Pamukkale Univ Muh Bilim Derg, XX(X), XX-XX, 20XX

Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

A novel solution approach for optimization of swarm UAV formation control problem under uncertain and dynamic constraints: Crazyfly 2.0 application

Belirsiz ve dinamik kısıtlar altında sürü İHA formasyon kontrol probleminin optimizasyonu için yeni bir çözüm yaklaşımı: Crazyfly 2.0 uygulaması

Ukbe Üsame UÇAR[1], *Burak TANYERİ*[2*]

[1]Department of Aircraft Maintenance and Repair, School of Civil Aviation, Fırat University, Elazığ, Türkiye.
uuucar@firat.edu.tr, btanyeri@firat.edu.tr

Received/Geliş Tarihi: 12.08.2024 Revision/Düzeltme Tarihi: 29.01.2025 doi: 10.5505/pajes.2025.09552
Accepted/Kabul Tarihi: 24.03.2025 Research Article/Araştırma Makalesi

Abstract

In this article, Swarm UAV Formation Control Problem which is Homogeneous, Time-Window, Central Control Architecture, Uncertain, Dynamic Structure, and Leaderless (HTUDL-S-UAV) are obtained. For the solution of the problem, a new solution algorithm with generic and dynamic properties based on the annealing simulation algorithm is developed. The formation control architecture is determined as 5 layers and a new geometric approach to unit circle systematics has been developed to create formations. Tra-Coll and CCA algorithms are proposed in the literature for tracking the trajectories of UAVs and preventing collisions. The application study is carried out on 9 different formations (Triangle, Square, Pentagon, V Shape, Crescent, Star, Rhombus Formation with 4 and 8, Line) and 7 different missions (Swarm Navigation Mission, Formation-Switching Mission, The mission to Remove UAV from the Swarm, The mission of adding UAV to the Swarm, Swarm Rotation Mission, Swarm Division/Unification Mission, Trajectory Tracking Mission as a Swarm) using Crazyfly 2.0 drones in a ROS simulation program and on the real system. The proposed solution approach carried out all of these tasks in line with the specific conditions of the mission and achieved 3rd place in the Teknofest-2021 Swarm UAV Competition in Turkey. Furthermore, thanks to the study, it is aimed to create a decision support system for the optimal success of strategic and critically important Swarm UAV missions and other fleet autonomous systems.

Keywords: UAV Swarm Formation Control Problem, Metaheuristic Algorithm, Formation Tracking and Obstacle Avoidance Networks, Geometric System Architecture

Öz

Bu makalede, Homojen, Zaman Pencereli, Merkezi Kontrol Mimarili, Belirsiz, Dinamik Yapılı ve Lidersiz (HTUDL-S-İHA) Sürü İHA Formasyon Kontrol Problemi elde edilmiştir. Problemin çözümü için tavlama benzetim algoritmasına dayalı jenerik ve dinamik özelliklere sahip yeni bir çözüm algoritması geliştirilmiştir. Formasyon kontrol mimarisi 5 katman olarak belirlenmiş ve formasyonların oluşturulması için birim çember sistematiğine yeni bir geometrik yaklaşım geliştirilmiştir. Literatürde İHA'ların yörüngelerinin takibi ve çarpışmaların önlenmesi için Tra-Coll ve CCA algoritmaları önerilmiştir. Uygulama çalışması 9 farklı formasyon (Üçgen, Kare, Beşgen, V Şekli, Hilal, Yıldız, 4'lü ve 8'li Eşkenar Dörtgen Formasyonu, Çizgi) ve 7 farklı görev (Sürü Navigasyon Görevi, Formasyon Değiştirme Görevi, İHA'yı Sürüden Çıkarma Görevi, İHA'yı Sürüye Ekleme Görevi, Sürü Rotasyon Görevi, Sürü Bölme/Birleştirme Görevi, Sürü Olarak Yörünge Takip Görevi) üzerinde Crazfly 2.0 İHA'ları kullanılarak ROS simülasyon programında ve gerçek sistem üzerinde gerçekleştirilmiştir. Önerilen çözüm yaklaşımı tüm bu görevleri görevin kendine özgü koşulları doğrultusunda yerine getirmiş ve Teknofest-2021 Sürü İHA Yarışması'nda Türkiye 3.lüğü elde etmiştir. Ayrıca çalışma sayesinde stratejik ve kritik öneme sahip Sürü İHA görevlerinin ve diğer filo otonom sistemlerinin optimum başarısı için bir karar destek sistemi oluşturulması hedeflenmektedir.

Anahtar kelimeler: İHA Sürü Formasyonu Kontrol Problemi, Metasezgisel Algoritma, Formasyon Takibi ve Engelden Kaçınma Ağları, Geometrik Sistem Mimarisi

1 Introduction

UAVs are autonomous systems that can be controlled remotely and can fly without the use of a pilot. These systems are less affected by geographical and meteorological conditions and become an effective means of transportation in cases of heavy traffic. By increasing their payload capacities, developing imaging systems, and improving power units, UAVs can move comfortably at long ranges and high altitudes. Due to these functional structures, the usage area of UAVs is expanding and they are used in swarms to fulfill their missions more effectively, quickly, flexibly, and reliably. Reconnaissance and surveillance, monitoring of traffic density, logistics, military operations, agriculture, and natural disasters such as fire and earthquake are the areas where Swarm UAVs are used intensively. One of the most important points in the use of UAV swarm is formation control. [1]. There is a need for an accurate formation control algorithm that includes many parameters and constraints to perform the tasks in a simultaneous and collaborative structure. The charge status of UAVs, the communication range of each, and avoidance of collision with each other are some of these constraints. In addition, in cases where a UAV disappears from the system or a new UAV is added to the system, the formation is not disrupted and the formation control algorithm responds quickly to changing situations are other constraints affecting the system. In recent years, researchers have been making an intense effort on the formation control of UAV Swarm [2- 9].

Swarm UAVs are generally divided into two groups homogeneous and heterogeneous. While all UAVs have the same characteristics in homogeneous swarms, UAVs in heterogeneous swarms may differ due to their payload

[*]Corresponding author/Yazışılan Yazar

capacity, automation levels, and platform configurations. In terms of control architecture, Swarm UAVs are divided into two centralized [10, 11] and decentralized [12] control architectures. In the central control architecture, UAVs do not communicate with each other, UAV information is collected in a center and UAVs are configured from this center. In the decentralized control architecture, UAVs communicate with each other and make the necessary decisions. Swarm UAVs are divided into three terms Static, Dynamic, and Hybrid. In a static swarm, the number of UAVs in the system is fixed and UAV tasks are predetermined. In these swarms, the number of UAVs in the system does not change and a new UAV cannot be included in the system. In dynamic swarms, a new UAV may be added to the system at any time or may leave the system. In the hybrid herd, there is a static swarm in the center and new individuals can be included in the system or leave the system in line with the permission of this static swarm [13].

In recent years, many methodologies related to formation control algorithms have been presented by researchers. Leader-follower-based strategy is generally used in these studies. In this strategy, a leader is generally determined in the swarm, and the formation is formed over this leader [1]. This strategy is used intensively by scientists because it facilitates application and analysis studies [14-28]. In real-life applications such as military operations and fires, leader-follower swarm strategies are insufficient due to not meeting the dynamic requirements. For this reason, researchers spend intense efforts on leaderless swarm strategies. Apart from the leader-follower, there are "Virtual Structure [29-31]", "Behavior-Based [32]", "Artificial Potential Field[33]", "Hierarchical Method [34,35]", "Consensus-Based [36-39]" and "Intelligent Control Approaches [40-44]" strategies as formation control mechanisms [45].

Many methods have been developed for Swarm UAV Formation Control Algorithms in the literature. Wu et al., obtained swarm formation control problem-based leader-follower and use the theory of consistency for solving the problem [46]. Dong et al., examined the swarm formation control problem where the speeds of UAVs are different from each other and formations change over time. They proposed a Formation Protocol Design considering time-varying the solution to the problem [47]. Liang et al., discussed the formation control problem-based leader-follower for the UAVs with fixed wings and considered limited movement and unknown distribution in the problem. Liang et al. discussed the formation control problem based on leader-follower for the UAVs with fixed wings and considered limited movement and unknown distribution in the problem [48]. Guo et al. focused on the relative position and formation control of the UAV swarms [49]. Fu et al. dealt with the swarm formation control and reconstruction problem for obstacle and unobstacle situations. In this study, they developed the collision estimate mechanism to avoid obstacles [50]. Yu et al. addressed the formation control problem in which swarm structure changes over time and carried out both numerical and experimental studies in the application section [51]. Speck and Bucci tackled the formation control problem that is decentralized for the UAV swarms which are fixed wings and proposed a new solution approach with multi-objective based on reinforcement learning formulation [52]. Zhu et al. handled the formation control problem with a leader-follower strategy for heterogeneous UAV swarm and concentrated on the display and verification system in this study [53]. Ali et al. developed a solution approach based on the Particle Swarm Optimization Algorithm for the swarm formation control problem consisting of 10 UAVs and used a leader-follower-based strategy [54]. Yang et al., conducted survey research on metaheuristic algorithms using swarm intelligence considering the studies done in literature in recent years [55].

Fu et al. developed a virtual leader-based control algorithm considering the "V" type and line type formations and made a simulation study [56]. Wu et al. proposed a consensus algorithm for formation control and used the Particle Swarm Optimization algorithm to avoid the obstacle [57]. Wang et al. examined the formation control problem in terms of discrete and continuous times [58]. Li and Fang focused on the static and dynamic obstacle avoidance problems of the swarm and realized simulation study for “V”, “W” and “X” formations [59]. Liu et al. obtained a formation control problem with limited time regarding anti-collision and enter saturation [60]. Shen et al. concentrated on reducing computation and communication difficulties when the number of UAVs in the formation increased [61]. Chen and Duan designed a two-layer solution architecture for the formation control problem of UAVs with fixed-wing [62]. Shen and Wei generated a control algorithm based on the behaviors of birds for the swarm control problem and realized a simulation study in Matlab [63]. An et al. used AESO and TV-BLF methods for swarm quadrotor formation control problems in terms of leader-follower and time-varying [64]. The solution methodology with two layers for the UAVs formation control problem was produced by Shao et al. This method, which has multiple leaders and followers, has been tested in simulation studies [65].

In addition to these articles, the articles published in 2024 were analyzed and summarized as follows. In general, the papers addressed issues related to the control of autonomous systems such as multi-agent systems, unmanned aerial vehicles (UAVs) and surface vehicles (SAVs). The main problems have been found to be the safe and stable management of heterogeneous and nonlinear systems, communication delays, tracking error constraints and coordination challenges. In particular, solutions have been developed to improve the performance of autonomous systems, focusing on specific application areas such as fixed-wing drones and UAV-ASV systems. Another focus of the studies is the safe and efficient implementation of control methods with low computational cost. Advanced control techniques such as local control barrier functions (CBFs), Lyapunov-based methods and leader-follower control laws have been used to solve these problems. In addition, fuzzy logic systems (FLS), virtual leaders and adaptive control approaches are also frequently used. The results obtained show that the proposed methods are validated through theoretical analysis and simulations and significantly improve the system performance. These studies, supported by simulations and experiments, have made significant contributions to making autonomous systems more reliable and effective [84-107].

In this study, Swarm UAV Formation Control Problems with Homogeneous, Time-Window, Central Control Architecture, Uncertain, Dynamic Structure, and Leaderless (HTUDL-S-UAV) are discussed and a new solution approach based on Annealing Simulation Algorithm has been developed to solve the problem. In the problem, 9 different formations and 7 different missions were defined and the effectiveness of the algorithm was tested on these tasks. In the testing phase, the algorithm was first implemented on Crazyfly 2.0 virtual drones on the ROS Simulation Program. In the next step, the algorithm performed the specified tasks on real Crazyfly 2.0 drones. This article is the first in the literature, as far as is known, due to the proposed problem and the developed solution architecture. The contributions of the article to the literature are expressed in the following items.

• There is no study in the literature in which the "Simulation Annealing Algorithm" is used in Swarm UAV Formation Control Architecture.

• It is the first study in the literature to consider 9 different formations and 7 different tasks together. The developed method differs from other solution methodologies in the literature as it provides solutions to all of these mission combinations.

• It is envisaged that the separation of the swarm into different formations and the merging of two swarms from different formations into a third different formation have been studied for the first time in the literature to the best of our knowledge.

•A new geometric solution approach based on the unit circle and center of gravity is proposed in the formation-creating architecture.

•The new heuristic algorithms for trajectory tracking and collision avoidance are proposed.

The rest of the article is arranged as follows. In Chapter 2, the problem is defined and the variables related to the problem are expressed. The solution architecture developed in Chapter 3 is presented. In Chapter 4, simulation and experimental applications are made. In addition, the application results are analyzed in this section. In Chapter 5, the article is summarized; general evaluations and suggestions for future studies are made.

2 Preliminaries and Problem Statement

2.1 Theory of the UAV Swarm Formation Control Problem

UAV Swarm Formation Control Problems is a multi-disciplinary problem that has been studied intensively in recent years and can be addressed from different perspectives

A swarm system with "n" elements has a weighted directed and undirected graph "$G = (W, E, A)$" structure formed by nodes set "$W = \{1,2, \dots, n\}$", set of edge "$E \subseteq \{(i,j) : i,j \in W\}$" and a weighted adjacency matrix $A = [a_{i,j}]_{N\times N}$ [1, 22]. In the graph, each UAV is expressed with the index "i=j" and the UAV cluster is represented by $N = \{1, \dots, i = j, \dots, n\}$.

$$A = \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} & \cdots & a_{1,n-2} & a_{1,n-1} & a_{1,n} \\ a_{2,1} & a_{2,2} & a_{2,3} & & a_{2,,n-2} & a_{2,n-1} & a_{2,n} \\ & \vdots & & \ddots & & \vdots & \\ a_{i,1} & a_{i,2} & a_{i,3} & \cdots & a_{i,n-2} & a_{i,n-1} & a_{i,n} \\ a_{n,1} & a_{n,2} & a_{n,3} & & a_{n,n-2} & a_{n,n-1} & a_{n,n} \end{bmatrix}$$ Equation 1.

In Equation 1, A Matrix defines whether there is a connection between nodes "i" and"j". If there is a path between nodes"i" and"j"; "$a_{i,j} = 1$", otherwise; "$a_{i,j} = 0$". Furthermore, it is "$a_{i,i} = 0$" in the matrix [1,22].

Finally, let's define the Laplacian Matrix $\left(L \in R^{N\times N} \text{ and } L = [l_{i,j}]_{N\times N}\right)$ which has an important place in describing the neighborhood relations of a graph. The following assumptions are made regarding the Laplacian Theorem in the Swarm Formation Control Problem on an undirected graph [1,66].

(i). The matrix L has at least one zero eigenvalue element and 1 is the corresponding eigenvector. Accordingly, L1=0.

(ii). If graph G consists of an architecture with a spanning tree, Then a simple eigenvalue of the matrix L is zero, and all of the other eigenvalues which are N-1 are made up of positive real sections.

2.2 HTUDL-S-UAV Problem

UAV Swarm Formation Control Problems is a multi-disciplinary problem that has been studied intensively in recent years and can be addressed from different perspectives according to application areas. Military operations [67-69], surveillance and reconnaissance activities [70-71], agriculture [72, 73], logistics [74, 75], and forest fires [76,77] are some of the areas where the problem is applied. Since there is more than one UAV in the problem, they have moved autonomously, the ideal formation geometry is revealed and the formation control algorithm is developed, communication between the swarm and the central computer requires the collaboration of many science fields (geometry, mathematical, industrial engineering, computer engineering, automotive engineering, electronic engineering) and takes on a multi-disciplinary structure. The HTUDL-S-UAV problem addressed in this article has the following characteristics.

• The All UAVs in the swarm have the same characteristics.

• Formation tasks must be completed within a certain time window and an unfulfilled task is considered unsuccessful. In addition, each UAV can stay in the air for a certain period due to its battery charge state. As the state of charge decreases, the stabilization of the UAV decreases and the UAV leaves its orbit. In this case, the UAV is damaged by hitting obstacles or other UAVs and causing the formation to deteriorate. For these reasons, UAVs must perform their duties within the specified time intervals.

• UAV information is monitored instantly on the central computer and all formation tasks are carried out on this computer. Commands are sent to UAVs by this computer. For this reason, the problem has central control architecture.

• There are different formation tasks in the problem and the transitions between these formations are determined randomly. Each formation mission has a different geometric structure, and therefore the number of UAVs varies in each mission. For this reason, the problem has a dynamic structure.

• In some formation missions, any UAV can be removed from the system at any "t" moment while the swarm is in the air. In this way, if any UAV leaves the swarm, it is tried to understand whether its formation is disrupted and the reaction of the algorithm. The problem has an uncertain structure because it is not clear when which UAV will be removed from the system and the order of formation missions is not clear.

• Due to the uncertain and dynamic nature of the problem, non-leader-based solution architecture is being developed. In this way, it is aimed to perform the formation task without dispersion in case of loss of UAV due to signal failure and charging status.

The problem stated in this article is proposed based on the TEKNOFEST-2021 Swarm UAV Competition. In the problem, there are 9 different formations (triangle, square, pentagon, v, crescent, star, equilateral quadrangle with 4 UAV and 8 UAV, line) and 7 different missions (navigation as a swarm, formation transformation, adding and removing individuals from a swarm,

swarm rotation, swarm division, and merging swarm trajectory tracking) to which these formations can be applied.

In the problem, UAVs start to move from different coordinate points and these points are determined randomly. In this case, generic solution geometry must be created for each formation. To overcome this problem in the article, a solution architecture based on coordinate-independent and analytical circle geometry is developed. This solution architecture is thought to be used for the first time in the literature. Information on the formations considered in the article and suggested generic solution geometries are given below.

2.3 Geometric Solution Approach

In the Geometric Solution Approach, a center of gravity is formed in the direction of "x" and "y" coordinates for UAVs at different starting points. This center is considered as the origin point. A radius r is generated according to the distance between the two UAVs in the formation and the geometric shape of the formation. Depending on this radius, a circle is created and UAVs are placed on this circle according to the origin coordinates and radius length. As a result, shapes of pentagonal, triangular or other formation types are generated with a distance between them equal to the distance between the two UAVs. At the same time, the "x" and "y" coordinates of each UAV in the formation can be calculated with this formulation. The most important innovation here, unlike other studies in the literature, is the creation of a center of gravity for the UAVs and the generation of the reference point of all UAVs with generic equations according to the radius "r" depending on the circle developed. In the literature, vector-based approaches are generally used, which are time-consuming and computationally expensive. With the method proposed here, reference points can be determined in a faster and more practical way. Formation types and proposed geometric formulations are described in the following sections.

2.3.1 Triangle Formation

In the triangle formation, it is desired that the UAVs, which are at random positions on the ground, change into a triangle form with an "x" distance between them within the "t" period. This "t" time and "x" distance can take different values depending on the type of task. The proposed solution geometry for the triangle formation is shown in Figure 1 and Equation 2.

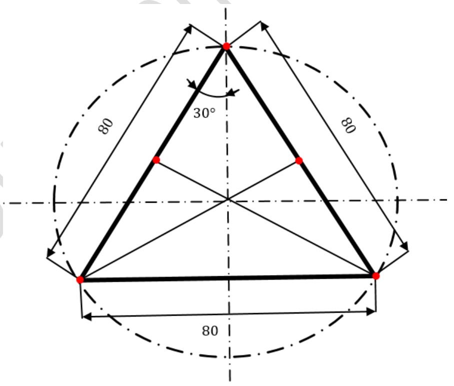


Figure 1. Triangle solution geometry

a	=	$distance\ between\ two\ UAVs$
x_i	=	$initial\ x\ coordinate\ of\ "i.UAV"$
$\bar{x}$	=	$\frac{\sum x_i}{3}$
y_i	=	$initial\ y\ coordinate\ of\ "i.UAV"$
$\bar{y}$	=	$\frac{\sum y_i}{3}$
R	=	$formation\ circle\ radius$
R	=	$\frac{2*\sqrt{a^2-\left(\frac{a}{2}\right)^2}}{3}$
x_1	=	$\bar{x}-R*\cos 30$
y_1	=	$\bar{y}-R*\sin 30$
x_2	=	$\bar{x}$
y_2	=	$\bar{y}+R$
x_3	=	$\bar{x}+R*\cos 30$
y_3	=	$\bar{y}-R*\sin 30$

Equation 2

2.3.2 Square Formation

In the square formation, 4 drones randomly positioned on the ground are expected to enter the formation at any "t" time, with an "x" unit distance between each of them. The "t" time and "x" distance here vary according to the problem type. The solution architecture developed for the square formation is shown in Figure 2 and Equation 3.

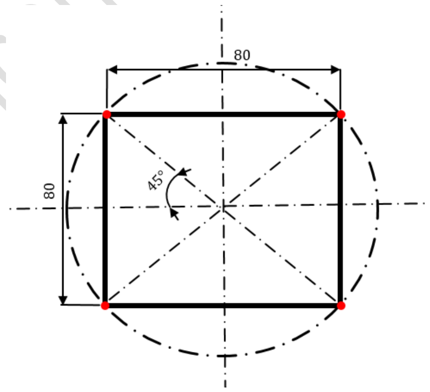


Figure 2. Square formation geometry

a	=	$distance\ between\ two\ UAVs$
x_i	=	$initial\ x\ coordinate\ of\ "i.UAV"$
$\bar{x}$	=	$\frac{\sum x_i}{4}$
y_i	=	$initial\ y\ coordinate\ of\ "i.UAV"$
$\bar{y}$	=	$\frac{\sum y_i}{4}$
R	=	$formation\ circle\ radius$
R	=	$\sqrt{\frac{a^2}{2}}$
x_1	=	$\bar{x}-R*\cos 45$
y_1	=	$\bar{y}-R*\sin 45$
x_2	=	$\bar{x}-R*\cos 45$
y_2	=	$\bar{y}+R*\sin 45$
x_3	=	$\bar{x}+R*\cos 45$
y_3	=	$\bar{y}+R*\sin 45$
x_4	=	$\bar{x}+R*\cos 45$
y_4	=	$\bar{y}-R*\sin 45$

Equation 3

2.3.3 Pentagon Formation

In the pentagonal formation, there are five drones randomly placed at different coordinates on the ground. In this formation, at any "t" moment determined by the competition jury, 5 drones are expected to enter the formation with an "x" distance between them. The solution mechanism based on the circle formulation suggested for the pentagonal formation is given in Figure 3 and Equation 4.

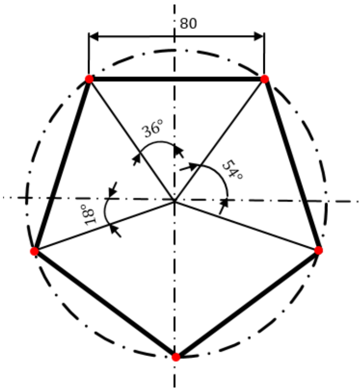


Figure 3. Pentagon formation geometry

a	=	*distance between two UAVs*
x_i	=	*initial x coordinate of "i.UAV"*
$\bar{x}$	=	$\frac{\sum x_i}{5}$
y_i	=	*initial y coordinate of "i.UAV"*
$\bar{y}$	=	$\frac{\sum y_i}{5}$
R	=	*formation circle radius*
R	=	$\left(\frac{\sqrt{50+10\sqrt{5}}}{10}\right) * a$
x_1	=	$\bar{x}$
y_1	=	$\bar{y} - R$
x_2	=	$\bar{x} - R * \cos 18$
y_2	=	$\bar{y} - R * \sin 18$
x_3	=	$\bar{x} - R * \cos 54$
y_3	=	$\bar{y} + R * \sin 54$
x_4	=	$\bar{x} + R * \cos 54$
y_4	=	$\bar{y} + R * \sin 54$
x_5	=	$\bar{x} + R * \cos 18$
y_5	=	$\bar{y} - R * \sin 18$

Equation 4

2.3.4 "V" Formation

In the V formation mission, 5 drones are randomly placed on the ground and then the drones are asked to line up in a "V" shape with an "x" distance between them at any "t" moment. The geometric solution steps for the V formation task are shown in Figure 4 and Equation 5.

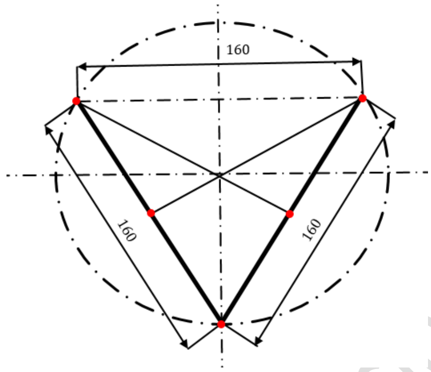


Figure 4. “V” formation geometry

a	=	*distance between two UAVs*
x_i	=	*initial x coordinate of "i.UAV"*
$\bar{x}$	=	$\frac{\sum x_i}{3}$
y_i	=	*initial y coordinate of "i.UAV"*
$\bar{y}$	=	$\frac{\sum y_i}{3}$
R	=	*formation circle radius*
R	=	$\frac{2 * \sqrt{a^2 - \left(\frac{a}{2}\right)^2}}{3}$
x_1	=	$\bar{x} - R * \cos 30$
y_1	=	$\bar{y} - R * \sin 30$
x_2	=	$\bar{x}$
y_2	=	$\bar{y} + R$
x_3	=	$\bar{x} + R * \cos 30$
y_3	=	$\bar{y} - R * \sin 30$

Equation 5

2.3.5 Crescent Formation

The crescent formation consists of 6 drones located at different starting coordinates. In the formation, the time is determined instantly by the jury, the distance between each drone is "x" units and this "x" distance can vary. The proposed geometric approach for crescent formation is shown in Figure 5 and Equation 6.

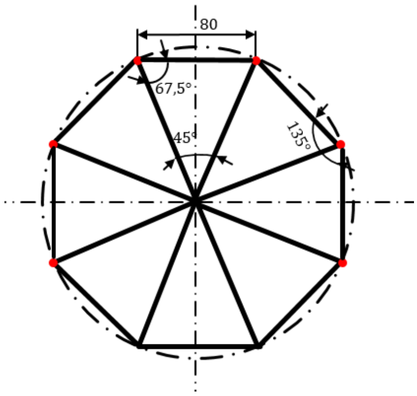


Figure 5. “V” formation geometry

a	=	$distance\ between\ two\ UAVs$
x_i	=	$initial\ x\ coordinate\ of\ "i.UAV"$
$\bar{x}$	=	$\frac{\sum x_i}{6}$
y_i	=	$initial\ y\ coordinate\ of\ "i.UAV"$
$\bar{y}$	=	$\frac{\sum y_i}{6}$
R	=	$formation\ circle\ radius$
R	=	$\sqrt{\frac{a^2}{2*(1-cos45)}}$
x_1	=	$(R*cos67.5°)$
y_1	=	$-(R*sin67.5°)$
x_2	=	$-(R*cos67.5°)$
y_2	=	$-(R*sin67.5°)$
x_3	=	$-(R*cos22.5°)$
y_3	=	$-(R*sin22.5°)$
x_4	=	$-(R*cos22.5°)$
y_4	=	$(R*sin22.5°)$
x_5	=	$-(R*cos67.5°)$
y_5	=	$(R*sin67.5°)$
x_6	=	$(R*cos67.5°)$
y_6	=	$(R*sin67.5°)$

Equation 6

2.3.6 Star Formation

The star formation consists of 10 drones, and initially, the drones are randomly deployed on the ground. At a "t" moment determined by the jury, the drones take off from the ground and must move to star formation within "a" time. Information about the formation is shown in Figure 6 and Equation 7.

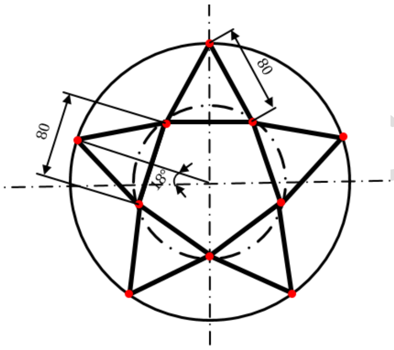


Figure 6. Star solution geometry

a	=	$distance\ between\ two\ UAVs$
x_i	=	$initial\ x\ coordinate\ of\ "i.UAV"$
$\bar{x}$	=	$\frac{\sum x_i}{10}$
y_i	=	$initial\ y\ coordinate\ of\ "i.UAV"$
$\bar{y}$	=	$\frac{\sum y_i}{10}$
R	=	$formation\ circle\ radius$
R	=	$\frac{\sqrt{25+10\sqrt{5}}}{10}*a$
b	=	$Distance\ from\ the\ center\ to\ the\ point\ at\ the\ ends\ of\ the\ star$
b	=	$r+\frac{\sqrt{3*a^2}}{4}$
x_1	=	$\bar{x}-b*\cos 54°$
y_1	=	$\bar{y}-b*\sin 54°$
x_2	=	$\bar{x}-b*\cos 18°$
y_2	=	$b*\sin 18°$

Equation 7

x_3	=	$\bar{x}$
y_3	=	b
x_4	=	$\bar{x}+b*\cos 18°$
y_4	=	$b*\sin 18°$
x_5	=	$\bar{x}-b*\cos 54°$
y_5	=	$\bar{y}-b*\sin 54°$
x_6	=	$\bar{x}$
y_6	=	$-R$
x_7	=	$\bar{x}-r*\cos 18°$
y_7	=	$\bar{y}-r*\sin 18°$
x_8	=	$\bar{x}-r*\cos 54°$
y_8	=	$r*\sin 54°$
x_9	=	$(r*cos54°)$
y_9	=	$(r*sin54°)$
x_{10}	=	$(r*cos18°)$
y_{10}	=	$-(r*sin18°)$

Equation 7

2.3.7 Rhombus Formation created from four UAVs

Information about the equilateral formation consisting of four drones is shown in Figure 7 and Equation 8.

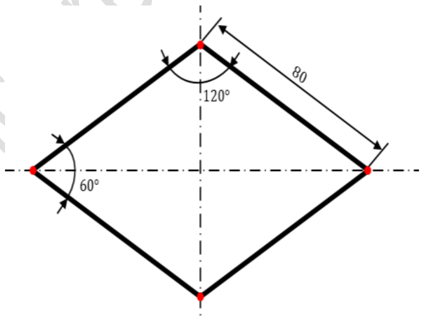


Figure 7. "V" formation geometry

a	=	$distance\ between\ two\ UAVs$
x_i	=	$initial\ x\ coordinate\ of\ "i.UAV"$
$\bar{x}$	=	$\frac{\sum x_i}{5}$
y_i	=	$initial\ y\ coordinate\ of\ "i.UAV"$
$\bar{y}$	=	$\frac{\sum y_i}{5}$
R	=	$formation\ circle\ radius$
R	=	$\frac{a}{2}\sqrt{3}$
x_1	=	$\bar{x}$
y_1	=	$\bar{y}-\frac{a}{2}$
x_2	=	$\bar{x}-R$
y_2	=	$\bar{y}$
x_3	=	$\bar{x}$
y_3	=	$\frac{a}{2}$
x_4	=	R
y_4	=	$\bar{y}$

Equation 8

2.3.8 Rhombus Formation created from four UAVs Rhombus Formation created from eight UAVs

In a rhombus formation with 8 drones, the distance between each drone should be equal. Drones rise from the ground at different coordinates and pass to the relevant formation within the "p" time with the command of the jury. The geometric representation and mathematical formulation of the relevant formation are shown in Figure 8 and Equation 9.

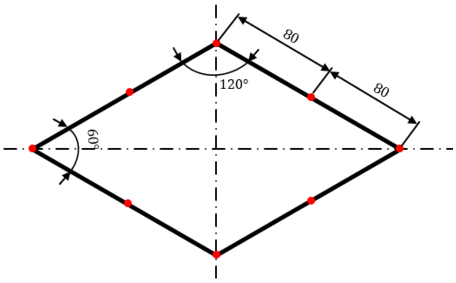


Figure 8. “V” formation geometry

a	$=$	$distance\ between\ two\ UAVs$
x_i	$=$	$initial\ x\ coordinate\ of\ "i.UAV"$
$\bar{x}$	$=$	$\frac{\sum x_i}{8}$
y_i	$=$	$initial\ y\ coordinate\ of\ "i.UAV"$
$\bar{y}$	$=$	$\frac{\sum y_i}{8}$
R	$=$	$formation\ circle\ radius$
R	$=$	$a\sqrt{3}$
x_1	$=$	$\bar{x}$
y_1	$=$	$\bar{y} - a$
x_2	$=$	$\bar{x} - \frac{R}{2}$
y_2	$=$	$\bar{y} - \frac{a}{2}$
x_3	$=$	$\bar{x} - R$
y_3	$=$	$\bar{y}$
x_4	$=$	$\frac{R}{2}$
y_4	$=$	$\frac{a}{2}$
x_5	$=$	$\bar{x}$
y_5	$=$	a
x_6	$=$	$\bar{x} - \frac{R}{2}$
y_6	$=$	$\frac{a}{2}$
x_7	$=$	R
y_7	$=$	$\bar{y}$
x_8	$=$	$\frac{R}{2}$
y_8	$=$	$-\frac{a}{2}$

Equation 9

2.3.9 Line Formation

In line formation, 5 drones taking off from different coordinates are required to move on a single line with a certain "x" distance between them. Information about the formation is shown in Figure 9 and Equation 10.

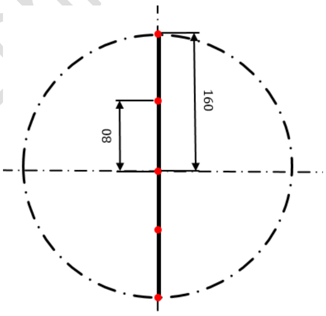


Figure 9. “V” formation geometry

a	$=$	$distance\ between\ two\ UAVs$
x_i	$=$	$initial\ x\ coordinate\ of\ "i.UAV"$
$\bar{x}$	$=$	$\frac{\sum x_i}{4}$
y_i	$=$	$initial\ y\ coordinate\ of\ "i.UAV"$
$\bar{y}$	$=$	$\frac{\sum y_i}{4}$
R	$=$	$formation\ circle\ radius$
R	$=$	$2 * a$
x_1	$=$	$\bar{x}$
y_1	$=$	$\bar{y}$
x_2	$=$	$\bar{x}$
y_2	$=$	$\frac{R}{2}$
x_3	$=$	$\bar{x}$
y_3	$=$	$\bar{x} - \frac{R}{2}$
x_4	$=$	$\bar{x}$
y_4	$=$	R
x_5	$=$	$\bar{x}$
y_5	$=$	$\bar{y} - R$

Equation 10

3 Solution Methodology

The formation control problem is a type of problem where the solution becomes very difficult as the number of individuals in the swarm increases and a manual solution is impossible. Solving the problem using mathematical modelling is difficult and takes a lot of time, since individuals in the system are constantly changing places, adding/removing individuals, and the type of task can change at any time. In addition, the difficulty of the problem increases when individuals do not collide with each other, and battery status and trajectory tracking are taken into account. In this article, a new solution approach is developed for the formation control problem by using a simulated annealing algorithm based on geometric models. The formation control architecture is used in solving the problem in section 3.1. and the developed solution algorithm is in sections 3.2., 3.3. and 3.4 are also shown.

3.1 Formation Control Architecture

Trajectory tracking, anti-collision, stabilization, modularity, efficiency, non-dissipation, and dynamics are some of these indicators. To realize these indicators in a successful swarm duty, an architecture consisting of hierarchical layers must be created. In this article, a 5-layer control architecture is created for the swarm routing task, as shown in Figure 10.

At the Mission Planning Level, the tasks described in Chapter 4 and the formations to be applied in these tasks are planned. Parameters such as formation time, take-off time, landing time, hovering time, starting coordinates, total mission time, and number of UAVs are entered into the algorithm at this level.

At the formation realization level, using the proposed algorithm in section 3.2., taking into account the parameters of the previous level, the UAVs to be taken in the formation and their positions at each "t" time are determined. While determining the UAV movement routes, it is aimed that the two UAVs will not collide with each other and that the mission will be completed before the UAV battery capacity is exceeded.

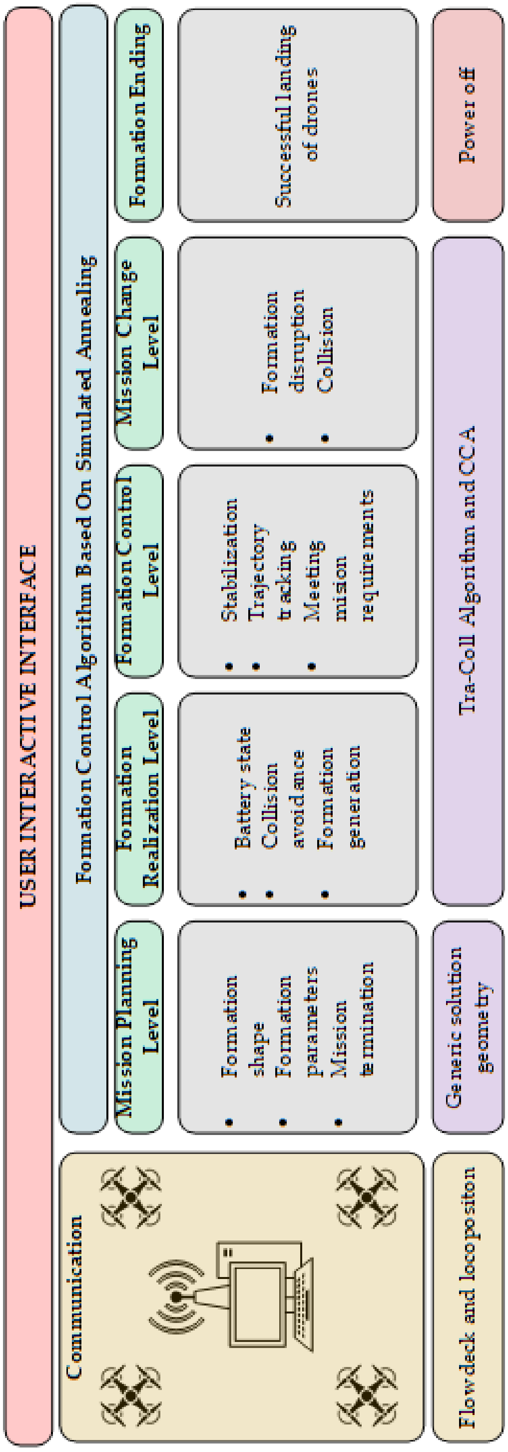


Figure 10. 5-layer formation control architecture [78].

3.2 Formation Control Algorithm Based On Simulated Annealing

In this paper, Formation Control Algorithm Based On Simulated Annealing (FCA-SA) is developed to solve the HTUDL-S-UAV. The simulated annealing algorithm, which is a stochastic search, Kirckpatrik et al., developed by taking the physical annealing process of solids as an example. The algorithm progresses as iterative and uses different movement mechanisms to improve solution quality. While the movements increasing solution quality are accepted as the initial solution, actions that do not improve solution quality are admitted with a certain percentage so as not to get stuck local optimum. The Boltzman stochastic factor ($P = e^{(-\Delta E/T)}$) is also used for the acceptance probability of the poor-quality solution. The simulated annealing has many parameters [79-81]. Many parameters need to be decided in the simulated annealing algorithm. The objective function, selection of neighbouring solutions, initial solution, initial temperature, and cooling rate can be given as an example of these parameters.

Table 1. Formation Optimization Algorithm Based on Simulated Annealing Method

→ *initial temperature* = 1000; *final temperatur* = 1;
→ *cooling rate* = 0.95; *enter mission type*;
→ *enter mission parameters*;
→ *enter initial UAV speed and control information*;
→ *Randomly generate an initial solution = init* $_x$;
→ *Calculate fitness value*;
→ $f(init\_x)$ = $Calculatefitnessfunction(init\_x)$;
while (***temperature*** ≤ ***final temperature***)
  → *x* = *new produced solution based on the swap mechanism*
  → *x* = [*order of mission*, *UAV x coordinate*, *UAV y coordinate*]
  $Calculatefitnessfunction(x)$
    → *update the global best solution and local best solution information to be passed to the next iteration according to the fitness function*;
    → *If the global solution does not improve for a certain number of iterations* → $PerturbationMechanism(x)$;
    → *temperature* = *temperature* ∗ *cooling rate*;
Calculatefitnessfunction(x)
  → *fitnessfunction* = *totalmissionduration* = *takeoff time* + *formation time* + *landing time*
    → *if the mission area has been exceeded* → *totalmissionduration* = *totalmissionduration* ∗ 1000;
    → *If the departure time is more than the jury's mission departure time* → *totalmissionduration* = *totalmissionduration* ∗ 1000;
    → *totalmissionduration* = $Tra - Coll\_Control(x)$;
    → *If totalmissionduration is greater than the total mission time specified by the jury* → *totalmissionduration* = *totalmissionduration* ∗ 1000;
Tra − Coll_Control(x)
    → *If two UAVs collided during the formation* → *totalmissionduration* = *totalmissionduration* ∗ 1000;
PertrurbationMechanism
   → *"Split the 'solution x' into two parts and reassemble it by swapping the parts*;

In this paper, the objective function is the minimization of the total mission (operation) time. The swap method is used as the neighbour generation mechanism. The initial solution, initial temperature, cooling rating, and final temperature, which is the stopping criterion, were determined as a result of simulation experiments. In line with this information, the developed interface and the solution algorithm proposed for the problem is demonstrated in figure 11 and table 1.

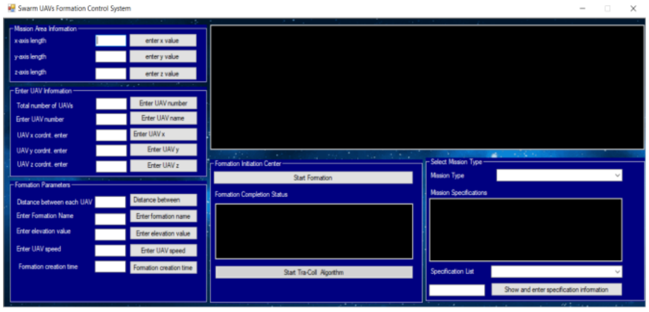


Figure 11. Interface developed for formation control.

Figure 11 shows the interface used for UAV pattern generation and control. In the system where mission information, number of UAVs and mission type are entered, the optimal formation structure and formation type are output. In addition, mission time and whether there is a collision or not are defined in the interface. Simulated Annealing algorithm is used in the interface.

3.3 Tra-Coll (Trajectory-Collision) Algorithm

Tra-Coll is an algorithm that controls whether it is progressing within the determined route of each UAV during operation. The algorithm tracks the distance of each UAV to the other UAVs, which is predetermined by the jury. If a deviation occurs in the trajectory or tracking distance, the algorithm instantly and automatically updates the heading of the UAV and keeps it on the mission route. The steps of the algorithm are provided below.

N	=	*Total number of UAV*
T	=	*Task end time*
$i = j$	=	*The index number of the UAV* $: i = j = 1, \dots, N$
t	=	*The time period in which the UAV is controlled* $: T = 1, \dots, T$
$x_{i,t}$	=	"x" *coordinate at* "t" *time of* "i". *UAV*
$y_{i,t}$	=	"y" *coordinate at* "t" *time of* "i". *UAV*
x_b	=	"x" *coordinate to be found along the trajectory*
y_b	=	"y" *coordinate to be found along the trajectory*
sm	=	*permissible amount of deviation from the relevc*

The deviation control for any "t" time is calculated according to the formula below.

In addition, the distance between each UAV needs to be maintained throughout the flight process. In this sense, the distances between UAVs are computed at every "t" time. If the distance between the UAV pair falls below the predetermined safety distance, the system gives a warning and updates the headings of the relevant UAVs to prevent collisions. Based on the above formulation, the distance between the two UAVs is calculated as follows.

$d_{i,j,t}$	=	*the distance between* UAV "i" and UAV "j" *at time t*	
$a_{i,j,t}$	=	*the safety distance between UAV a and UAV "b" at time t*	Equation 12.
$d_{i,j,t}$	=	$\sqrt{(x_{i,t} - x_{j,t})^2 - (y_{i,t} - y_{j,t})^2} \quad \forall i, j, t \& i \neq j$	

In addition, the distance between each UAV needs to be maintained throughout the flight process. In this sense, the distances between UAVs are computed at every "t" time. If the distance between the UAV pair falls below the predetermined safety distance, the system gives a warning and updates the headings of the relevant UAVs to prevent collisions. Based on the above formulation, the distance between the two UAVs is calculated as follows.

According to the above distance, the distance between the two UAVs is checked by the formula below.

$$d_{i,j,t} \geq a_{i,j,t} \qquad \text{Equation 13.}$$

3.4 Collision Control Algorithm

The Collision Control Algorithm (CCA) is a control mechanism used in the FCA-SA. This mechanism controls whether the UAVs collide at any time in the form produced in the solutions in the Algorithm. The information related to the algorithm is given in Figure 12 and Equation 14.

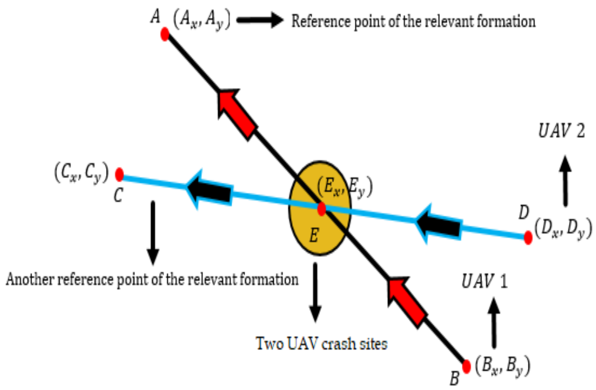


Figure 12. UAV collision control architecture.

$$T = \frac{(D_y - C_y) * (C_x - A_x) - (C_y - A_y) * (D_x - C_x)}{(D_y - C_y) * (B_x - A_x) - (B_y - A_y) * (D_x - C_x)}$$

$$E_x = A_x + (B_x - A_x) * T$$

$$E_y = A_y + (B_y - A_y) * T$$

$$t_1 = \frac{|BE|}{V_1} \qquad t_2 = \frac{|DE|}{V_2} \qquad \text{Equation 14.}$$

$$t_1 = t_2 \Rightarrow \textit{There is a collision, the solution is cancelled.}$$

$$t_1 \neq t_2 \Rightarrow \textit{there is no collision, the solution is valid}$$

4 Experimental Study and Analysis

In this article, the missions in the Teknofest 2021 Swarm UAV Competition are considered for the experimental study. These missions have an important to test the performance of the proposed algorithm in terms of genericity and dynamic. The information about these duties is provided below in Table 1.

Table 1. The missions in the application studies.

Mission No	Mission Name
1	Swarm Navigation Mission
2	Formation-Switching Mission
3	The mission to remove UAV from the Swarm
4	The mission of adding UAV to the Swarm
5	Swarm Rotation Mission
6	Swarm Division/Unification Mission
7	Trajectory Tracking Mission as a Swarm

Crazyfly 2.0 drone was used in Teknofest 2021 Swarm UAV Competition. Since Crazyfly 2.0 drone was used in Teknofest 2021 Swarm UAV Competition, all applications in the article were carried out on this drone. The flight area has a width of 3.5 m, a length of 3.5, and a height of 2 m, and is shown in the figure. "Loco positioning nodes" are placed at each corner of this flight area and are used for positioning UAVs. Besides, the "Loco positioning deck" and "Flow deck" are installed on each UAV for the positioning system. In Figures 13 and 14, the flight area set up for the experiments and the visuals of the flights are given.

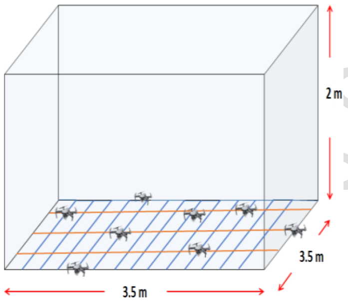


Figure 13. Flight area technical dimensions

Figure 14. Real swarm flight area [82]

4.1 Swarm Navigation Mission

In this task, the swarm will be navigated to the desired landmarks in a way that preserves the desired formation. The flock will take off in the desired formation at an altitude of 1 meter and within 3 seconds, with a distance of 1 meter between them. After the takeoff phase, the swarm will maintain its formation for 15 seconds. Aiming at the specified landmarks, the swarm will begin its navigation mission. The swarm must reach each landmark within 3 seconds at the most. When the flock reaches each landmark, it will maintain its formation for 20 seconds and switch to the other landmark. Finally, the swarm will be returned to the starting point. At the final landmark, the herd will wait 20 seconds and move on to the descent phase. The swarm landing phase will take 5 seconds. Triangles will be determined by the jury. At all of these stages, the altitude of the swarm, and the distance between the UAVs and its formation should be maintained [83]. The information about Swarm Navigation Mission is given in Figure 15.

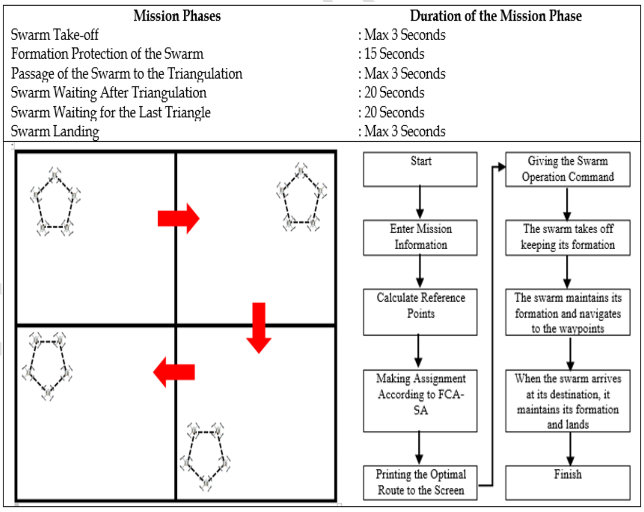
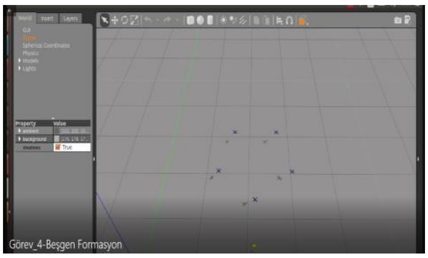


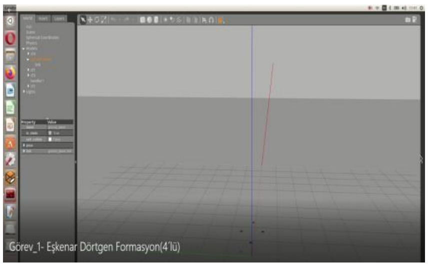
Figure 15. Swarm Navigation Mission and the solution architecture

In Figure 15, Swarm Navigation Mission for Pentagon Formation is illustrated. The most important point in the mission, each UAV remains in the same position throughout the operation. The developed algorithm has successfully performed the navigation task in all different formations. As an example, simulation videos of navigation tasks for the crescent formation and square formation are shown in links 1 and 2.



Link 1. Crescent formation

Görev_1-Hilal Formasyon.mp4 - Google Drive



Link 2. Rhombus formation

Görev_1-Eşkenar Dörtgen Formasyon(4´lü).mp4 - Google Drive

4.2 Formation-Switching Mission

In this mission, the swarm must take off in the formation requested by the jury and switch to a second different formation requested by the jury. The swarm will take off at an altitude of 1 meter to the desired formation and within 3 seconds, which will be 1 meter between the UAVs. It will retain its formation for "x" seconds after the take-off phase is complete. After this stage, the swarm will be asked to switch to the desired second formation within 3 seconds. During and after the transition phase, the herd should maintain its altitude and the distance between the UAVs. The 2nd formation must be protected for "y" seconds. After the formation protection phase, the swarm should descend within 3 seconds. Starting from the starting formation, the competitors may be asked to take more than one formation. Features related to this mission are shown in Figure 16 [83].

Mission Phases	Duration of the Mission Phase
Swarm Take-off	: Max 3 Seconds
Formation Protection of the Swarm	: 20 Seconds
Formation Switching Time	: Max 3 Seconds
Second Formation Protection Time	: 20 Seconds
Swarm Landing	: Max 3 Seconds

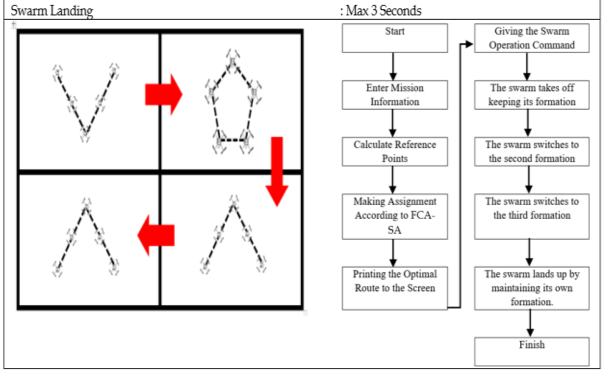
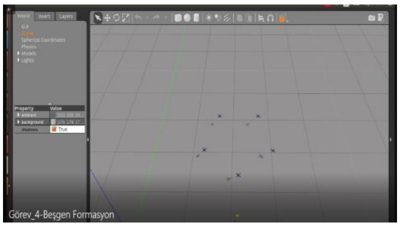


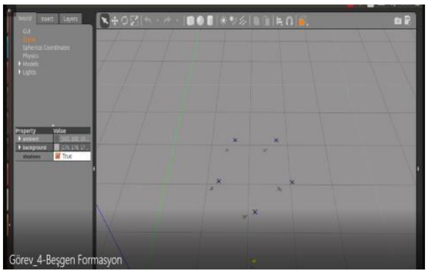
Figure 16. Swarm Navigation Mission and the solution architecture

The results of the application study for this task are given in the links below.



Link 3. Pentagon>Line>Pentagon formation

Görev_2-Beşgen-Çizgi-Beşgen Formasyon.mp4 - Google Drive



Link 4. Square-Rhombus-Square formation

Görev-2-Kare-Eşkenar_Dörtgen(4'lü)-Kare_Formasyon.m4v - Google Drive

4.3 The Mission to Remove UAVs from the Swarm

UAVs randomly deployed on the ground rise to an altitude of 1 meter at the same time. Then the command to enter the formation is sent to the swarm system and the UAVs enter the desired formation. The entry time to the formation must be less than 3 seconds. After the formation is formed, a random UAV is selected and removed from the swarm manually by a person in charge. The remaining herd members wait while maintaining their altitude and formation for the specified time. Then the landing command is sent and it lands on the ground keeping the swarm formation. The details of the stated mission are shown in the figure below [83].

Mission Phases	Duration of the Mission Phase
Swarm Take-off	: Max 3 Seconds
Formation Protection of the Swarm	: 15 Seconds
Removing Any UAV from the Swarm	: -
Altitude, Formation, and Distance Protection after UAV Take-off	: 15 Seconds
Swarm Landing	: Max 3 Seconds

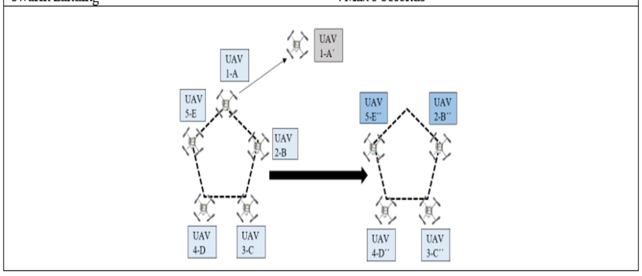


Figure 17. Swarm Navigation Mission and the solution architecture

Since there is no guide UAV in the developed formation creation algorithm and the whole system is created by utilizing the formation center of gravity, other individuals will not be affected by this situation when any related individual leaves the formation. In this mechanism, the rapid change in the "x", and "y" coordinates of the UAV is taken into account in the determination of the individual removed from the swarm. If the change difference between the relevant coordinates is greater than the predetermined parameter value, the algorithm will perceive this change as removing the individual from the system and will make the related UAV passive. The formulation in table 2 will be applied in calculating the relevant difference.

Table 2. Coordinate Change Detection Algorithm.

cp	$=$	$maximum\ difference\ between\ coordinates\ betw$ $+ 1"$
$y_{i,t}$	$=$	$"y"\ coordinate\ of\ the\ "i."\ UAV\ at\ "(t)."\ time$

$x_{i,t+1} =$ "x" *coordinate of the* "*i.*" *UAV at* "(*t* + 1)." *time*

$y_{i,t+1}$ "y" *coordinate of the* "*i.*" *UAV at* "(*t* + 1)." *time*

$for\ t = 1; t \leq 15; t++$

$for\ i = 1; i \leq Number\ of\ UAVs; i++$

$if((|x_{i,t+1} - x_{i,t}|) > cp\ or\ (|y_{i,t+1} - y_{i,t}|) > cp\ )$

Remove "*i. UAV*" *from swarm array*

Some of the visuals related to the application work made by using the developed solution algorithm and taking into account the task information is shown in links 5 and 6.

4.4 Swarm Rotation Mission

In this task, the swarm is required to turn at certain angles and reach the desired points while maintaining its formation. Information regarding the swarm rotation task is given in Figure 18.

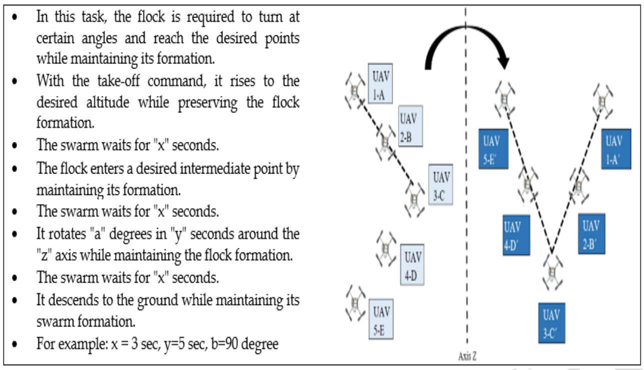


Figure 18. The Swarm Rotation Mission and the Solution Architecture

It is desirable to perform this mission at any angle, both clockwise and counterclockwise. To solve this problem, it is planned that the UAVs will make their turns by advancing with one-degree angles at v speed on the unit circle drawn according to the center of gravity of the formation. The unit circle structure and pentagonal formation examples related to the method are shown in Figures 19 and 20.

Figure 19. Unit Circle Made of Angles of One Degree

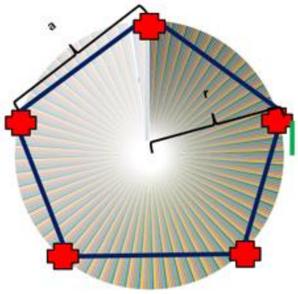


Figure 20. Pentagonal Formation with "a" Length, "r" Radius

In Figure 20, the length "a" indicates the distance between each UAV. According to the "a" value, the "r" radius is calculated for each formation in Table 3.

According to the formulas in Table 3, "x" and "y" coordinates for each degree are computed as in Table 4. Based on the radius formulas above, the "v" forward speed of the UAV is calculated using the formula below.

$$v = \frac{2 * \pi * r}{12} \qquad \textit{Equation 14.}$$

Table 4. Coordinate calculation for each degree in the rotation task

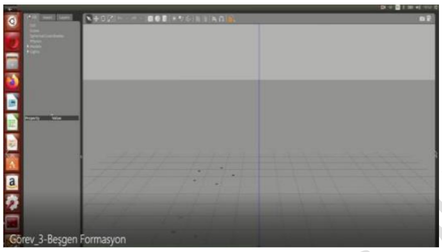
Angle (α)	***Coordinate information***	"x" ***coordinate of the UAV***	"y" ***coordinate of the UAV***
0	x_0, y_0	x_0	y_0
1	x_1, y_1	$x_1 = r * cos(\alpha)$	$y_1 = r * cos(\alpha)$
2	x_2, y_2	$x_2 = r * cos(\alpha)$	$y_2 = r * cos(\alpha)$
3	x_3, y_3	$x_3 = r * cos(\alpha)$	$y_3 = r * cos(\alpha)$
***	***	***	***
***	***	***	***
***	***	***	***
***	***	***	***
***	***	***	***
***	***	***	***
358	x_{358}, y_{358}	$x_{358} = r * cos(\alpha)$	$y_{358} = r * cos(\alpha)$
359	x_{359}, y_{359}	$x_{359} = r * cos(\alpha)$	$y_{359} = r * cos(\alpha)$
360	x_{360}, y_{360}	$x_{360} = r * cos(\alpha)$	$y_{360} = r * cos(\alpha)$

The algorithm developed for the rotation mission of the UAVs is shown in the above table 5.

Table 5. Rotation mission algorithm

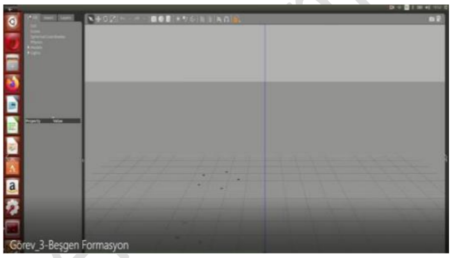
```
Step 1.  x[i, k]
         = "x" position ofthe "i. " UAV in the "k. " step & x[i, 0]
         = the current reference position"
         y[i, k]
         = "y" position ofthe "i. " UAV in the "k. " step & y[i, 0]
         = the current reference position"
         ang[i, k] =
         the angle of the i.  UAV in the "k". step & ang[i, 0] =
         the current
Step 2.  for k = 1; k ≤ 360;   k + +
             for i = 1; i ≤ the number of UAVs; i + +
                 if the rotation is clockwise
                     ang[i, k] =  ang[i, k − 1] + 1
                     x_{i,k} = r ∗ cos(ang[i, k]) & y_{i,k}
                                   = r
                                   ∗ sin(ang[i, k])
                     if (ang[i, k]  > 360) then ang[i, k]
                                   = 0
                 if the rotation is counterclockwise
                     ang[i, k] =  ang[i, k − 1] − 1
                     x_{i,k} = r ∗ cos(ang[i, k]) & y_{i,k}
                                   = r
                                   ∗ sin(ang[i, k])
                     if (ang[i, k]  < 0) then ang[i, k]
                                   = 360
             end
         end
```

Some of the application studies for the rotation mission are given in the link below.



Link 5. Rotation mission for pentagon formation

Görev_4-Beşgen Formasyon.mp4 - Google Drive



Link 6. Rotation mission for the square formation

Görev_4-Kare Formasyon.m4v - Google Drive

4.5 Swarm Division/Unification Mission

The mission details for Swarm Division/Unification are shown in Figure 21.

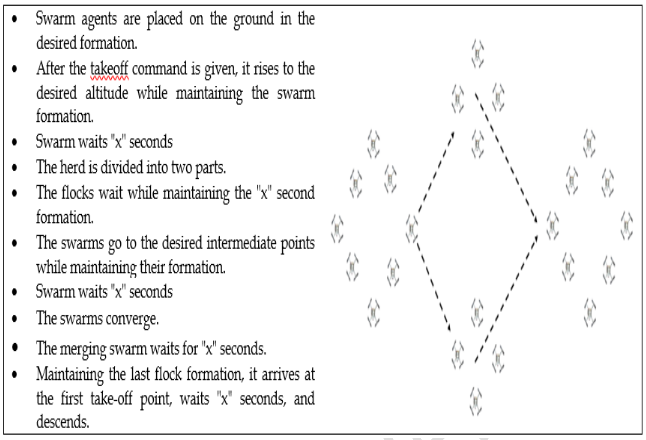


Figure 21. The Swarm Rotation Mission and the Solution Architecture

The solution approach used in the merger and separation task is expressed below on the star formation. Initially, the flock in star formation is divided into V and pentagonal formations. In the next stage, the two swarms separated will merge to form a "star formation".

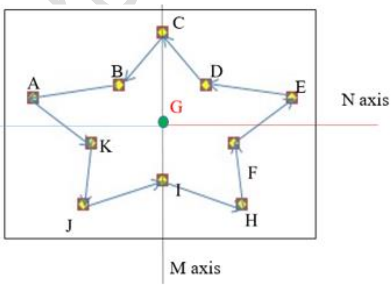


Figure 22. Star formation in the starting phase

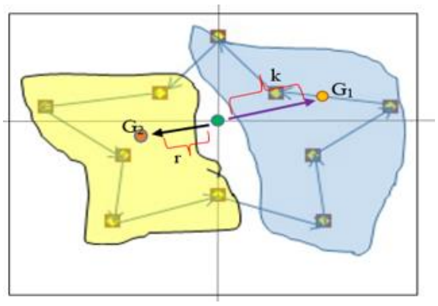


Figure 23. Centers of gravity of pentagonal and V formations

In the formation in Figure 22, there is a UAV at each reference point and these are indicated by letters. The first task in the separation of formations is to determine which UAV will join which formation and which reference points will be assigned. According to the number of individuals in the formation, the UAVs will be assigned to two different arrays according to the "M" axis and each array will form the UAVs of the relevant formation. While forming groups, the closest UAVs to each other are selected and clustered. Based on the determined UAV groups, the centers of gravity of each group are established. Then, reference diagonal points are determined by reference to these centroids and using the formation generation algorithms in section 2.2. Finally, according to the results obtained from the FCA-SA, the UAVs in the clusters are assigned to the reference points. The centers of gravity of pentagonal and triangular formations are shown in Figure 23, and the formations and reference points to which UAVs are assigned as a result of swarm separation in Figure 24.

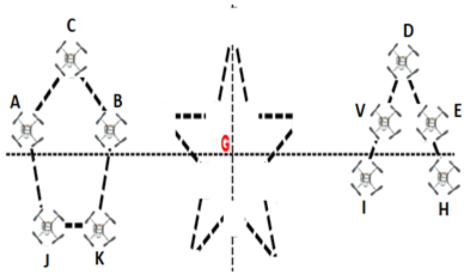


Figure 24. UAVs assigned to separate swarms

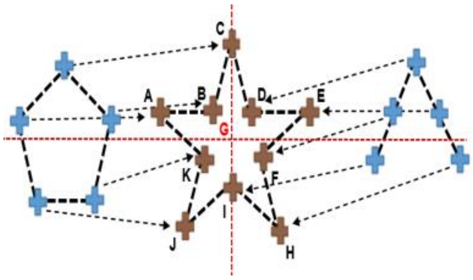
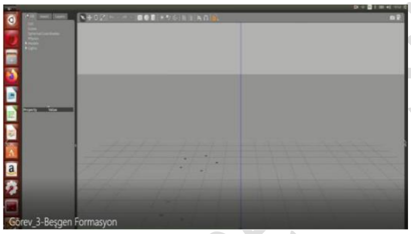


Figure 25. Reunification of the swarms

In the merger task, the center of gravity of the merger formation of the previously separated swarms is determined as the center of gravity of the mission area. According to this center of gravity, the reference diagonal points of the desired formation are determined and the function of assigning UAVs in two different swarms to the relevant reference points is performed. The FCA-SA Algorithm is used to determine which UAV will be assigned to which point. A visual representation of the swarm reunion is shown in Figure 25. The videos of the experimental studies for this mission are shown in links 7 and 8.



Link 7. Rhombus(8's) → 2x Rhombus(4's) → Rhombus(8's) Formation

Görev_5-Eşkenar Dörtgen(8'li),2x-Eşkenar Dörtgen(4'lü),Eşkenar Dörtgen(8'li) Formasyon.mp4 - Google Drive

Link 8. Rhombus(8's) → Rhombus(4's) and Square → Rhombus (8's) Formation

Görev_5-Eşkenar Dörtgen(8'li), Kare, Eşkenar Dörtgen(4'lü), Eşkenar Dörtgen(8'li) Formasyon.mp4 - Google Drive

4.6 Trajectory Tracking Mission as a Swarm

In this mission, the swarm takes off in the designated formation and completes the operation by following the pattern defined by the jury. The specifications for the mission are shown in Figure 26.

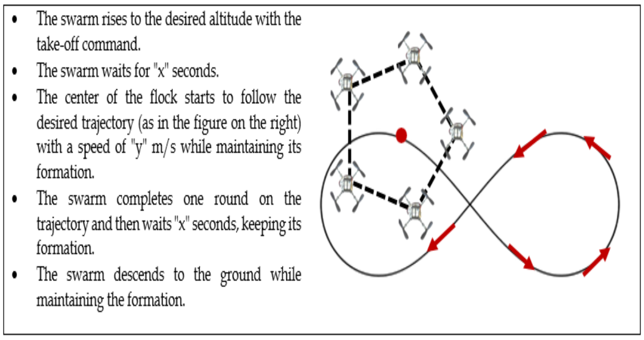
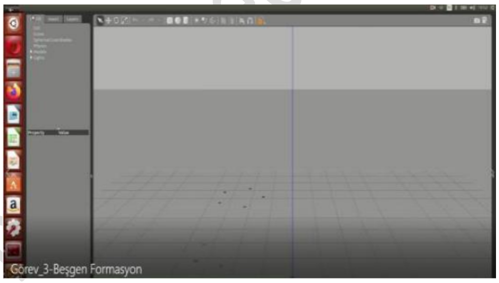


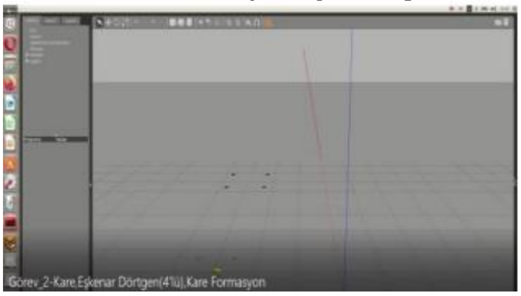
Figure 26. Trajectory Tracking Mission as a Swarm and the solution architecture

Some of the application studies related to the mission performed using FCA-SA are shown in links 9 and 10.



Link 9. Square formation

Görev-6- Kare Formasyon .mp4 - Google Drive



Link 10. Rhombus Formation (4's)

Görev_6- Eşkenar Dörtgen(4'lü) Formasyon .mp4 - Google Drive

4.7 Experimental Design and Application

In this paper, nine different missions and six different formation types are defined. For each formation task, five different formation types were defined and the success of the algorithm was tested on a total of 30 scenarios. With this experiments set, the performance of the algorithm was tested for different starting positions, number of IHAs, formation types and formation tasks. Summary information about the sample experimental set is given in table 6.

Table 6. Sample Experiment Set

Scenario No: M..F...

Mission Name	Swarm Navigation	**Departure Time**	3 seconds
Formation Type	Pentagon	**Duration of Stay in Formation**	20 seconds
Number of UAVs	3	**Time for the swarm to move to the next point**	30 seconds
Distance between UAVs	0.8 meter	**Landing duration**	5 seconds
Mission Height	1 meter	**Mission Area**	3.5 meter (x) 3.5 meter (y) 2 meter (z)
UAV Start Location Information			
UAV velocity	5 meter/seconds		
	Coordinate Information		
	x	**y**	**z**
UAV-1	0.5	0.5	0
UAV-2	1	1	0
UAV-3	1.5	1.5	0
UAV-4	2	2	0
UAV-5	2.5	2.5	0
Mission Location Information			
Starting Point	**Navigation-1**	**Navigation-1**	**Landing Point**
[0,0,0]	[1,1,1]	[2,2,1]	[2,2,0]

Table 6 shows the number of UAVs, mission specifications, formation types and locations in the relevant scenario. This information differs in each scenario.

When clicking on the scenario names in Table 7, detailed information about the scenarios is presented. In addition, the UAV assignments and total mission time for the formation as a result of the optimization are presented in Table 7. For example, in the M1F2 scenario, 5 UAVs were used and the swarm navigation task (4.1) was performed. As a result of the optimization, UAV 1 was assigned to reference point 0 of the triangle formation and UAV 2 was assigned to reference point 3. The minimum mission time was calculated as 56,53211. The details of the task are given in the link in the first and last column of the table. The time spent by each UAV in M1F2 during the relevant mission is shown in Table 8. The UAV with the highest mission time in the table constituted the final mission duration of the formation.

Table 7. Scenario information and application study results

Scenario No (Link)	Mission Type	Mission Name	Total Number of UAVs	Optimal Mission Time (seconds)	Optimal Mission Details (Link)
M1F1	1	4.1.	3	56,6448	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2] - [0, 1, 2]				
M1F2	1	4.1.	5	56,79881	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4] - [1, 0, 3, 2, 4]				
M1F3	1	4.1.	5	57,13983	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4] - [0, 2, 4, 1, 3]				
M1F4	1	4.1.	6	57,38266	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5] - [2, 1, 0, 5, 3, 4]				
M2F1	2	4.2.	5	36,82478	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4] - [1, 0, 3, 4, 2]				
M2F2	2	4.2.	5	36,84202	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4] - [2, 0, 3, 4, 1]				
M2F3	2	4.2.	5	36,86703	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4] - [1, 0, 3, 4, 2]				
M2F4	2	4.2.	5	37,49077	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4] - [1, 3, 2, 4, 0]				
M3F1	3	4.3.	5	31,81641	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4] - [2, 0, 3, 1, 4]				
M3F2	3	4.3.	6	32,37558	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5] - [2, 0, 5, 3, 1, 4]				
M3F3	3	4.3.	10	32,03764	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5,6,7,8,9] - [0, 3, 4, 5, 7, 1, 8, 6, 9, 2]				
M3F4	3	4.3.	4	31,77630	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3] - [0, 3, 1, 2]				
M4F1	4	4.4.	10	48,865507	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5,6,7,8,9] - [0, 6, 4, 5, 2, 1, 9, 3, 8, 7]				

Table 7. Scenario information and application study results

Scenario No (Link)	Mission Type	Mission Name	Total Number of UAVs	Optimal Mission Time (seconds)	Optimal Mission Details (Link)
M4F2	4	4.4.	6	49,257288	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5] - [2, 5, 0, 1, 3, 4]				
M4F3	4	4.4.	4	47,943598	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3] - [0, 3, 1, 2]				
M4F4	4	4.4.	3	47,3187067	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2] - [1, 0, 2]				
M5F1	5	4.5.	8	63,31696	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5,6,7] - [6, 1, 0, 3, 5, 7, 4, 2]				
M5F2	5	4.5.	10	63,058963	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5,6,7,8,9] - [0, 6, 7, 5, 2, 8, 4, 3, 9, 1]				
M5F3	5	4.5.	8	63,290337	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5,6,7] - [7, 1, 0, 3, 6, 5, 4, 2]				
M5F4	5	4.5.	10	62,783912	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5,6,7,8,9] - [3, 6, 4, 2, 7, 8, 0, 9, 5, 1]				
M6F1	6	4.6.	4	35,398707	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3] - [0, 3, 2, 1]				
M6F2	6	4.6.	3	34,857218	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2] - [1, 0, 2]				
M6F3	6	4.6.	6	39,2844345	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4,5] - [2, 4, 0, 3, 1, 5]				
M6F4	6	4.6.	5	36,76892755	OptRest
	[Reference Point] – [label of the UAV]				
	[0,1,2,3,4] - [1, 3, 0, 4, 2]				

Table 8. Time spent by each UAV in the M1F2 mission

Stage	**UAV1**	**UAV2**	**UAV3**
Take-off	0,310630752	0,249087255	0,210875426
Formation Protection	15	15	15
Transition to Next Point	0,410744581	0,410000007	0,410744581
Formation Protection	20	20	20
Return to the starting flock point	0,410744581	0,410000007	0,410744581
Formation Protection	20	20	20
Landing	0,4	0,4	0,4
Total time	56,53211	56,46908	56,43236
Stage	**UAV4**	**UAV5**	
Take-off	0,100158962	0,264398358	
Formation Protection	15	15	
Transition to Next Point	0,410744581	0,410744581	
Formation Protection	20	20	
Return to the starting flock point	0,410744581	0,410744581	
Formation Protection	20	20	
Landing	0,4	0,4	
Total time	56,32164	56,48588	
General Mission Time = MAX(UAV1, UAV2, UAV3, UAV4, UAV) = 56,53211			

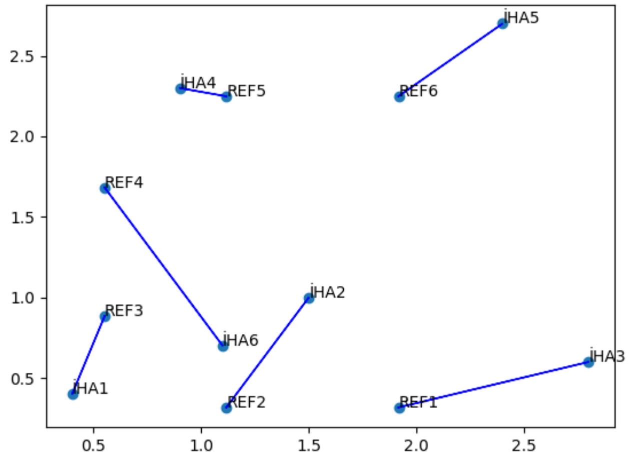


Figure 27. UAV Start Coordinates and Creating of Reference Point for Crescent Formation in M1F4 (İHA=UAV, REF=Reference Point).

In the M1F4 problem in Figure 27, 6 UAVs were asked to create a crescent formation and perform the navigation task (4.1). As a result of the optimization study, the method created 6 different reference points for the crescent formation based on the geometric solution approach and assigned UAVs to the reference points according to the mission parameters and UAV technical constraints.

The UAVs were initially dropped at different points and entered the crescent formation in the air after the take-off order. The initial coordinates of the UAVs were UAV1: [0.58, 2.99, 0.0], UAV2: [1.04, 1.57, 0.0], UAV3: [2.06, 2.92, 0.0]. Then, the UAV formed the relevant formation and navigated as a swarm. Finally, the landing took place. The steps of the swarm throughout the mission are shown in Figure 28.

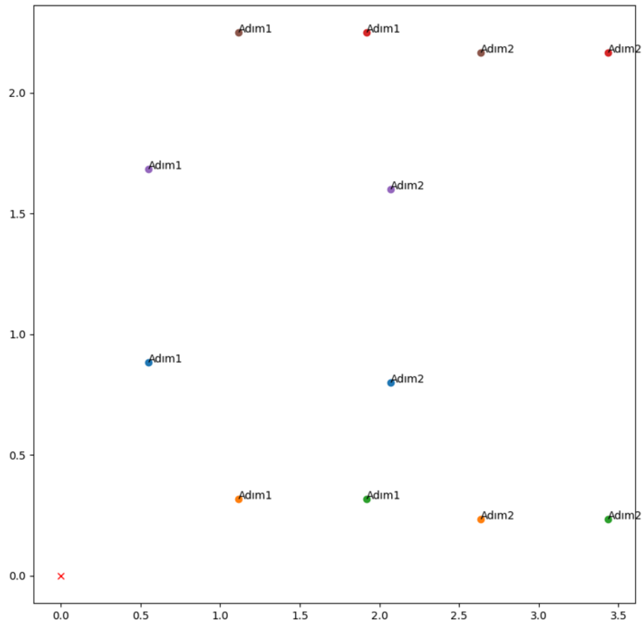


Figure 28. Step-by-step movement of UAVs throughout the mission for M1F4 (Adım= Step).

Figure 28 shows the movements of the UAVs in the x and y axis at a height of 1 meter.

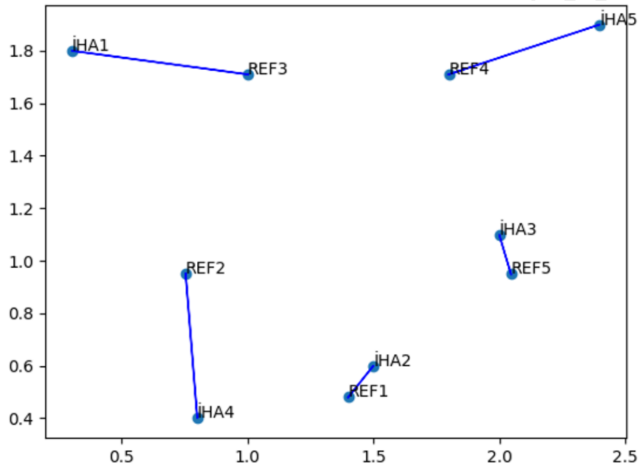


Figure 29. UAV Start Coordinates and Creating of Reference Point for Pentagon Formation in M6F4.

Figure 29 shows the UAV initial coordinates for the M6F4 mission (UAV 1: [0.30, 1.80, 0.00] UAV 2: [1.50, 0.60, 0.00] UAV 3: [2.00, 1.10, 0.00] UAV 4: [0.80, 0.40, 0.00] UAV 5: [2.40, 1.90, 0.00]) and the reference points and UAV assignments determined as a result of the optimization are shown. In this scenario, the task of swarming trajectory tracking (4.6) with a pentagonal formation is performed and the movements of the UAVs during the mission are shown in Figure 30.

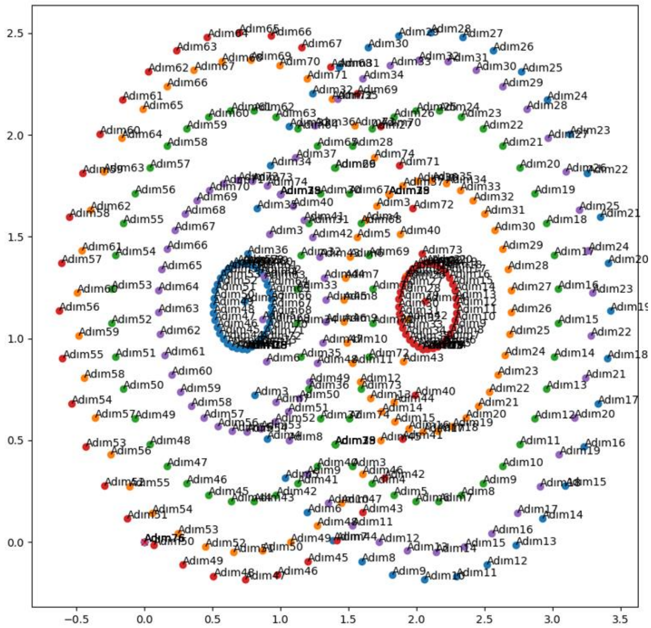


Figure 30. Step-by-step movement of UAVs throughout the mission for M6F4

Figure 30 graphically shows the movement of the flock in the pentagonal formation during the mission period. In the figure, the coordinates of each UAV are tracked in stages.

In addition, the results for all scenarios are shown in the “OptRes” links.

5 Conclusion

The formation control for Swarm Unmanned Aerial Vehicles is an optimization problem that includes many constraints and parameters. In this article, the problem is examined under the conditions "homogeneous", " Time-Window ", "Central Control Architecture", "Uncertain", "Dynamic Structure", and "Leaderless ". The FCA-SA Algorithm, which is a new solution approach, is developed to solve the problem and the proposed methodology is implemented on real data used in the TEKNOFEST-2021 Swarm UAV Competition. The competition consists of 9 different formations and 7 different tasks, and the tasks are required to be completed within the specified time limits under the task area and time constraints. The application study using Crazfly 2.0 drones was carried out on the ROS Simulation Platform and in a real competition environment. As a result of the experimental studies, the developed algorithm completed all the tasks within the minimum operation time. In addition, it was determined that the swarms did not disrupt their formation, the UAVs did not collide with each other and did not deviate from their trajectories during the operations. The proposed solution approach reacted quickly to all formation changes and task changes and was able to generate the optimal tour route within seconds. As a result of the scenario studies, the robustness of the algorithm was proven on different data sets. Furthermore, the analysis results showed that the UAVs completed their mission without violating the competition area boundary. Finally, the algorithm has produced optimal solutions for tasks involving uncertain situations and dynamic conditions. Thanks to this structure, the algorithm will be able to be used in the routing of different autonomous vehicles and the control of their formations.

In future studies, UAV formation control is an area that has been intensively studied in recent years and will continue to be studied in the coming years due to both defense problems and the development of UAV technologies. It is predicted that the first priority area for researchers will be applications in the defense sector and in the battlefield. Formation of formations by taking into account certain and uncertain situations in this field will create new branch problems. Secondly, applications in the field of agriculture are expected to have a wide range of applications. The use of these technologies in problems such as spraying, fertilization, development of agricultural products, protection from pests and other animals will create an application area for UAV formation control. In addition, unmanned land and sea vehicles will continue to constitute other application areas of this formation control problem.

With the development of new mathematical models for these problems and the use of artificial intelligence and metaheuristic algorithms in a hybrid way, it is predicted that more effective solutions will be obtained in shorter times. In addition, hybridization of swarm UAV problems with image processing techniques and the problems of preventing communication interference can be different study topics for researchers. Finally, it is expected that researchers will be directed to multi-objective optimization studies by working with different UAVs and considering different parameters and objectives.

6 Author contribution statements

In this paper, author 1 generates optimal tour routes using the simulated annealing algorithm and taking into account the specific requirements of each mission. He implemented the routes on swarm drones and reported the results.

Author 2, in this paper, created the geometric architectures of the formation control algorithms and realized their technical drawings and designs. He analyzed and reported the implementation results.

7 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

8 References

[1] He, L., Bai, P., Liang, X., Zhang, J., and Wang, W. "Feedback formation control of UAV swarm with multiple implicit leaders". Aerospace Science and Technology, 72, 327-334, 2018.

[2] Oh, K. K., Park, M. C., and Ahn, H. S. "A survey of multi-agent formation control". Automatica, 53, 424-440, 2015.

[3] Couceiro, M. S., Vargas, P. A., Rocha, R. P., and Ferreira, N. M. "Benchmark of swarm robotics distributed techniques in a search task". Robotics and Autonomous Systems, 62(2), 200-213, 2014.

[4] Olfati-Saber, R. "Flocking for multi-agent dynamic systems: Algorithms and theory". IEEE Transactions on automatic control, 51(3), 401-420, 2006.

[5] Toksöz, M. A., Oğuz, S., and Gazi, V. "Decentralized formation control of a swarm of quadrotor helicopters". In 2019 IEEE 15th International Conference on Control and Automation (ICCA), 1006-1013, IEEE, July 2019.

[6] Turpin, M., Michael, N., and Kumar, V. "Concurrent assignment and planning of trajectories for large teams of interchangeable robots". In 2013 IEEE International Conference on Robotics and Automation, 842-848, IEEE, May 2013.

[7] Olfati-Saber, R., Fax, J. A., and Murray, R. M. "Consensus and cooperation in networked multi-agent systems". Proceedings of the IEEE, 95(1), 215-233, 2007.

[8] You, D. I., and Shim, D. H. "Autonomous formation flight test of multi-micro aerial vehicles". Journal of Intelligent & Robotic Systems, 61(1), 321-337, 2011.

[9] Zhi-wei, H., Jia-hong, L., Ling, C., and Bing, W. "A hierarchical architecture for formation control of multi-UAV". Procedia Engineering, 29, 3846-3851, 2012.

[10] Li, S., Shao, X., Zhang, W., and Zhang, Q. "Distributed multicircular circumnavigation control for UAVs with desired angular spacing". Defence Technology, 2023.

[11] Wang, J., Wu, Y. X., Chen, Y. Q., and Ju, S. "Multi-UAVs collaborative tracking of moving target with maximized visibility in urban environment". Journal of the Franklin Institute, 359(11), 5512-5532, 2022.

[12] Chai, S., Yang, Z., Huang, J., Li, X., Zhao, Y., and Zhou, D. "Cooperative UAV search strategy based on DMPC-AACO algorithm in restricted communication scenarios". Defence Technology, 2023.

[13] Sürü İHA Sistemleri Modern Harp İçin Bir Gelecek Öngörüsü, Araştirma Raporu Şubat 2019. https://thinktech.stm.com.tr/uploads/docs/1608905682_stm-suru-iha-sistemleri.pdf? Accessed: 02.02.2022

[14] Rout, R., and Subudhi, B. "A backstepping approach for the formation control of multiple autonomous underwater vehicles using a leader–follower strategy". Journal of Marine Engineering & Technology, 15(1), 38-46, 2016.

[15] Wang, J., Wang, C., Wei, Y., and Zhang, C. "Sliding mode based neural adaptive formation control of underactuated AUVs with leader-follower strategy". Applied Ocean Research, 94, 101971, 2020.

[16] Gao, Z., and Guo, G. "Fixed-time leader-follower formation control of autonomous underwater vehicles with event-triggered intermittent communications". IEEE Access, 6, 27902-27911, 2018.

[17] Ghamry, K. A., and Zhang, Y. "Formation control of multiple quadrotors based on leader-follower

method". In 2015 International Conference on Unmanned Aircraft Systems (ICUAS), 1037-1042, IEEE, June 2015.

[18] Han, Z., Guo, K., Xie, L., and Lin, Z. "Integrated relative localization and leader–follower formation control". IEEE Transactions on Automatic Control, 64(1), 20-34, 2018.

[19] Raghuwaiya, K., Sharma, B., and Vanualailai, J. "Leader-follower based locally rigid formation control". Journal of Advanced Transportation, 2018.

[20] Tong, W. U., Jie, W. A. N. G., and Bailing, T. I. A. N. "Periodic event-triggered formation control for multi-UAV systems with collision avoidance". Chinese Journal of Aeronautics, 35(8), 193-203, 2022.

[21] Ullah, N., Mehmood, Y., Aslam, J., Shaoping, W. A. N. G., and Phoungthong, K. "Fractional order adaptive robust formation control of multiple quad-rotor UAVs with parametric uncertainties and wind disturbances". Chinese Journal of Aeronautics, 35(8), 204-220, 2022.

[22] Dai, J., Hu, Q., Liu, X., Zhang, Y., and Zhu, J. "Cluster head selection method of multiple UAVs under COVID-19situation". Computer Communications, 196, 141-147, 2022.

[23] Cheng, W., Jiang, B., Zhang, K., and Ding, S. X. "Robust finite-time cooperative formation control of UGV-UAV with model uncertainties and actuator faults". Journal of the Franklin Institute, 358(17), 8811-8837, 2021.

[24] Liu, H., Meng, Q., Peng, F., and Lewis, F. L. "Heterogeneous formation control of multiple UAVs with limited-input leader via reinforcement learning". Neurocomputing, 412, 63-71, 2020.

[25] Xie, Y., Han, L., Dong, X., Li, Q., and Ren, Z. "Bio-inspired adaptive formation tracking control for swarm systems with application to UAV swarm systems". Neurocomputing, 453, 272-285, 2021.

[26] Jiaqi, S., Li, T., Hongtao, Z., Xiaofeng, L., and Tianying, X. "Adaptive multi-UAV path planning method based on improved gray wolf algorithm". Computers and Electrical Engineering, 104, 108377, 2022.

[27] Hartley, J., Shum, H. P., Ho, E. S., Wang, H., & Ramamoorthy, S. "Formation control for UAVs using a Flux Guided approach". Expert Systems with Applications, 205, 117665, 2022.

[28] Li, J., Liu, J., Huangfu, S., Cao, G., & Yu, D. Leader-follower formation of light-weight UAVs with novel active disturbance rejection control. Applied Mathematical Modelling, 117, 577-591, 2023.

[29] Do, H. T., Hua, H. T., Nguyen, M. T., Nguyen, C. V., Nguyen, H. T., Nguyen, H. T., & Nguyen, N. T. "Formation control algorithms for multiple-uavs: a comprehensive survey". EAI Endorsed Transactions on Industrial Networks and Intelligent Systems, 8(27), e3-e3, 2021.

[30] Zheng, X., Zong, C., Cheng, J., Xu, J., Xin, S., Tu, C., ... and Wang, W. "Visually smooth multi-UAV formation transformation". Graphical Models, 116, 101111, 2021.

[31] Hartley, J., Shum, H. P., Ho, E. S., Wang, H., & Ramamoorthy, S. "Formation control for UAVs using a Flux Guided approach". Expert Systems with Applications, 205, 117665, 2022.

[32] Qiang, F. E. N. G., Xingshuo, H. A. I., Bo, S. U. N., Yi, R. E. N., Zili, W. A. N. G., Dezhen, Y. A. N. G., ... and Ronggen, F. E. N. G. "Resilience optimization for multi-UAV formation reconfiguration via enhanced pigeon-inspired optimization". Chinese Journal of Aeronautics, 35(1), 110-123, 2022.

[33] Yan, Z., Han, L., Li, X., Dong, X., Li, Q., and Ren, Z. Event-"Triggered formation control for time-delayed discrete-Time multi-Agent system applied to multi-UAV formation flying". Journal of the Franklin Institute, 360(5), 3677-3699, 2023.

[34] Wu, Y., Gou, J., Ji, H., & Deng, J. "Hierarchical mission replanning for multiple UAV formations performing tasks in dynamic situation". Computer Communications, 2023.

[35] Zear, A., Ranga, V., and Bhushan, K. "Coordinated network partition detection and bi-connected inter-partition topology creation in damaged sensor networks using multiple UAVs". Computer Communications, 203, 15-29, 2023.

[36] Dou, L., Cai, S., Zhang, X., Su, X., and Zhang, R. "Event-triggered-based adaptive dynamic programming for distributed formation control of multi-UAV". Journal of the Franklin Institute, 359(8), 3671-3691, 2022.

[37] Zhao, T., Yu, X., Liu, P., and Liu, L. "Ultraviolet anti-collision and localization algorithm in UAV formation network". Optik, 192, 162919, 2019.

[38] Trujillo, M. A., Becerra, H. M., Gómez-Gutiérrez, D., Ruiz-León, J., and Ramírez-Treviño, A. "Hierarchical task-based formation control and collision avoidance of UAVs in finite time". European Journal of Control, 60, 48-64, 2021.

[39] Alam, M. M., & Moh, S. "Joint topology control and routing in a UAV swarm for crowd surveillance". Journal of Network and Computer Applications, 204, 103427, 2022.

[40] Huang, J., and Sun, W. "A method of feasible trajectory planning for UAV formation based on bi-directional fast search tree". Optik, 221, 165213, 2020.

[41] Xu, J., Deng, Z., Ren, X., Xu, L., and Liu, D. "Invulnerability optimization of UAV formation

based on super wires adding strategy". Chaos, Solitons & Fractals, 140, 110185, 2020.

[42] Li, Y., Xu, Y., Xue, X., Liu, X., & Liu, X. "Optimal spraying task assignment problem in crop protection with multi-UAV systems and its order irrelevant enumeration solution". Biosystems Engineering, 214, 177-192, 2022.

[43] Jiaqi, S., Li, T., Hongtao, Z., Xiaofeng, L., and Tianying, X. "Adaptive multi-UAV path planning method based on improved gray wolf algorithm". Computers and Electrical Engineering, 104, 108377, 2022.

[44] Pang, B., Low, K. H., and Lv, C. "Adaptive conflict resolution for multi-UAV 4D routes optimization using stochastic fractal search algorithm". Transportation Research Part C: Emerging Technologies, 139, 103666, 2022.

[45] Do, H. T., Hua, H. T., Nguyen, M. T., Nguyen, C. V., Nguyen, H. T., Nguyen, H. T., and Nguyen, N. T. "Formation control algorithms for multiple-uavs: a comprehensive survey". EAI Endorsed Transactions on Industrial Networks and Intelligent Systems, 8(27), e3-e3. 2021.

[46] Wu, X., Yang, Z., Huo, J., and Zhang, J. "UAV formation control based on consistency". In 2015 7th international conference on modelling, identification and control (ICMIC), 1-5, IEEE, 2015, December.

[47] Dong, X., Yu, B., Shi, Z., and Zhong, Y. "Time-varying formation control for unmanned aerial vehicles: Theories and applications". IEEE Transactions on Control Systems Technology, 23(1), 340-348, 2014.

[48] Liang, Y., Dong, Q., and Zhao, Y. "Adaptive leader–follower formation control for swarms of unmanned aerial vehicles with motion constraints and unknown disturbances". Chinese Journal of Aeronautics, 33(11), 2972-2988, 2020.

[49] Guo, K., Li, X., and Xie, L. "Simultaneous cooperative relative localization and distributed formation control for multiple UAVs". Science China Information Sciences, 63(1), 1-3, 2020.

[50] Fu, X., Pan, J., Wang, H., and Gao, X. "A formation maintenance and reconstruction method of UAV swarm based on distributed control". Aerospace Science and Technology, 104, 105981, 2020.

[51] Yu, B., Dong, X., Shi, Z., & Zhong, Y. "Formation control for quadrotor swarm systems: Algorithms and experiments". In Proceedings of the 32nd Chinese control conference, 7099-7104, IEEE, July 2013.

[52] Speck, C., and Bucci, D. J. "Distributed UAV swarm formation control via object-focused, multi-objective SARSA". In 2018 Annual American Control Conference (ACC), 6596-6601, IEEE, June 2018.

[53] Zhu, C., Liang, X., He, L., and Liu, L. "Demonstration and verification system for UAV formation control". In 2017 3rd IEEE International Conference on Control Science and Systems Engineering (ICCSSE), 56-60, IEEE, August 2017.

[54] Ali, Z. A., Han, Z., and Masood, R. J. "Collective motion and self-organization of a swarm of UAVs: A cluster-based architecture". Sensors, 21(11), 3820, 2021.

[55] Yang, F., Wang, P., Zhang, Y., Zheng, L., and Lu, J. "Survey of swarm intelligence optimization algorithms". In 2017 IEEE International Conference on Unmanned Systems (ICUS), 544-549, IEEE, October 2017.

[56] Fu, X., Pan, J., Wang, H., and Gao, X. "A formation maintenance and reconstruction method of UAV swarm based on distributed control". Aerospace Science and Technology, 104, 105981, 2020.

[57] Wu, Y., Gou, J., Hu, X., and Huang, Y. "A new consensus theory-based method for formation control and obstacle avoidance of UAVs". Aerospace Science and Technology, 107, 106332, 2020.

[58] Wang, J., Han, L., Dong, X., Li, Q., and Ren, Z. "Distributed sliding mode control for time-varying formation tracking of multi-UAV system with a dynamic leader". Aerospace Science and Technology, 111, 106549, 2021.

[59] Li, S., and Fang, X. "A modified adaptive formation of UAV swarm by pigeon flock behavior within local visual field". Aerospace Science and Technology, 114, 106736, 2021.

[60] Liu, B., Li, A., Guo, Y., and Wang, C. "Adaptive distributed finite-time formation control for multi-UAVs under input saturation without collisions". Aerospace Science and Technology, 120, 107252, 2022.

[61] Shen, J., Wang, S., and Zhan, X. "Multi-UAV cluster-based cooperative navigation with fault detection and exclusion capability". Aerospace Science and Technology, 124, 107570, 2022.

[62] Chen, L., and Duan, H. "Collision-free formation-containment control for a group of UAVs with unknown disturbances". Aerospace Science and Technology, 126, 107618, 2022.

[63] Shen, Y., and Wei, C. "Multi-UAV flocking control with individual properties inspired by bird behavior". Aerospace Science and Technology, 130, 107882, 2022.

[64] An, B., Wang, B., Fan, H., Liu, L., Hu, H., and Wang, Y. "Fully distributed prescribed performance formation control for UAVs with unknown maneuver of leader". Aerospace Science and Technology, 130, 107886, 2022.

[65] Shao, X., Liu, H., Zhang, W., Zhao, J., and Zhang, Q. "Path driven formation-containment control of multiple UAVs: A path-following framework". Aerospace Science and Technology, 135, 108168, 2023.

[66] Yu, B., Dong, X., Shi, Z., & Zhong, Y. "Formation control for quadrotor swarm systems: Algorithms and experiments". In Proceedings of The 32nd Chinese Control Conference, 7099-7104, IEEE, July 2013.

[67] Xiaoning, Z. "Analysis of military application of UAV swarm technology". In 2020 3rd International Conference on Unmanned Systems (ICUS), 1200-1204, IEEE, November 2020.

[68] Cevik, P., Kocaman, I., Akgul, A. S., and Akca, B. "The small and silent force multiplier: a swarm UAV—electronic attack". Journal of Intelligent & Robotic Systems, 70(1), 595-608, 2013.

[69] Xiong, F., Li, A., Wang, H., and Tang, L. "An SDN-MQTT based communication system for battlefield UAV swarms". IEEE Communications Magazine, 57(8), 41-47, 2019.

[70] Gulosh, N. J. "Employment of intelligence, surveillance, and reconnaissance drone swarms to enhance ground combat operations". Naval Postgraduate School Monterey United States, 2018.

[71] Li, R., and Ma, H. "Research on UAV swarm cooperative reconnaissance and combat technology". In 2020 3rd International Conference on Unmanned Systems (ICUS), 996-999, IEEE, November 2020.

[72] Ju, C., and Son, H. I. "Multiple UAV systems for agricultural applications: Control, implementation, and evaluation". Electronics, 7(9), 162, 2018.

[73] Mukherjee, A., Misra, S., and Raghuwanshi, N. S. "A survey of unmanned aerial sensing solutions in precision agriculture". Journal of Network and Computer Applications, 148, 102461, 2019.

[74] Thornton, S., and Gallasch, G. E. "Swarming logistics for tactical last-mile delivery". In International Conference on Science and Innovation for Land Power Vol. 2018, September 2018.

[75] Kuru, K., Ansell, D., Khan, W., and Yetgin, H. "Analysis and optimization of unmanned aerial vehicle swarms in logistics: An intelligent delivery platform". IEEE Access, 7, 15804-15831, 2019.

[76] Ghamry, K. A., Kamel, M. A., and Zhang, Y. "Multiple UAVs in forest fire fighting mission using particle swarm optimization". In 2017 International Conference On Unmanned Aircraft Systems (ICUAS), 1404-1409. IEEE, June 2017.

[77] Brust, M. R., and Strimbu, B. M. "A networked swarm model for UAV deployment in the assessment of forest environments". In 2015 IEEE Tenth international conference on intelligent sensors, sensor networks and information processing (ISSNIP) ,1-6, IEEE, April 2015.

[78] Zhi-wei, H., Jia-hong, L., Ling, C., & Bing, W. "A hierarchical architecture for formation control of multi-UAV". Procedia Engineering, 29, 3846-3851, 2012.

[79] Shuttleworth, R., Golden, B. L., Smith, S. and Wasil, E. "Advances In Meter Reading: Heuristic Solution Of The Close Enough Traveling Salesman Problem Over A Street Network. In The Vehicle Routing Problem: Latest Advances and New Challenges", 487-501, United States of America, 2008.

[80] Erdoğan Akbulut, H., Özçelik, F., & Saraç, T. "Fakülte seviyesinde üniversite ders çizelgeleme problemi için bir tavlama benzetimi algoritması". Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi, 30(1), 17-30, 2024.

[81] Özden, G., & Sarıçiçek, İ. "Çapraz sevkiyatta kamyon çizelgeleme problemi için çözüm yaklaşımları". Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi, 25(1), 82-88, 2019.

[82] Tanyeri, B., Bayrak, Z. U., and Uçar, U. U. "The Experimental Study of Attitude Stabilization Control for Programmable Nano Quadcopter". Journal of Aviation, 6(1), 1-11, 2022.

[83] Sürü İnsansız Hava Aracı (İHA) Yarışması Teknik Şartnamesi, Teknofest, 2021.

[84] Golmisheh, F. M., & Shamaghdari, S. (2024). Heterogeneous optimal formation control of nonlinear multi-agent systems with unknown dynamics by safe reinforcement learning. Applied Mathematics and Computation, 460, 128302.

[85] Du, Z., Qu, X., Shi, J., & Lu, J. (2024). Formation control of fixed-wing UAVs with communication delay. ISA transactions, 146, 154-164.

[86] Peng, H., Huang, B., Jin, M., Zhu, C., & Zhuang, J. (2024). Distributed finite-time bearing-based formation control for underactuated surface vessels with Levant differentiator. ISA transactions, 147, 239-251.

[87] Zhu, Y., Li, S., Guo, G., Yuan, P., & Bai, J. (2024). Formation control of UAV–USV based on distributed event-triggered adaptive MPC with virtual trajectory restriction. Ocean Engineering, 294, 116850.

[88] Li, X., Qin, H., Li, L., & Xue, Y. (2024). Adaptive fixed-time fuzzy formation control for multiple AUV systems considering time-varying tracking error constraints and asymmetric actuator saturation. Ocean Engineering, 297, 116936.

[89] Shi, J., Ye, M., Ding, L., & Xu, S. (2024). Distributed least-distance formation control for Euler–Lagrange systems: A game-based approach. Control Engineering Practice, 142, 105743.

[90] Rai, A., & Mou, S. (2024). Safe region multi-agent formation control with velocity tracking. Systems & Control Letters, 186, 105776.

[91] Fei, Y., Shi, P., Li, Y., Liu, Y., & Qu, X. (2024). Formation control of multi-agent systems with actuator saturation via neural-based sliding mode estimators. Knowledge-Based Systems, 284, 111292.

[92] Xi, J., Wang, C., Wang, L., Qin, M., Xia, K., & Zheng, Y. (2024). Optimal formation strategy for interconnected quadrotor drones: Theory and experiment. Aerospace Science and Technology, 144, 108771.

[93] Qi, X. (2024). Event-Triggered Predictive Control Algorithm for Multi-AUV Formation Modeling. Informatica, 48(9).

[94] Yıldız, B. (2024). İnsansız Hava Aracı (iha) Sürüsünün Akıllı Yol Planlaması. Doktora Tezi. Konya Teknik Üniversitesi, Konya, TÜRKİYE.

[95] Lee, J., Ji, D., Cho, H., Baeg, S., & Jeong, S. (2024). Fault-Coping Algorithm for Improving Leader–Follower Swarm-Control Algorithm of Unmanned Surface Vehicles. Applied Sciences, 14(8), 3444.

[96] Yiğit, A., Kalaycý, A. O., & Akdemir, E. (2024, May). Autonomous TDOA Localization via Swarm UAV Concept. In 2024 32nd Signal Processing and Communications Applications Conference (SIU) (pp. 1-4). IEEE.

[97] Huang, Y., Meng, Z., & Dimarogonas, D. V. (2024). Prescribed performance formation control for second-order multi-agent systems with connectivity and collision constraints. Automatica, 160, 111412.

[98] Yu, K., Li, Y., Lv, M., & Tong, S. (2024). Distributed Optimal Formation Control of Multiple Unmanned Surface Vehicles with Stackelberg Differential Graphical Game. IEEE Transactions on Artificial Intelligence.

[99] Imran, I. H., Kurtulus, D. F., Memon, A. M., Goli, S., Kouser, T., & Alhems, L. M. (2024). Distributed Robust Formation Control of Heterogeneous Multi-UAVs with Disturbance Rejection. IEEE Access.

[100] Bu, Y., Yan, Y., & Yang, Y. (2024). Advancement challenges in UAV swarm formation control: A comprehensive review. Drones, 8(7), 320.

[101] Li, M., Liu, H., Xie, F., & Huang, H. (2024). Adaptive Distributed Control for Leader–Follower Formation Based on a Recurrent SAC Algorithm. Electronics, 13(17), 3513.

[102] Wu, J., Luo, C., Min, G., & McClean, S. (2024). Formation Control Algorithms for Multi-UAV Systems with Unstable Topologies and Hybrid Delays. IEEE Transactions on Vehicular Technology.

[103] Nguyen, K., Dang, V. T., Pham, D. D., & Dao, P. N. (2024). Formation control scheme with reinforcement learning strategy for a group of multiple surface vehicles. International Journal of Robust and Nonlinear Control, 34(3), 2252-2279.

[104] Liu, Y., Liu, J., He, Z., Li, Z., Zhang, Q., & Ding, Z. (2024). A survey of multi-agent systems on distributed formation control. Unmanned Systems, 12(05), 913-926.

[105] Okutan, H. E., & Baykara, M. (2024, October). OptiRoute: Operational Routing Algorithm for Swarm Robots. In 2024 Innovations in Intelligent Systems and Applications Conference (ASYU) (pp. 1-6). IEEE.

[106] Li, H., Hu, J., Zhou, Q., & Ghosh, B. K. (2024). Safe formation control of multiple unmanned aerial vehicles: control design and safety-stability analysis. Control Theory and Technology, 1-13.

[107] Wang, D., Ge, S. S., Liang, X., & Li, D. (2024). Time-synchronized formation control of unmanned surface vehicles. IEEE Transactions on Intelligent Vehicles.