar işlemcilerindeki gelişmeler sayesinde, operasyon sahasında daha çok İnsansız Hava Araçları (İHA) kullanılmaya başlanmıştır. Kullanılan İHA'ların ve çeşitlerinin hızla artması ile birlikte, heterojen İHA filolarının rota planlamaları için yeni yaklaşımlar, harekât araştırmacıları için ilgi çekici bir alan olagelmıştır. Bu çalışmada, değişik imkan ve kabiliyetlerdeki İHA'lardan oluşan heterojen filoların statik araç rotalama problemleri (ARP) için tam sayılı programlama çözüm modeli önerilmiştir. İHA ve ARP'lerinin tanımları ile askeri operasyonlar için önemleri açıklanmış, ayrıca homojen ve heterojen İHA tanımları detaylandırılmıştır. Bir önceki çalışma genişletilmiş ve literatür ile karşılaştırmaları verilmiştir.

Anahtar Kelimeler: Statik Araç Rotalama, İnsansız Hava Araçları, Tam sayılı Programlama

Introduction

The uses and the market for UAVs have increased in both military and civilian applications recently. This trend has motivated researchers to study the various aspects of UAVs. The vehicle routing problem is important one of them. Today's developments in computational techniques and communication technology allow us to control and manage a fleet of hundreds of UAVs in the area of operations in which larger and more complex military systems are used. As a result, managing these strategic systems is becoming more important. In the past decades, a lot of research has been done to find the best route for unmanned vehicles in military operations. "In today's military, unmanned systems are highly desired by

¹ Yazışma Adresi: Kara Harp Okulu, Savunma Bilimleri Enstitüsü, Harekât Araştırması AD, Ankara, cercan@tsk.tr.

² Prof. Gazi Üniversitesi, Mühendislik Fakültesi, Endüstri Müh. Böl., Ankara, ctemel@gazi.edu.tr.

combatant commanders for their versatility and persistence” in that context (U.S. DoD, 2011).

“UAVs have shown promise in a wide range of applications” (Bhattacharya and Başar, 2010). As the number of UAVs and their heterogeneities increase, precise route planning is required to handle the management of them. “The development of UAVs was originally driven by the need for remediation of hazardous waste sites in which human intervention was costly and dangerous. Although that is still a driving force, there is also the military’s need for intelligence gathering and operational support in the face of reduced manpower” (Schoenwald, 2000). Future air forces will consist of pilotless UAVs to handle the challenging and unusual conditions which are very different from the traditional operational area (Dror and Powell, 1993). From these requirements will emerge more heterogeneous UAVs and will motivate the operational research community to find new approaches to the routing problems of heterogeneous UAV fleets.

Homogeneous UAVs are those that share the same capabilities whereas those that have different capabilities are called heterogeneous UAVs. Modern military operations are shifting from the homogeneous to heterogeneous UAV concepts as a result of hybrid-threat missions. “Operations will require multiple UAVs functioning in a cooperative mode, sharing resources and complementing other air, ground, sea-surface and underwater assets” as depicted in Figure-1. “Thus, it is essential to abstract from current implemented approaches and considerations, and view an ensemble of multiple and heterogeneous unmanned vehicles as a ‘system of systems’, where a single UAV is functioning as a ‘sensor’ or as an ‘agent’ or as a ‘node’ “ (Valavanis, 2007). UAV routing planning is one of the core steps to effectively exploit the capabilities of heterogeneous UAVs.

The motivation for this work is to propose a solution in a reasonable time of an extended heterogeneous version of the previously studied (Gencer et al., 2009) routing problem. In this paper, we describe a methodology of heterogeneous vehicle routing for mission planning in a military operation. This paper is organized as follows: Section 2 contains some basic information about the UAVs and the vehicle routing problems (VRP). Section 3 introduces the related work and the solution approaches. The problem is stated in Section 4. Section 5 provides a solution method for the UAV VRP. Conclusions are provided in Section 6 and future problems are given in Section 7.

Unmanned Systems and Static Vehicle Routing Problems

An unmanned system (UMS) is described by Vargas (2012) as an “electro-mechanical system, with no human operator aboard, that is able to exert its power to perform designed missions. May be mobile or stationary. Includes categories of unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), unmanned underwater vehicles (UUV), unmanned surface vehicles (USV), unattended munitions (UM), and unattended ground sensors (UGS)”. Among the UMSs, UAVs are the most common and important ones. Hence, the most (\$30,820.32 million) of the UMS resources (\$32,705.30 million) is allocated for UAVs (US DoD UAV Roadmap, 2011).

Although there are lots of classifications of UAVs like strategic, operational and tactical, the US DoD (2010) categorizes them as detailed in the Table-1.

Table 1. Unmanned Aerial System Categories
(Original Source: US DoD, U.S. Army Roadmap for 2010-2035)

Category	Max Gross Takeoff Weight	Normal Operating Altitude (Feet)	Airspeed	Current Army UAS in Operation
Group 1	< 20 Pounds	< 1200 above ground level	< 100 Knots	RQ-11B Raven
Group 2	21-55 Pounds	< 3500 above ground level	< 250 Knots	No current System
Group 3	< 1320 Pounds	< 18000 mean sea level		RQ-7B Shadow
Group 4	> 1320 Pounds	> 18000 mean sea level	Any Airspeed	MQ-5B, MQ-1C
Group 5				No current System

UAV missions include but are not limited to:

- Environmental remediation,
- Detonation/defusing of live ammunition,
- Aerial photography,
- Search and rescue,
- Meteorology missions,
- Telecommunications,
- Navigation within an area to gather data,
- Transportation of goods,
- Performance of repetitive and dangerous tasks,
- Reconnaissance, surveillance, and target acquisition,
- Combat synthetic aperture radar,
- Deception operations,
- Maritime operations (naval fire support, over-the-horizon targeting, antiship missile defense, ship classification),
- Electronic warfare and signals intelligence,
- Nuclear, biological and chemical reconnaissance,
- Special and psychological operations,
- Route and landing zone reconnaissance support,
- Adjustment of indirect fire and close air support,
- Battle damage assessment and many others (Kumar, 1997; Goraj, 2003; Odom, 2002; Ercan and Gencer, 2013).

There is a growing and wide range of open issues for research in both military and the civilian UAV applications (US DoD 2005; Wilson 2007). The various mission applications which recently increased the military operational tempo in network enabled warfare are depicted in Figure 1. In this figure, today's uses of UAVs in reconnaissance missions and the integration with other manned or unmanned systems in the concept are displayed.

Not only to have these privileged systems but also to use them efficiently is critical to modern militaries. One of the most important issues dealing with the efficiency of their use is to plan their use in the Air Tasking Order (ATO). This order includes the necessary route for UAVs to follow. The ATO can be prepared either manually or via automated means. If the number of targets is small, then it is easy to plan manually, otherwise a wiser scientific approach will be necessary to find the optimal or near optimal routes for the various assets.

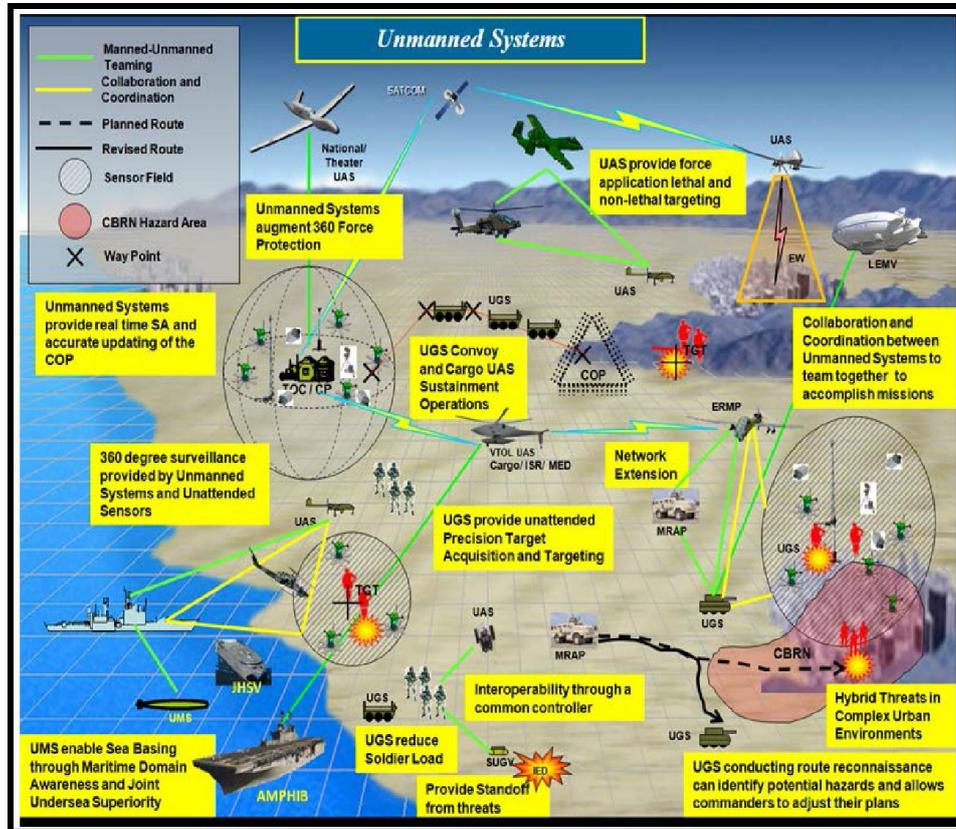


Figure 1. Example of a UMS Full Spectrum Dominance Concept (Ronny A. Vargas, 2012) (Original Source: Maneuver, Aviation and Soldier Division, "Initial Capabilities Report for Unmanned Systems (Air, Ground, and Maritime)," prepared for a Material Development Decision, draft version 2.2 (Fort Monroe, VA: 2010), Appendix A).

The first paper on VRP, "Optimum Routing of a Fleet of Gasoline Delivery Trucks between a Bulk Terminal and a Large Number of Service Stations Supplied by the Terminal," was introduced by Dantzig and Ramser half century before. Since 1959, there have been many approaches to a solution of this kind of problem. In our kind of problems, VRP deals with the optimal set of routes to be followed by UAVs to observe a predefined set of targets.

There are five versions of VRPs according to their constraint, objective function, environment, path and route situations (Toth and Vigo, 2001; Ercan and Gencer, 2013). The reader is referred to read Toth and Vigo (2001) for more details about the variations of VRPs. Static VRP is one of the extensions of classical VRP according to the environment in which all the targets' information are assumed to be known by the planner

prior to the mission and does not change after the ATO is published. Hence, ATO is prepared before the first UAV begins to search and does not need to be updated during the missions. In other words, there are no “immediate”, “unexpected”, “on-call” or “advance” targets during the mission.

In the next section, the works related to the UAV VRP issue and their approaches are introduced.

Related Works and Solution Approaches

The routing solutions have been widely studied for either ground-based vehicles or the robotics in 2D. These approaches to a solution influenced and are mostly used for UAV routing problems too. The UAV VRP has many different variants from the perspective of not only the problem extensions but also the solution techniques. Several solution algorithms used for predefined targets have been proposed for VRPs so far. These solutions can be categorized into two main classes: exact and heuristics algorithms. The main drawback of the exact algorithms is the computation time. To find the optimal route, which is guaranteed, they need more computational time than the heuristic algorithms. However, in some cases of the VRPs, the optimal routing may be more important than the planning time or the planner may have enough time to wait for the optimal solution. This is because route planning is done before the mission and uploaded to the UAV ATOs prior to taking off, which means there is a reasonable amount of time to plan the optimal trajectory.

The UAV VRP can be modeled as either a single mixed-integer linear programming problem, like in Richard et al.(2002) which gets the globally optimal solution, or a heuristic tabu search algorithm may be applied to find the acceptable near optimal cooperative assignment for a UAV (Ryan et al., 1998).

Among the numerous studies for UAV VRPs, Jun and Andrea (2002) have proposed a path routing based on the threats. Jin et al. (2006) considered “a heterogeneous team of cooperating UAVs drawn from several distinct classes and engaged in a search and action mission over a spatially extended battlefield with targets of several types”. In Rabbath et al. (2004) an overview of coordinated control of UAVs with their complexities was presented.

Shetty et al. (2008) studied the VRP to serve UAVs for predetermined targets. “The vital aspect of this paper is the integrated optimal utilization of available resources, weaponry and flight time, while allocating targets to UAVs and sequencing them to maximize service to

targets based on their criticality”. Pohl and Lamont (2008) developed an innovative algorithm to route the multiple autonomous UAVs.

Lim et al. (2008) described “hybrid ant colony algorithms (HACAs) proposed for path planning in sparse graphs. HACAs represent “ant-inspired” algorithms incorporated with a local search procedure and some heuristic techniques for uncovering feasible route(s) or path(s) in a sparse graph within tractable time”. Peng and Gau (2008) considered the stochastic observation time for multiple UAVs. Kim et al. (2008) studied the online autonomous UAV VRP with limited information.

In other interesting studies, Murray and Karwan (2010) presented an extensible modeling framework in which “airborne resources must be reassigned to time-sensitive tasks in response to changes in battlespace conditions”. Edison and Shima (2011) proposed the genetic algorithm for the stochastic search.

Kavraki et al. (1996), Hsu et al. (1997), Shanmugavel et al. (2006) and Pachikara et al. (2009) are the rare researchers who have studied the higher dimensionals for UAVs.

Tompkins (2004), Gennery (1999), Hebert (2001), Chadler et al. (2000) are some of the researchers who have dealt with the UAV/space applications but mostly focus on kinematic approaches of routing problems.

The safety of the UAVs is achieved by considering obstacles in the real world. In the literature, buildings, other aircraft, enemy radars or forests are assumed to be obstacles (Bortoff, 2000; Bicchi and Pallottino, 2000; Mclain, 2000; Doweck et al., 2001; Beard et al., 2002, Li et al., 2002, Yang and Zhao 2004; Shanmugavel et al., 2005; Eun and Bang, 2006; Zeitlin and Mclaughlin, 2007; Mittal and Deb, 2007; Duan et al., 2009).

A recent paper by Henchey et al. (2013) demonstrated the flight dynamics and the wind effects in UAV routing. The paper by Bednowitz et al. (2013) explored dispatching and loitering policies for UAVs. Muffali et al. (2012) considered simultaneous selection of sensors and routing for UAVs. The other recent interesting paper by Royset et al. (2009) studied the constrained shortest path for UAVs.

The heuristic approaches suffer from finding the global optimal route. By contrast to the well-worn UAV applications, some routine missions, like either “aerial photography” or “operations in a totally known area” need static UAV route planning. In this kind of operations, the mission for the UAVs is to follow the pre-defined ATO trajectory and observe the targets in the planned order and time. In this way, the ATO can be planned formerly and the ground-based pilot/operator could control more

UAVs during the mission. In this paper, a static VRP for heterogeneous UAVs based on an exact algorithm is studied as an extension of Gencer et al. (2009)'s previous work.

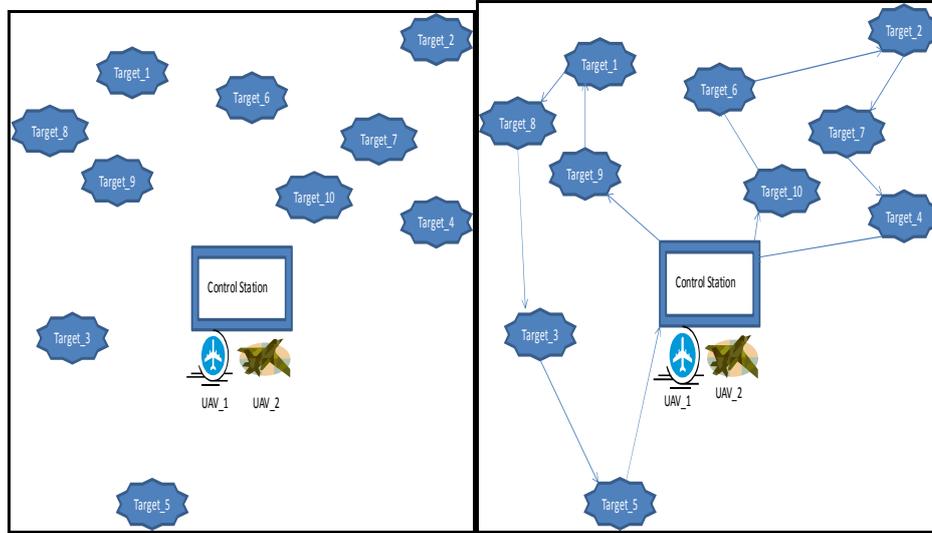
Problem Statements

One of the most expensive systems, UAVs, have become an indispensable force multiplier for military forces since their emergence. The increased use of the UAVs and the greater dependence on them, with less manpower requirements, triggers the efforts to optimize the static trajectory plans.

The problem studied in this paper is to find the best trajectory for UAVs among the targets under the specified constraints. It will be assumed that all targets have known positions and known threats before the planning period. Other assumptions in this planning period are as follows:

- UAVs are heterogeneous meaning that they may have different capabilities.
- The speed and cost of each UAV are known and fixed but may be different.
- The number of UAVs and targets are known prior to mission planning.
- There are hard time windows for each target. The UAVs are expected to observe the targets between these time windows specified for each of them. It is not allowed for UAVs to observe the targets before or after these periods.
- There is one airport to take off from and land on.

Figure 2 depicts the planning for the problem as an example. In the snapshot, there are two UAVs and 10 "advance" targets in a reconnaissance mission. UAV_1 and UAV_2 are different from each other as they are heterogeneous. There is only one available airport base (serves also as a control station) for landing and taking off which also manages and controls the UAVs. The problem is "what should be the routes for UAVs to observe all the targets at a minimum cost?".

**Figure 2.** Static Targets.**Figure 3.** Assigned Targets to UAVs.

Let us assume that Figure 3 shows the result of the optimized route for the ATO. Targets 9, 1, 8, 3 and 5 are assigned to UAV-1 at the very beginning of the mission while targets 10, 6, 2, 7 and 4 are assigned to UAV-2. The UAVs are expected to follow these routes sequentially and land at the same airport. These kinds of targets are called “advance” or “planned” targets and can be referred to as static targets since the plans for the mission had been received before the routing process began.

The target area threats are taken into consideration in this paper, which is more realistic, unlike the references mentioned in Section 3 that assumed the buildings, enemy radars or forest to be obstacles. For instance, if the target has a “docka” kind of heavy machine gun, then the UAV should fly at least 3500 m over the target in order to be safe, which is the maximum range of the gun.

The following section gives an integer programming-based solution approach to find the minimum route for this kind of VRP in a smarter way.

An Integer Programming Based Proposed Model

A mathematical model for a general homogeneous VRP problem is presented as follows (Gencer et al., 2009):

Notations:

i, j :Set of targets,

v :Set of vehicles,

$(ti)_i$:Initial value of time window at target 'i',

$(ts)_i$:Last value of time window at target 'i',

d_{ij} :Travelling distance from target "i" to target "j",

y_{ij} :Travelling time from target "i" to target "j",

M :Very big number,

T_i :Time to arrive at target 'i',

x_{ij}^v :If UAV "v" travels from the target "i" to the target "j", then $x_{ij}^v=1$, otherwise 0.

Objective Function:

$$\text{Min } Z = \sum_{i=0}^{i=n} \sum_{j=0}^{j=n} \sum_{v=1}^{v=V} d_{ij} x_{ij}^v \quad (1)$$

Constraints:

$$\sum_{v=1}^{v=V} \sum_{j=0}^{j=n} x_{ij}^v = 1 \quad \text{for } \forall i (i \neq 0, i \neq n+1) \quad (2)$$

$$\sum_{v=1}^{v=V} \sum_{i=0}^{i=n} x_{ij}^v = 1 \quad \text{for } \forall j (j \neq 0, j \neq n+1) \quad (3)$$

$$\sum_{i=0}^{i=n} x_{ik}^v - \sum_{j=0}^{j=n} x_{kj}^v = 0 \quad \text{for } \forall k, v \quad (4)$$

$$\sum_{i=0}^{i=n} x_{i0}^v = 1 \quad \text{for } \forall v \quad (5)$$

$$\sum_{j=0}^{j=n} x_{0j}^v = 1 \quad \text{for } \forall v \quad (6)$$

$$T_i \geq (ti)_i \quad \text{for } \forall i \quad (7)$$

$$T_i \leq (ts)_i \quad \text{for } \forall i \quad (8)$$

$$T_{i+} + y_{ij} - T_j \leq M(1 - \sum_{v=1}^{v=V} x_{ij}^v) \quad \text{for } \forall i, j \quad (9)$$

$$x_{ij}^v = 0-1 \quad T_i \geq 0 \quad \text{for } \forall i \quad (10)$$

In the proposed model, (1) describes the objective function which minimizes the total routes. Constraint (2) and (3) impose a restriction that exactly one UAV can observe and leaves each target, respectively. Constraint (4) provides that if UAV observes a target, it must leave that target too. Analogously, constraints (5) and (6) impose that each UAV takes off from an airport and returns to the same airport to land. Constraints (7) and (8) are the time windows for targets. Targets must be observed after “ t_i ” but not later than “ t_s ”. Constraint (9) assigns the total time of fly of each UAV to T.

In our work, an integer programming algorithm is proposed and solved by the GAMS 21.5 (General Algebraic Modeling System) packet programming by an Intel Pentium Toshiba computer of 1.86 GHz processor and 504 MB RAM. Our approach is an extension of Gencer et al. (2009) but differs in that:

- The UAVs are not homogeneous but heterogeneous.
- The altitudes of UAVs are not constant and may be different according to the threats near the targets.
- The service time for each target is considered. Service times might be different for each target.
- The threats along the way are considered for each UAV. The way from any target to another one might be dangerous or forbidden.

- Three dimensions (3D) are considered. Targets have a third altitude coordinate besides latitude and longitude coordinates.
- Fewer constraints are used. Constraint 3 and 6 are not used.
- The threats from the targets themselves have been considered.
- Six variants of the static model are studied. This paper introduces 6 different models as detailed in Table 2.

Table 2. Static Model Descriptions

	One UAV/ More UAVs	Time window/ No TW	Homogeneous/ Heterogeneous
Model 1	One UAV	No TW	-
Model 2	One UAV	TW	-
Model 3	Multiple UAVs	No TW	Homogenous
Model 4	Multiple UAVs	No TW	Heterogeneous
Model 5	Multiple UAVs	TW	Homogenous
Model 6	Multiple UAVs	TW	Heterogeneous

As shown in the Table 2, Model-1 and Model-2 are for just one UAV, and the rest are for a UAV fleet. Model-2 is the TW extension of Model 1. Model-4 has heterogeneous UAV fleet unlike in Model-3 which has a homogenous UAV fleet. Either Model-3 or Model-4 has no TW constraint. Model-6 and Model-5 are the TW extensives of Model-4 and Model-3 respectively. Model-6 and Model-4 are the heterogeneous extension of Gencer et al. (2009).

To show the results, the same test problems proposed by Gencer et al. (2009) are used with the following six extensions:

1. In the GAMS formulation, UAVs are considered to be heterogeneous, not homogeneous. As they are heterogeneous, each UAV may have a different speed.

Different speeds affect the travelling time (y_{ij}). In the GAMS formula, " y_{ij} " is calculated according to the used UAV's speed as:

Travelling time (i,j)=d(i,j)/speed(ar)

2. Unlikely, the altitudes of UAVs are not constant. The altitudes of UAVs are calculated according to both the height of the targets and the threats from them. A safe altitude for each target is considered which defines the minimum altitude for the UAV to fly over that target. By doing this, in each step the altitudes of the UAVs and the distance above the targets may differ.

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}$$

3. The service time affects the operational time and may affect the path of the UAVs according to their endurance. In the previous study, the service time was not considered. The service time for each target is added to the formulation which is more realistic. Each target shall need a different time to be observed according to their importance, which should be included in the plans. The service time for each target is inserted in the formula as a parameter:

$$T(i) + \text{Travelling time}(i,j) + \text{ser}(i) - T(j) = L = 5000 * (1 - \text{SUM}(\text{ar}, X(\text{ar}, i, j)))$$

In the formulation “ar” stands for each UAV.

4. The threats along the way may be considered for each UAV. The way from one to another might be dangerous or forbidden. In the formulation a matrix table (table ok(i,j)) is added to the formulation that enables users to prohibit some of the ways between the targets. If the condition satisfies the given constraint, then the program assigns the feasible path, otherwise the prohibited path between the targets is not considered. The target can only be assigned to a UAV if the following condition is satisfied: -table ok(i,j)- which means there is no known or given threat along the way from target “i” to target “j”.

By doing this, the model looks for both the point reconnaissance and the road reconnaissance at the same time.

5. All the distance and cost calculations are computed in 3D which is necessary for the applications of UAV route planning. In the previous study, the distance between two targets was calculated as:

$$d_{12} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

In the proposed model, the distances and the costs are calculated in 3D with considering the threats from the targets as well like:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + ((z_i + e_i) - (z_j + e_j))^2}$$

In the formulation ‘ z ’ is the altitude of the target in the field and ‘ e ’ is the safe distance which describes the minimum height for UAVs to fly over the target.

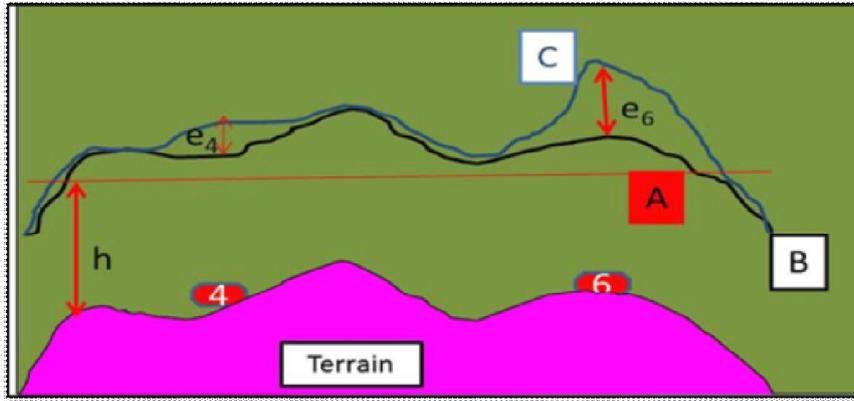


Figure 4. Real Military Flight Path Applications for UAVs.

As a graphic view of the constraint from the military perspective, it is not the case to either plan the path just “ h ” feet over the terrain as depicted “A” nor to plan it “ h ” feet over the targets as depicted “B” in the Figure 4. Flight path “C” which deals with the threats (e_4 and e_6) from the targets (4 and 6) shall be the real considerations for the UAV flight paths to fly safely.

6. For the UAV applications, the computational complexity is the most important requirement since the flight path planning has to occur quickly due to fast vehicle dynamics (Yang and Sukkarieh, 2008) and a rapidly changing military environment. More constraints make the algorithms run slowly. Formulas 2 and 4 are enough to assure that once UAV observe a target, it leaves that target. Hence, formulas 3 and 6 are not used in the GAMS formulation, due to the fact that they are inactive constraints. Formulas 4 and 5 are enough to assure that if one UAV takes off from an airport, it returns to the same airport to land at.

Although aforementioned six extensions are formulated differently;

- The UAV speeds are taken into consideration as 250 km/h,
- The ‘ z ’ coordinates, the ‘ e ’ safety distances and the service times (ser(i)) for the targets are considered as 0 sec,
- All the ways among the targets are allowed in GAMS,

to be able to compare the results with Gencer et al. (2009).

The exact approaches have the same basic problem of exponentially increasing computation time with the problem size (Chandler and Pachter,

1998). The most remarkable and nitty-gritty difference between Gencer et al. (2009) and the proposed model is not only the heterogeneity but also the processing time. In the integer programming and GAMS solutions, less constraints mean less computation time. Offering less constraints (if not necessary) will allow solving the same problems more quickly. Hence, the comparisons of the proposed model with the previous work with no TW constraint is depicted in Table-3 and with the TW constraint in Table-4.

Table 3. The Comparison Result without the TW Constraint

Number of Targets		Number of Vehicles							
		1		2		3		4	
		*	**	*	**	*	**	*	**
5	T	0.05	0.002	0.05	0.018	0.05	0.017	0.05	0.047
	C	341	341	381	381	425	425	494	494
	R	D-4-5-3-2-1	D-4-5-3-2-1	1:D-4-1 2:D-2-3-5-1	1:D-4-1 2:D-2-3-5-1	1:D-5-1 2:D-2-3-1 3:D-4-1	1:D-4-1 2:D-2-3-1 3:D-5-1	1:D-5-1 2:D-3-1 3:D-2-1 4:D-4-1	1:D-5-1 2:D-2-1 3:D-3-1 4:D-4-1
10	T	1.24	0.019	3.19	0.019	1.32	0.038	2.09	0.022
15	T	38.23	0.021	146.8	0.051	2.91	0.069	16.47	0.064

* Gencer et al.(2009), ** Cihan and Gencer, D:Dummy, T: Time, C: Cost, R: Route.

Table 4. The Comparison Result with the TW Constraint

Number of Targets		Number of Vehicles							
		1		2		3		4	
		*	**	*	**	*	**	*	**
5	T	0.05	0.018	0.05	0.01	0.05	0.001	0.05	0.001
10	T	1.15	0.001	5.71	0.031	3.35	0.02	5.11	0.016
15	T	382.34	0.018	471	0.016	231.35	0.016	1135	0.018

As shown in Table-3 and Table-4, the newly proposed algorithm has lower computational complexity as compared to Gencer et al (2009). It has generated the competitive results in comparison with the previous one.

Discussion and Conclusion

With the unexpected advances in space and communication technology, next generation UAV fleets will be characterized by their heterogeneity since there will be numerous different types of them. As the number of UAVs increase, fewer pilots will be able to be allocated for their control in the ground control stations.

As the UAV technologies boom and the targets learn more how to survive better in the field, the militaries will have to operate in a highly unknown and hybrid-threat environment in the coming decades. Thus, more intelligent algorithms will be required for the heterogeneous UAV routings in the specific missions.

Transitioning from unique UAV routing to joint routing, the VRPs will be considered to be able to perform the tasks within a joint/multinational multidimensional network enabled capability doctrine. One of the main challenges for UAV development is pre-planned flight path optimization. Hence, the processing time is the critical issue for the route planning for the UAVs. We review and compare our algorithm to the existing literature in order to improve its performance in terms of the solution quality and computational time. This work can be thought of as an extension of the previous one (Gencer et al, 2009) which also uses IP in order to find the optimum flight path for homogenous UAVs in 2D. Although satisfactory results were achieved, the drawback of the previous approach was the need for planning for a heterogeneous UAV fleet in 3D to include the threats from the targets themselves. In this paper, the solution is formulated as IP and solved by GAMS packet programming in a totally known static environment. In this way, the proposed model provides a more realistic approach for military applications.

The same test scenario problems mentioned in the previous one are used to test the proposed model. The results demonstrate that the new algorithm gives the heterogeneous UAV flight paths much faster without violating the given constraints. The computational results of the experiment stated that new model outperforms the old one.

These kinds of studies will contribute to the following challenges in UAV-based military operations:

- Creating military reconnaissance mission and planning efficiency,
- Lessening operator\pilot requirements,
- Increasing battlespace awareness for the real UAV applications,
- Lessening cost,
- Providing decision support information to commanders and reducing the decision cycle,
- Increasing autonomous heterogeneous UAVs,
- Lessening training requirements for ground based operators or pilots,
- Creating the ability to control more UAVs at the same time remotely,
- Lessening communication bandwidth requirements.

Future Works

With the pilot and operator shortages, “flying Asimos” will be the core of military operations in the next decades. Future works shall focus on the dynamic VRPs in an unknown 3D environment. The collaborations of UAVs among with themselves and other manned\unmanned systems as depicted in the Figure-1 should be considered.

The approach taken in this paper is relatively easy to handle, as the obstacles are fixed with respect to the place and the time. For the dynamic situations, the collision avoidances and kinematic constraints should be considered for the future studies.

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Genişletilmiş Özet

Heterojen İHA Filosu Rotalama Problemi için Tam Sayılı Programlama Modeli

Son yıllarda İnsansız Hava Araçları (İHA) pazarı ve kullanımı, gerek sivil gerekse askeri uygulamalarda inanılmaz oranda artmıştır. Bu trend, araştırmacıları İHA'lar konusunda farklı alanlarda çalışmaya motive etmiştir. Araç Rotalama Problemleri (ARP) bunların başında gelmektedir. Haberleşme ve bilgisayar teknolojilerindeki son gelişmeler, büyük ve daha karmaşık sistemlerin kullanıldığı operasyon sahasında yüzlerce İHA'nın kontrol ve yönetimini mümkün kılmıştır. Geçen yıllarda, İHA rota planlamaları konusunda çok sayıda bilimsel çalışmalar yapılmıştır.

İHA'ların sayıları ve çeşitleri arttıkça, bunları daha iyi yönetebilmek için akıllı rota planlamalarına olan ihtiyaç da artmaktadır. Artan bu ihtiyaçlar, heterojen İHA rota planlamaları konusunda bilimsel çalışmalar için hareket araştırmacılarını motive edecektir.

Aynı imkan ve kabiliyete sahip olan İHA'lar homojen, farklı imkan ve kabiliyetlere sahip İHA'lar ise heterojen olarak isimlendirilmektedir. Günümüz orduları, farklı tipteki ihtiyaçlar sebebiyle homojen İHA konseptinden heterojen İHA konseptine geçme eğilimindedirler. İHA rota planlamaları, heterojen İHA kabiliyetlerinin etkin bir şekilde kullanılmasını sağlayacak önemli etkenlerden bir tanesidir.

Bu çalışmada, askeri operasyonlarda kullanılan heterojen İHA'ların nota planlaması için daha kısa zamanda çözüm sunabilecek bir model önerilmiştir.

İnsansız Sistemler ve Statik Araç Rotalama Problemleri

İnsansız sistemler, insan müdahalesi olmadan verilen görevleri icra edebilecek şekilde hareket edebilen yer, hava, sualtı, suüstü araçlarından oluşan elektro-mekanik sistemlerdir (Vargas, 2012). İHA'lar, insansız sistemler içerisinde en yaygın kullanılan ve en önemli olanıdır. ABD'de 2011 yılı başkanlık bütçesinden insansız sistemler için ayrılan kaynağın %94'lük büyük bir bölümünün İHA'lar için ayrılması, bunun en çarpıcı göstergesidir (ABD İHA Yol Haritası, 2011).

Silahlı Kuvvetler için, İHA'lar gibi değerli sistemlere sahip olmak önemli olmakla birlikte, envantere bulunan bu sistemlerin etkin olarak kullanılması da önem arz etmektedir. Bu kapsamda, İHA'ların rota planlamaları elle veya bilimsel olarak hazırlanabilir. Ancak, verimli bir planlama için bilimsel yaklaşımlar özellikle hedef sayısının çok olduğu durumlarda en iyi rotanın bulunması için elzemdir.

ARP için çözüm yaklaşımları iki başlık altında toplanabilir: Kesin ve sezgisel algoritmalar. Kesin algoritmaların zayıf tarafı, en iyi çözümün bulunması için ihtiyaç duyulan işlem zamanıdır. Ancak bazı statik durumlarda, bu çalışmanın da ana konusu olan en iyi rotanın bulunması, işlem zamanından daha öncelikli olabilir. Bunun sebebi, rutin bazı askeri uygulamalarda statik rota planlamaları, İHA'ların göreve başlamalarından çok önce yapılması ve en iyi rotanın bulunması için yeterince zamanın olmasından kaynaklanmaktadır.

Problem

Savunma bütçelerinde dahi “ayağını yorganına göre uzat” prensibini göz ardı edemeyiz. İHA'lar keşfedildikleri andan itibaren, silahlı kuvvetler için önemli bir kuvvet çarpanı olmuşlardır. Kullanımlarının artması ve operatör sayılarının azalması, statik rota planlamalarını en iyileyecek çalışmaları tetiklemiştir.

Bu çalışmada, belirlenen bazı operasyonel tehditler altında, planlanan hedeflerin hepsini dolaşacak en iyi rotanın bulunması amaçlanmıştır. Çalışmada, daha gerçekçi askeri ortamın modellenebilmesi için;

- İHA'ların heterojen olduğu ve değişik dayanıklılıklarının olabileceği,
- Herbir İHA'nın hızlarının bilindiği ve sabit olduğu ancak birbirlerinden farklı olabileceği,
- İHA ve hedef sayılarının planlama öncesi bilindiği,

- Herbir hedef için zaman penceresi (ZP) kısıtı olduğu ve İHA'lar tarafından hedeflerin verilen ZP içerisinde gözetlenebileceği,
- İniş ve kalkış için tek bir yer kontrol istasyonunun olduğu kabul edilmiştir.

Tamsayı Programlama Tabanlı Bir Model Önerisi

Çalışmada, İHA ARP için tamsayı programlama çözüm önerisi sunulmuş ve GAMS paket programı ile çözülmüştür. Bir önceki (Gencer vd., 2009) çalışma genişletilmiş ve çözüm için gereken işlem süresi kısaltılmıştır. Bir önceki çalışmadan farklı olarak;

- İHA'lar homojen değil heterojen olarak ele alınmış,
- İHA'ların uçuş yükseklikleri sabit değil, hedeflerdeki tehditlere bağlı olarak değişken kabul edilmiş,
- Herbir hedef için servis süresi eklenmiş,
- Hedef servis sürelerinin birbirinden farklı olabilmesi sağlanmış,
- Hedefler arasındaki bazı yolların uçuşa kapatılabilme imkanı tanınmış,
- Enlem ve boylam bilgileri ile birlikte yükseklik bilgileri de ele alınarak 3 boyutlu rotalar çalışılmış,
- Daha az kısıt kullanılarak işlem süreleri azaltılmış,
- Hedeflerin bizzat kendi imkanlarından kaynaklanan tehditler probleme dahil edilmiş ve statik problemin 6 değişik versiyonu incelenmiştir.

Bazı değerler, önceki çalışmadaki veriler esas alınarak GAMS paket programında kodlanarak çözülmüş ve önceki çalışma ile karşılaştırılmıştır. Bu çalışmayı bir öncekinden farklı kılan özellik sadece işlem zamanının kısaltılması değil aynı zamanda problemin heterojen olarak ele alınmasıdır.

Tartışma ve Sonuç

Uzay ve haberleşme teknolojilerindeki hızlı ilerlemeler sayesinde, İHA'ların sonraki nesilleri daha da farklılaşacak, heterojenleşecek ve daha az operatör müdahalesine ihtiyaç duyacaktır.

İHA teknolojilerinin ilerlemesiyle, geleceğin orduları daha karmaşık tehditler barındıran ortamlarda operasyon yapmak zorunda kalacaklardır. Heterojen İHA'ların varlığı sebebiyle, rota planlamaları için daha gelişmiş algoritmalara ihtiyaç duyulacaktır. Birleşik/çokuluslu çok boyutlu ağ

destekli yetenek konseptine uygun olarak, tek İHA yönetiminden müşterek/birleşik İHA yönetimine geçilecektir.

GAMS 21.5 programından elde edilen sonuçlara göre, önerilen model bir önceki modele göre daha kısa sürede sonuç üretebilmekte ve heterojen filolar için de kullanılabilir. Bir önceki çalışmanın senaryası, test senaryası olarak kullanılmış, böylelikle kısıtlar ihlal edilmeden daha kısa sürede çözüme ulaşılabileceği gösterilmeye çalışılmıştır. Bu tür çalışmaların, İHA destekli yapılan askeri uygulamalarda;

- Askeri keşif görev etkinliğinin arttırılacağı,
- Durumsal farkındalığın arttırılacağı,
- Operasyon maliyetinin azaltılacağı,
- Karar desteği sağlanacağı ve karar döngüsünün kısaltılacağı,
- Daha otonom İHA'ların göreve sevk edileceği,
- Eğitim ihtiyacının azaltılacağı,
- İhtiyaç duyulan pilot/operatör sayısının azalacağı,
- Operasyon esnasında ihtiyaç duyulan haberleşme bant genişliği ihtiyacının azaltılacağı öngörülmektedir.