Modification Swarm UAV Flocking Method: Prioritization and Collision Avoidance for Efficient Mission Execution

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ABSTRACT

The use of drones or Unmanned Aerial Vehicles (UAVs) for various civil, public, and military purposes, including border surveillance, traffic management, and disaster response, is becoming increasingly common. UAVs are also employed to deliver medications and medical aid to hard-to-reach areas. The risk of drone collisions is a significant concern during operations, especially in swarm situations. Flocking methods are typically used to manage drone movements to avoid collisions, but they do not prioritize mission importance or battery status. As a result, colliding drones tend to avoid each other, which can extend flight times and the paths taken. This research aims to modify the flocking method to improve UAV operations efficiency and safety by prioritizing drones based on mission urgency and battery status, thereby enhancing flight path efficiency and reducing travel time.

Keywords: UAV, Swarm Drone, Flocking Method, Priority Drone, Disaster Response.

INTRODUCTION

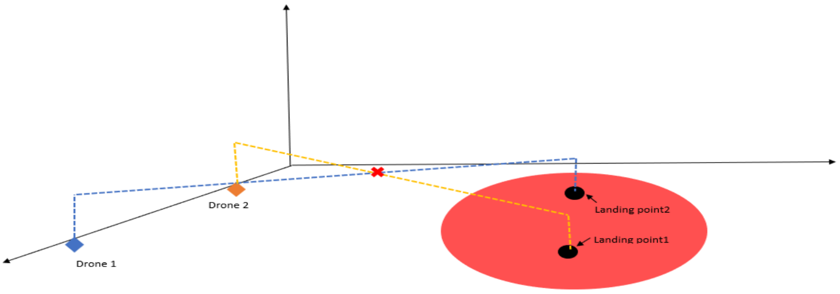


Figure 1. Illustration of Two Drones with Overlapping Flight Paths

Drones or Unmanned Aerial Vehicles (UAVs) are widely used in public, military, and civil applications.[11] For over 25 years, military UAVs have been utilized as tools for border surveillance. Additionally, UAVs can be employed by the public for purposes such as traffic monitoring, policing, and other examples. UAVs can also serve as disaster alerts and monitor hard-to-reach locations [7]. They can deliver medications and other medical necessities to these areas. In disaster situations, drones will fly together with other drones for a specific purpose or in swarm mode [6]. Swarm UAVs or swarm drones are modeled after natural animal colonies, such as bees and birds. Their collective behavior enables them to perform tasks that are difficult or impossible for individual group members to achieve [5]. For safe and orderly drone operations, one of the main concerns is the risk of collision with other drones in operation. This is related to the hazards and risks that may arise when drones are operating in a certain area. Therefore, collision detection and prevention are critical components.[8] To avoid collisions between operating drones, a method that allows drones to fly together harmoniously is required.

The image above shows that two drones have their own flight paths, but the path of drone 1 intersects with the path of drone 2, meaning they could collide. To avoid a collision, the drones can alter their flight paths. One way to avoid collisions is by using the flocking method, which aims to ensure that all drones move simultaneously without colliding and maintain a consistent relative formation.[9] However, the flocking method does not prioritize drones, so drones at risk of collision avoid each other, resulting in longer flight paths and more time to reach the target [4]. Therefore, this method will be modified to prioritize drones based on mission urgency and battery power, making the drone's flight path more efficient and reducing flight time.

LITERATURE REVIEW

Flocking Method

The flocking method is used when a group of robots or UAVs (Unmanned Aerial Vehicles) move together in swarm mode, similar to animals that live in groups, such as birds or fish.[12] Alignment, cohesion, and separation are the three main principles of the flocking method [1].

1. Alignment :
    - Purpose : Alignment aims to ensure that the direction of movement of each group member is aligned with the direction of movement of other group members [1].
    - Implementation : Robots or UAVs observe the relative direction of movement of others and then adjust their own direction to follow the average direction [1].
2. Cohesion :
    - Purpose : Cohesion aims to help group members stay close to each other [2].
    - Implementation : Each robot or UAV typically moves towards the center of mass of the group, or to the midpoint between themselves and other group members [2].
3. Separation :
    - Purpose : Separation aims to prevent collisions and ensure that each group member maintains a safe distance from others [3].
    - Implementation : Robots or UAVa monitor the distance from others and adjusts their movements to maintain a minimum safe distance, preventing collisions [3].

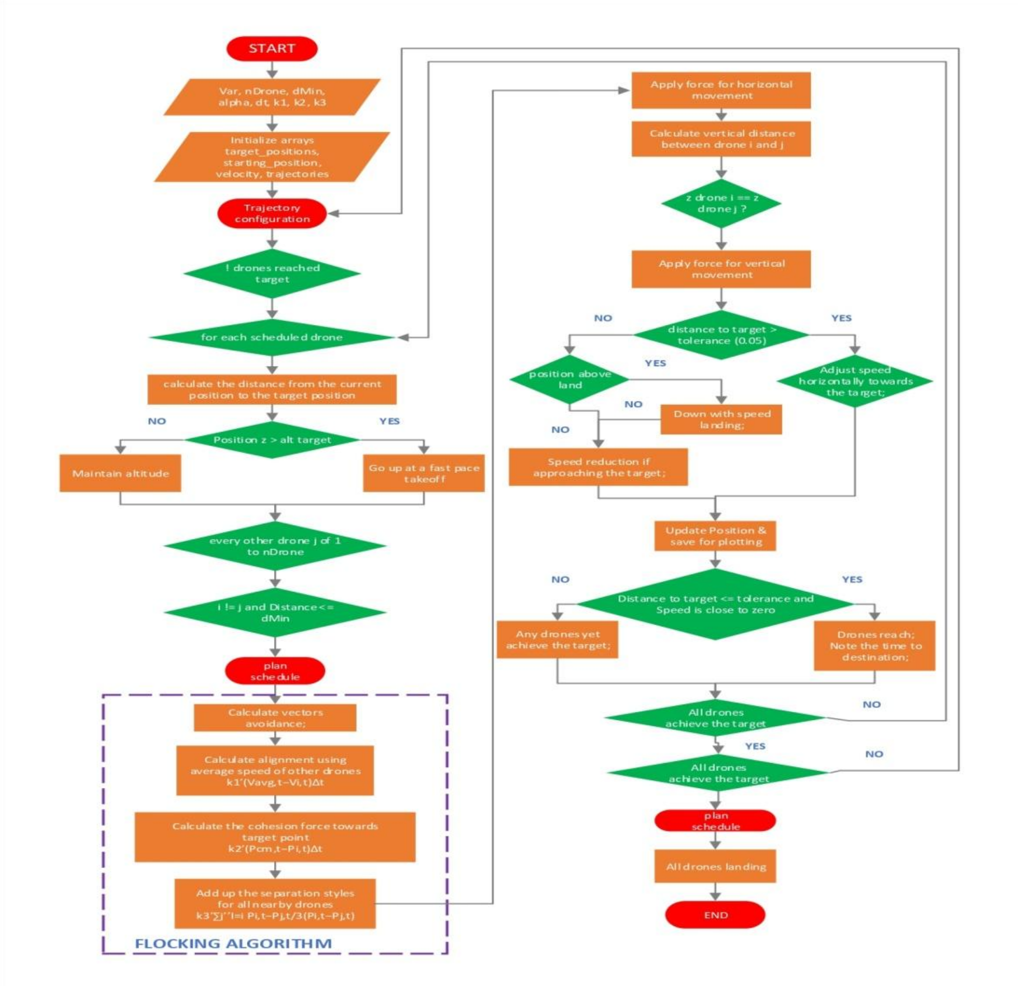


Figure 2. System Design

Figure (2) below is the system design that will be used in this research to operate the UAV swarm using the flocking method. Through this system design, it is hoped that the drones will be able to maintain their formation, thereby preventing collisions between drones.

METHODOLOGY

Flocking Method Before Modification

Flocking is commonly used in multi-robot systems, where multiple robots work together in an area. The goal of flocking is to ensure that all robots move together without collisions and maintain a consistent relative formation.[10] The flocking method can be applied to swarm drones to help the drones avoid collisions by moving right and left in two dimensions.

$P[i,t] = [x_{i,t},\ y_{i,t}]$

$V[i,t] = [x_{i,t},\ y_{i,t}]$

Where $x_{i,t}$, and $y_{i,t}$ are time-dependent functions representing the position and velocity of the drone in two dimensions.

Besides the flocking method, which can only perform two-dimensional avoidance, no drone is prioritized in collision avoidance. As a result, any drones that meet at the intersection of flight paths will avoid each other, making the flight paths taken by the drones less efficient.

The general equation for flocking in this context can be formulated as follows:

$$V[i,t+1] = V[i,t] + k_1.\ \left(V_{avg,t} - V[i,t]\right).\Delta t + k_2\left(P_{cm,t} - P[i,t]\right).\Delta t + k_3 \sum_{j\neq i} \frac{p[i,t]-p[j,t]}{\|p[i,t]-p[j,t]\|}$$

- $V[i,t]$is the velocity matrix for robot i at time t, with columns representing the x and y components, respectively.
- $P[i,t]$is the position matrix for drone i at time t, with columns representing the$x$ and y components, respectively.
- $P\left[cm,\ t\right]$is the position matrix of the center of mass at time t, calculated as the average position of all drones.
- $V_{avg,t}$is the average velocity of all drones at time t.
- $k_1,\ k_2,\ k_3$are the flocking constants for alignment, cohesion, and separation, respectively.

A. Alignment

$k_1.\ \left(V_{avg,t} - V[i,t]\right).\Delta t$

Calculate how the current speed of a drone and the reactions of other drones to changes in speed are handled.

B. Cohesian

$k_2\left(P_{cm,t} - P[i,t]\right).\Delta t$

Attempt to pull the drone toward the center of the group, which helps the group stay together.

C. Separation

$$k_3 \sum_{j\neq i} \frac{p[i,t]-p[j,t]}{\|p[i,t]-p[j,t]\|}$$

Drones must maintain a safe distance from other drones. To avoid collisions, reduce speed when approaching other drones.

Modification of the Flocking Method

Modify the flocking algorithm to avoid collisions by extending it to three-dimensional movement: right, left, up, and down. This can be achieved by adding a Z position component, as well as updating each element of the model. The position equations can be described as follows:

$P[i,t] = [x_{i,t},\ y_{i,t},\ z_{i,t}]$

$v[i,t] = [v_{xi,t},\ v_{yi,t},\ v_{zi,t}]$

Where $x_{i,t},\ y_{i,t},\ z_{i,t}$ are time-dependent functions representing the position and velocity of the drone in three dimensions.

In addition to modifying the algorithm to enable drones to avoid three-dimensional collisions, the flocking method is also modified to determine which drone has higher priority over others. This is influenced by the mission and battery capacity of the drones, so the drone with the most important mission and the lowest battery capacity will have higher priority when encountering other drones.

The following is an optimized flocking algorithm that includes drone prioritization and 3D collision avoidance:

$$V_{i,t+1} = V_{i,t} + \left(k_1^{'}\left(V_{avg,t} - V_{i,t}\right)\Delta t + k_2^{'}\left(P_{cm,t} - P_{i,t}\right)\Delta t + k_3^{'} \sum\nolimits_{j \neq i} \frac{P_{i,t} - P_{j,t}}{\left\|P_{i,t} - P_{j,t}\right\|^3} \right)$$

$if\ mission\ \neq [1,\ 2]\ ,\ battery_{dron\ e_i} > battery_{dron\ e_{1+1}}$

- $V[i,t]$is the velocity matrix for robot i at time t, with columns representing the$x$, y, and z components, respectively.
- $P[i,t]$is the position matrix for drone i at time t, with columns representing the x, y, and z components, respectively.
- $P\left[cm,\ t\right]$is the position matrix of the center of mass at time t, calculated as the average position of all drones.
- $V_{avg,t}$is the average velocity of all drones at time t
- $k_1^{'}, k_2^{'},\ k_3^{'}$are dynamic flocking constants for alignment, cohesion, and separation, respectively.

If a drone has mission 1 "water" and mission 2 "medicine," and the battery of drone iii is lower than that of drone i+1i+1i+1, then no avoidance is necessary, and the other drone with lower priority will perform the avoidance.

A. Parameter Adaptation Based on Group Density

In the equations above, $k_1^{'},\ k_2^{'},\ k_3^{'}$ are dynamic constants that can enhance the effectiveness and safety of drone group movement in varying environments.

$$k_1^{'} = \frac{k_1}{1 + \alpha . N_{close}}$$

$$k_2^{'} = \frac{k_2}{1 + \beta . N_{close}}$$

$$k_3^{'} = k_3 . \left(1 - \gamma . N_{far}\right)$$

N_{close} and N_{far} are the number of drones within the close and far radii, predicted through the x, y, and z coordinates, respectively. α, β, and γ are parameters that adjust sensitivity to density.

B. Alignment

$$k_1^{'}\left(V_{avg,t} - V_{i,t}\right)\Delta t$$

The alignment in the optimized flocking method can also calculate the impact of speed differences between other drones and the current speed of the drone on the current speed adjustments. What distinguishes this is that $k_1^{'}$ is dynamic, which enhances effectiveness and safety.

C. Cohesian

$$k_2^{'}\left(P_{cm,t} - P_{i,t}\right)\Delta t$$

The cohesion in the optimized flocking method also helps keep the group of drones together. However, the dynamic $k_2^{'}$, which takes into account the number of nearby drones, further enhances safety.

D. Separation

$$k_3^{'} \sum\nolimits_{j \neq i} \frac{P_{i,t} - P_{j,t}}{\left\|P_{i,t} - P_{j,t}\right\|^3}$$

Separation will ensure that drones maintain a safe distance from other drones, avoiding collisions by reducing speed when approaching another drone too closely. This will be maximized by $k_3^{'}$, which will increase the drone's awareness of other nearby drones.

Flight Path Modification

By using pathfinding algorithms to determine the shortest route before flight and using this information to adjust the velocity vectors in flocking, the modification of flight paths is expected to shorten the drone's flight time. Thus, when a drone avoids collisions, it will return to the previously established flight route. In other words, they are not only reactive to the positions of other drones but also proactive in moving towards the route deemed most efficient.

$$V_{i,t+1} = V_{i,t} + fa(\Delta t, d_{i,target}\ , p_i) \left(k_1^{'}\left(V_{avg,t} - V_{i,t}\right)\Delta t + k_2^{'}\left(P_{cm,t} - P_{i,t}\right)\Delta t + k_3^{'} \sum\nolimits_{j \neq i} \frac{P_{i,t} - P_{j,t}}{\left\|P_{i,t} - P_{j,t}\right\|^3} \right)$$

$$if\ mission\ \neq [1,\ 2]\ ,\ battery_{dron\ e_i} > battery_{dron\ e_{1+1}}$$

The adjustment function fa dynamically adjusts the flocking parameters based on operational and environmental conditions, allowing the drone to modify its flight strategy in real-time to achieve the most efficient flight time and path.

A. Flight Time Variable (Effect of Time Interval(ϵ))

$$\epsilon(\Delta \mathrm{t}) = exp(-\lambda . \Delta t)$$

Where λ is the time damping constant used to adjust the speed response to changes, which can also make the time more efficient.

B. Flight Path Variable

$$\left(1+\frac{\alpha}{1+exp\left(-\beta\left(d_{i,target}-\delta\right)\right)}\right)$$

Using a sigmoid function to adjust the impact based on the distance to the target, with α, β, and δ controlling the shape and sensitivity of the curve. This will make the travel distance more effective.

- α (Alpha) : This is the scaling parameter that determines the maximum amplitude of the impact distance can have on the regulated output. In this context, α determines how much the maximum impact increases above the baseline of 1. A higher α value will increase the maximum response of the function to distance.
- β (Beta) : This parameter controls the steepness of the sigmoid function. A higher β value will make the transition from low to high values sharper. This is effective in making the drone more responsive to small changes in distance around the value δ (for example, making the drone more sensitive right around critical threshold points).
- δ (Delta) : This sets the midpoint of the sigmoid function, where the output is the average of its minimum and maximum values. In this case, δrepresents the distance at which the influence begins to increase significantly. Thus δ acts as the halfway point of the sigmoid curve where the change occurs from low to high values.

C. Effect of Group Density

$\left(1+\gamma.log(1+p_i)\right)$

The logarithmic factor increases the impact of separation as density increases, where γ adjusts the strength of this effect.

Experiment And Analysis

Unmodified Flocking Method

In the first simulation, the unmodified flocking method was used for collision avoidance in drones. Figure (3) below is a three-dimensional graph of the simulation results.

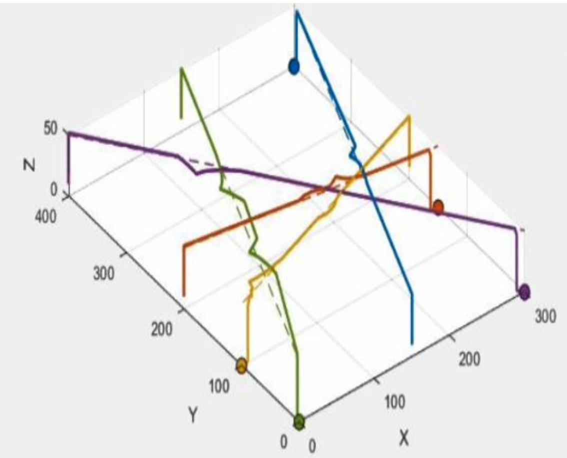


Figure 3. Three-Dimensional Graph of Unmodified Flocking Method

In the graph, there are several intersection points on the drone paths that increase the potential for collisions, requiring the drones to alter their flight paths to avoid collisions. This can be more clearly seen through the top-down two-dimensional graph of the x and y coordinates.

The following graph of x and y positions shows the top-down view of the drone's movement, illustrating how the drone avoids collisions by moving in two dimensions, to the right and left. However, in the flocking method prior to this modification, drones that meet at an intersection point would avoid each other, which results in the traveled distance being less efficient.

A modification to the flocking method can be made by determining which drone will be prioritized to pass according to its original path, while the other drone will attempt to avoid it.The drone's collision avoidance by moving in two dimensions using the flocking method can also be demonstrated by observing the following side view graph (z, x).

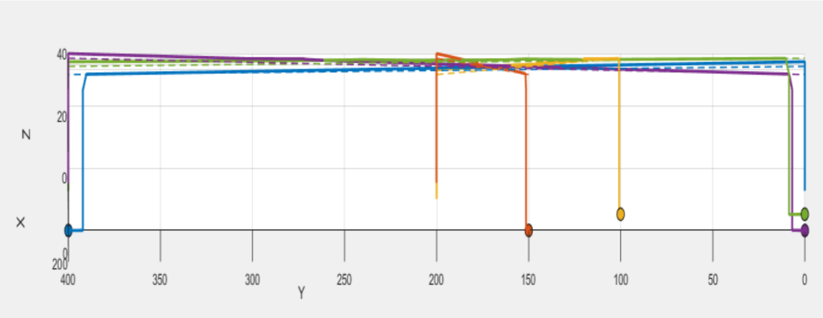


Figure 4. Two-Dimensional Graph (Z, Y) of Unmodified Flocking Method

In the following graph in figure (4), no drones are seen changing altitude, indicating that drones are only performing collision avoidance by moving two-dimensionally to the right and left.
From these graphs, several flight path intersections are identified as follows.

1. Potential Colission Point 1

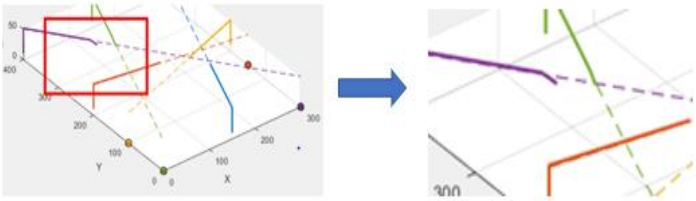


Figure 5. Potential Colission Point 1 of Unmodified Flocking Method

In figure(5) above, there is a potential collision between drone 4 (purple) and drone 5 (green).

2. Potential Colission Point 2

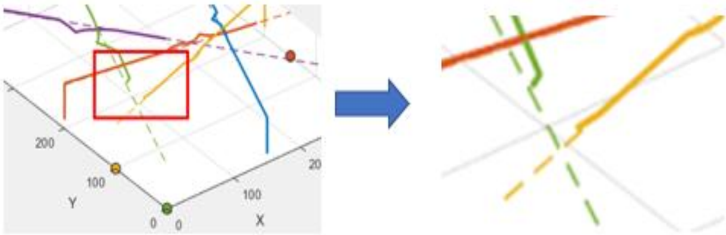


Figure 6. Potential Colission Point 2 of Unmodified Flocking Method

In figure(6) above, there is a potential collision between drone 5 (green) and drone 3 (yellow).

3. Potential Colission Point 3

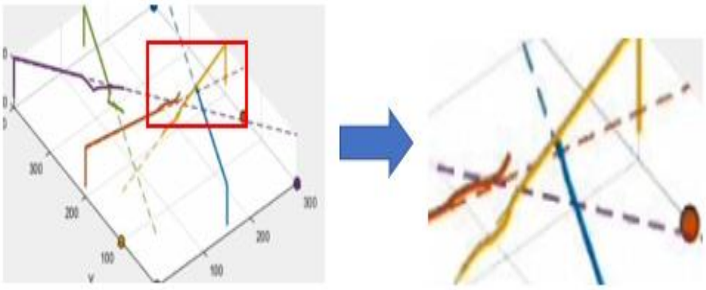


Figure 7. Potential Colission Point 3 of Unmodified Flocking Method

In figure (7) above, there is a potential collision between drone 2 (orange) and drone 1 (blue).

A. Elevation Graph of the Unmodified Flocking Method Simulation

The elevation graph will show when drones change their altitude. In figure (8) below is an elevation graph from the first simulation using the unmodified grouping method.

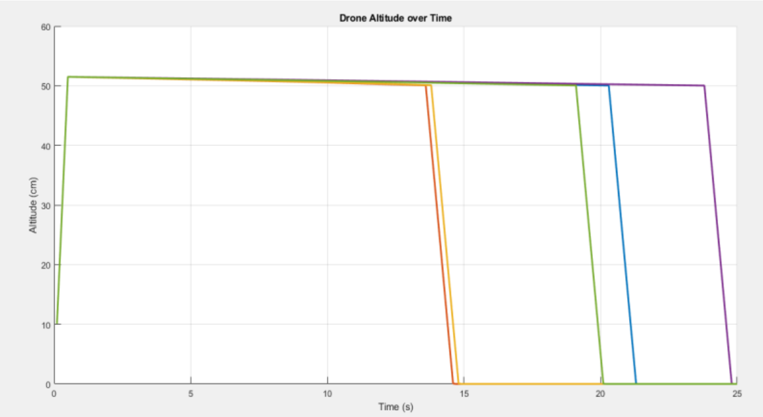


Figure 8. Elevation Graph of the Unmodified Flocking Method Simulation

Based on the elevation graph below, drones only change altitude during takeoff and landing. This reinforces the evidence that drones do not alter their altitude to avoid collisions.

B. Speed Graph of the Unmodified Flocking Method Simulation

The speed graph can illustrate the changes in speed made by the drones as part of their efforts to avoid collisions. In figure (9) below is an speed graph from the first simulation using the unmodified grouping method.

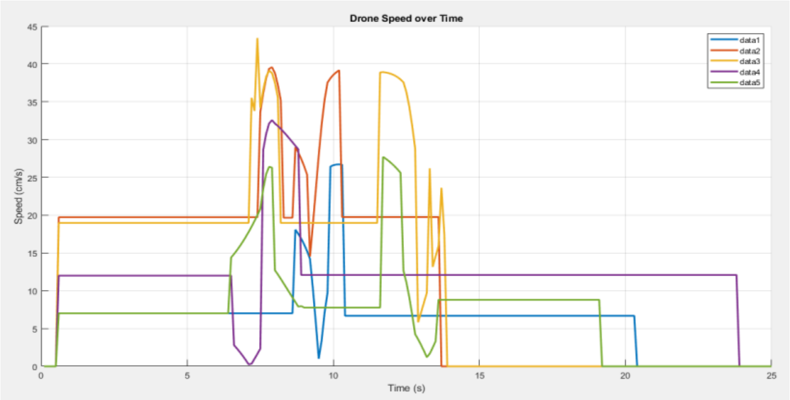
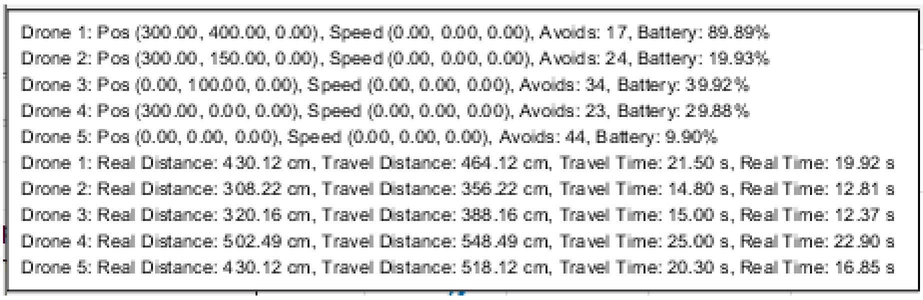


Figure 9. Speed Graph of the Unmodified Flocking Method Simulation

The speed graph shows that drones can adjust their speed to regulate the distance from other drones to avoid collisions.

C. Arrival Time and Travel Distance

The simulation obtains data as in figure (10) below:



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Drone 1: Pos (300.00, 400.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 17, Battery: 89.89%
Drone 2: Pos (300.00, 150.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 24, Battery: 19.93%
Drone 3: Pos (0.00, 100.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 34, Battery: 39.92%
Drone 4: Pos (300.00, 0.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 23, Battery: 29.88%
Drone 5: Pos (0.00, 0.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 44, Battery: 9.90%
Drone 1: Real Distance: 430.12 cm, Travel Distance: 464.12 cm, Travel Time: 21.50 s, Real Time: 19.92 s
Drone 2: Real Distance: 308.22 cm, Travel Distance: 356.22 cm, Travel Time: 14.80 s, Real Time: 12.81 s
Drone 3: Real Distance: 320.16 cm, Travel Distance: 388.16 cm, Travel Time: 15.00 s, Real Time: 12.37 s
Drone 4: Real Distance: 502.49 cm, Travel Distance: 548.49 cm, Travel Time: 25.00 s, Real Time: 22.90 s
Drone 5: Real Distance: 430.12 cm, Travel Distance: 518.12 cm, Travel Time: 20.30 s, Real Time: 16.85 s
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Figure 10. simulation data of the Unmodified Flocking Method Simulation

The data is as follows:

- Real Time : The time required for the drone to reach the target without collision avoidance.
- Travel Time : The time required for the drone to reach the target after implementing collision avoidance efforts.

- Real Distance : The distance from the drone's starting point to its arrival point if no path changes are made.
- Travel Distance : The distance from the drone's starting point to its arrival point after implementing collision avoidance efforts, which results in changes to the flight path.

Table 1. Distance and Time Data in Simulationof the Unmodified Flocking Method Simulation

Drone	Real Distance	Real Time	Travel Distance	Travel Time
Drone1	430.12 cm	19.92 s	464.12 cm	21.5 s
Drone2	308.22 cm	12.81 s	356.22 cm	14.8 s
Drone3	320.16 cm	12.37 s	388.16 cm	15 s
Drone4	502.49 cm	22.9 s	548.49 cm	25 s
Drone5	430.12 cm	16.85 s	518.12 cm	20.3s

The data in table (1) below shows how long it takes for drones using the unmodified flocking method to reach their destination. The longer the flight path taken by the drone, the longer the arrival time will be.

D. Difference Between Travel Time and Real Time

Based on the simulations conducted, The difference between real time and the travel time required for the drone to reach the target point can be determined as in table 2 below.

Table 2. Travel Time and Real Time Data in Simulationof the Unmodified Flocking Method Simulation

Drone	Real Time	Travel Time
Drone1	19.92 s	21.5 s
Drone2	12.81 s	14.8 s
Drone3	12.37 s	15 s
Drone4	22.9 s	25 s
Drone5	16.85 s	20.3s

Based on the table above, the following graph is obtained:

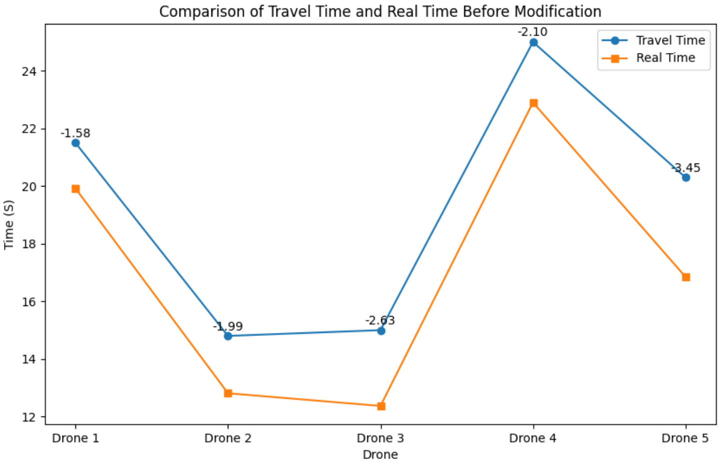


Figure 11. graph of the difference between travel time and real time of the Unmodified Flocking Method Simulation

Graph in figure (11)shows a difference in time between the real time, where the drone made no collision avoidance efforts, and the travel time after the drone made several attempts at collision avoidance. The differences are as follows:

- Drone 1: 1.58 s
- Drone 2: 1.99 s
- Drone 3: 2.63 s
- Drone 4: 2.1 s
- Drone 5: 3.45 s

This time difference occurs due to the collision avoidance efforts that require the drone to alter its flight path, resulting in longer travel times.

E. Difference Between Travel Distance and Real Distance

Based on the simulations conducted, The difference between the actual distance and the travel distance required for the drone to reach the target point can be determined as in table (3).

Table 3. Between Travel Distance and Real Distance Data in Simulation of the Unmodified Flocking Method Simulation

Drone	**Real Distance**	**Travel Distance**
Drone1	430.12 cm	464.12 cm
Drone2	308.22 cm	356.22 cm
Drone3	320.16 cm	388.16 cm
Drone4	502.49 cm	548.49 cm
Drone5	430.12 cm	518.12 cm

Based on the table above, the following graph is obtained:

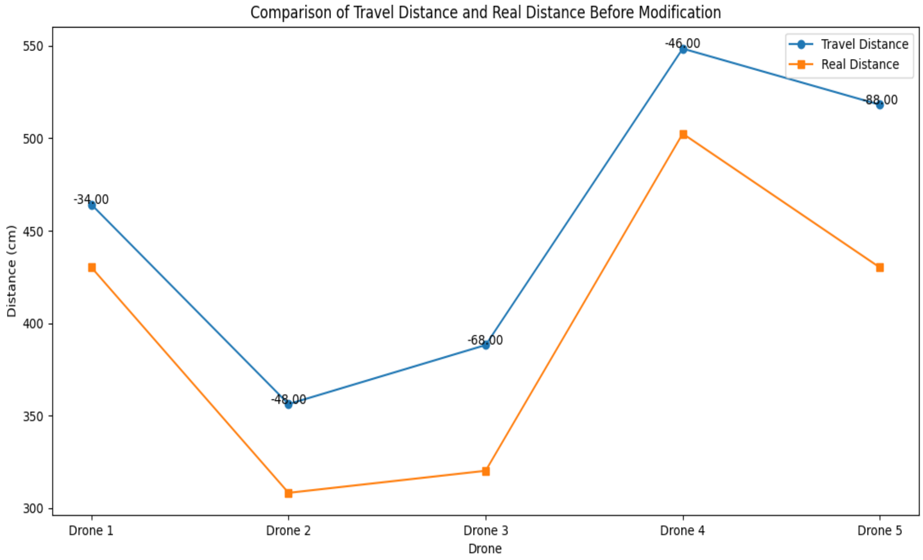


Figure 12. graph of the difference between travel distance and real distance of the Unmodified Flocking Method Simulation

In Figure (12) it can be seen that there is a difference in the distance traveled by the drone compared to the real distance based on the flight path that has been determined. This difference occurs because the drone's collision avoidance efforts require it to alter its flight path, resulting in a longer route. The results are as follows:

- Drone 1: 34 cm
- Drone 2: 48 cm
- Drone 3: 68 cm
- Drone 4: 46 cm
- Drone 5: 88 cm

Modified Flocking Method

In addition to experimenting with the unmodified flocking method, experiments were also conducted using the modified flocking method in the second simulation. This modification aims to enable three-dimensional collision avoidance and prioritize drones with urgent missions and low battery levels. Figure (13) below is a three-dimensional graph of the simulation carried out.

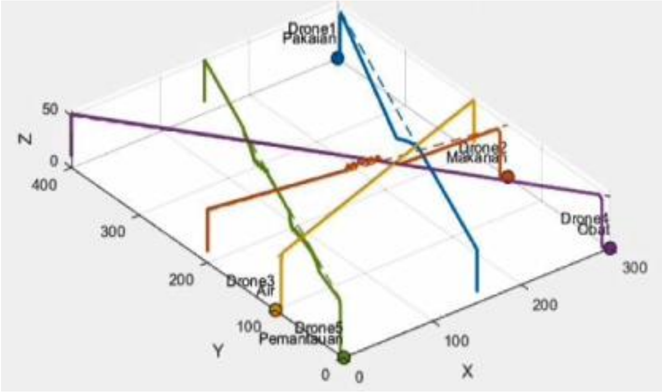


Figure 13. Three-Dimensional Graph of Modified Flocking Method

The graph shows several intersection points on the drone's path that could increase the potential for collisions, requiring the drone to alter its flight path to avoid collisions. With the modified flocking method, it is expected that drones will be able to avoid collisions in all directions: right, left, up, and down. Collision avoidance by moving right and left can be observed through the top-down position graph (x, y) as shown in figure (14) below.

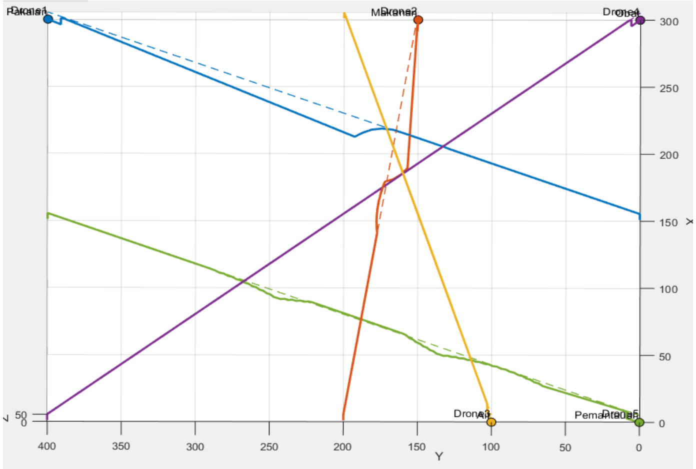


Figure 14. Two-Dimensional Graph of Modified Flocking Method

The following graph of x and y positions shows the top-down view of the drone's movement, illustrating how the drone avoids collisions by moving in two dimensions, to the right and left. However, in the flocking method prior to this modification, drones that meet at an intersection point would avoid each other, which results in the traveled distance being less efficient. A modification to the flocking method can be made by determining which drone will be prioritized to pass according to its original path, while the other drone will attempt to avoid it.The drone's collision avoidance by moving in two dimensions using the flocking method can also be demonstrated by observing the following side view graph (z, x).

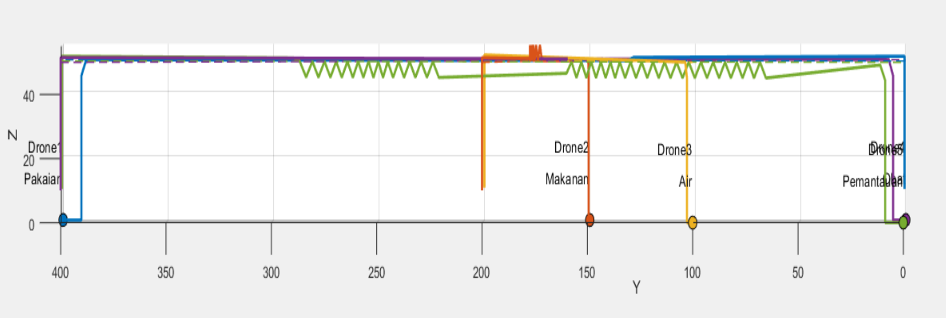


Figure 15. Two-Dimensional Graph (Z, Y) of Modified Flocking Method

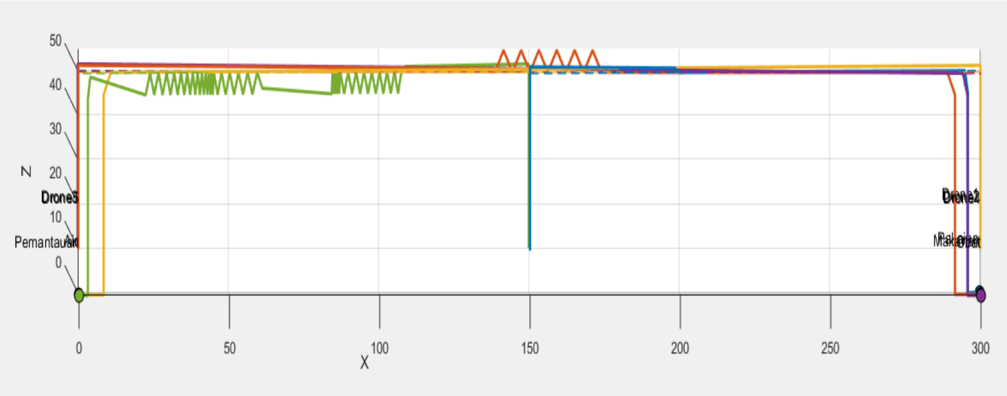


Figure 16. Two-Dimensional Graph (Z, X) of Modified Flocking Method

The z,y and z,x position graphs are as shown in figures (15) and figure (16) below display the drone's movement from a side view. The altitude changes performed by the drones are visible, indicating that the drones can move in three dimensions to avoid collisions.

In addition to altitude changes for collision avoidance, the modified flocking method also incorporates prioritization of drones. In scenario 1, drones with higher priority based on their mission are Drone 3 (yellow) with a mission to carry water and Drone 4 (purple) with a mission to carry medicine. Consequently, other drones with lower priority Drone 1 (blue) with a mission to carry clothes, Drone 2 (orange) with a mission to carry food, and Drone 5 (green) with a monitoring mission must avoid collisions when encountering the higher-priority drones.

Based on the graphs above, there are several intersection points on the drones' paths that could increase the potential for collisions. Below are some points with potential collisions among the drones:

1. Potential Colission Point 1

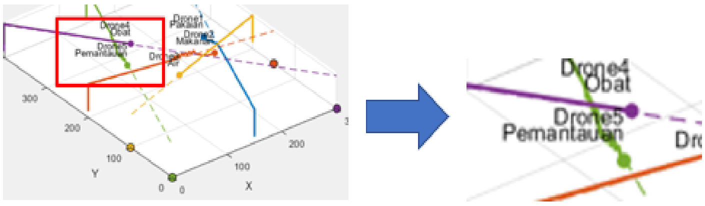


Figure 17. Potential Colission Point 1 of Modified Flocking Method

Figure 17 above shows the potential for a collision between Drone 4 (purple) and Drone 5 (green).

2. Potential Colission Point 2

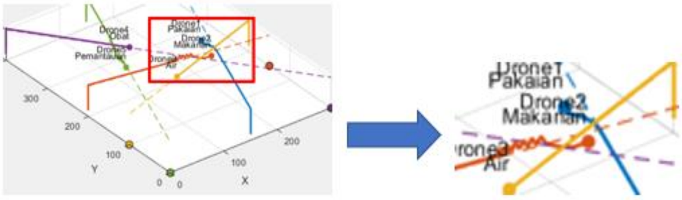


Figure 18. Potential Colission Point 2 of Modified Flocking Method

Figure 18 above shows the potential for a collision between Drone 2 (orange) and Drone 1 (blue).

3. Potential Colission Point 3

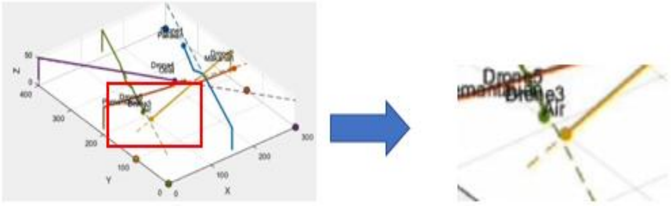


Figure 19. Potential Colission Point 3 of Modified Flocking Method

Figure 19 above shows the potential for a collision between Drone 5 (green) and Drone 3 (yellow).

A. Elevation Graph of the Modified Flocking Method

The height chart shows when drones adjust their altitude to avoid collisions. Figure (20) below is a elevation graph from the Scenario 1 simulation using the modified batching method.

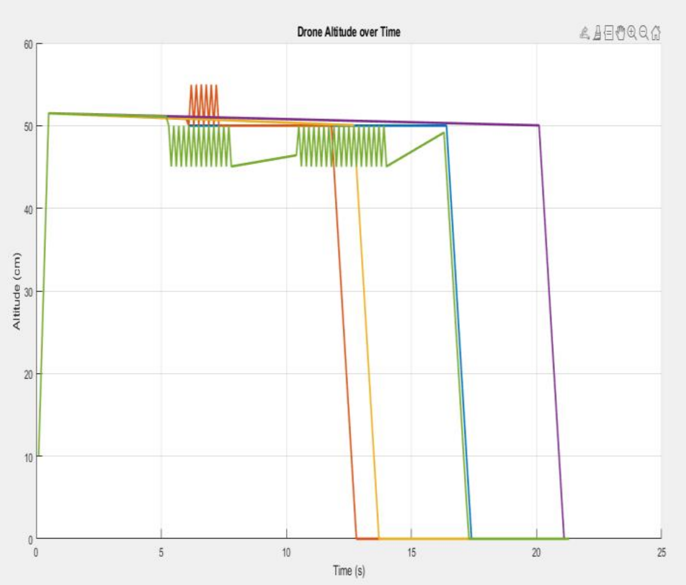


Figure 20. Elevation Graph of the Modified Flocking Method Simulation

The elevation graph also shows that drones adjust their altitude midway through their journey to the target. This indicates that drones can change their altitude to avoid collisions. In the chart, the drone that changes altitude twice is Drone 5 (green). The first altitude adjustment is made to avoid a collision at Potential Collision 1 with Drone 4 (purple). The second altitude adjustment of Drone 5 (green) is made to avoid a collision at Potential Collision 3 with Drone 3 (yellow). After successfully avoiding the collisions, the drone returns to its original altitude.

B. Speed Graph of the Modified Flocking Method

The speed chart illustrates the changes in speed made by drones as one of their efforts to avoid collisions. Figure (21) below is the speed chart from Scenario 1 simulation using the modified flocking method.

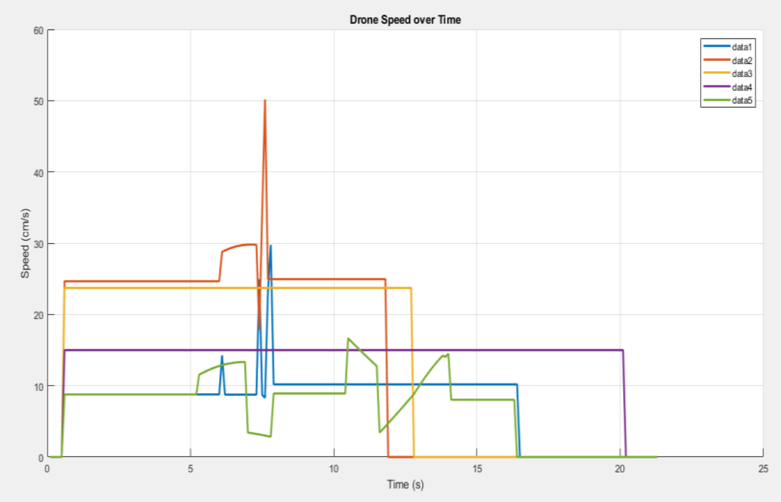
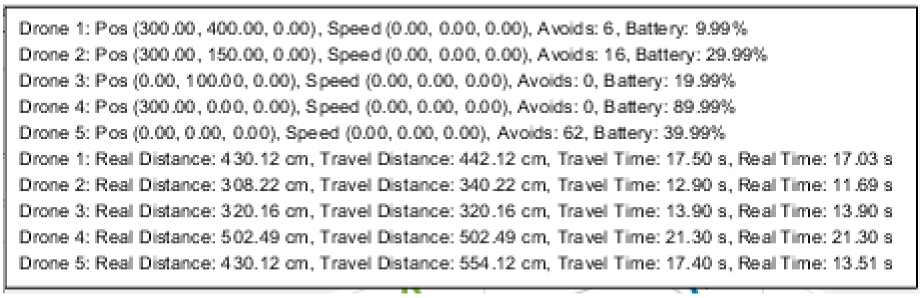


Figure 21. Speed Graph of the Modified Flocking Method Simulation

The speed chart shows that drones can adjust their speed to manage the distance from other drones and avoid collisions. Drones with higher priority tend to maintain their speed as they do not need to avoid collisions.

C. Arrival Time and Travel Distance

The simulation obtains data as in figure (22) below:



```
Drone 1: Pos (300.00, 400.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 6, Battery: 9.99%
Drone 2: Pos (300.00, 150.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 16, Battery: 29.99%
Drone 3: Pos (0.00, 100.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 0, Battery: 19.99%
Drone 4: Pos (300.00, 0.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 0, Battery: 89.99%
Drone 5: Pos (0.00, 0.00, 0.00), Speed (0.00, 0.00, 0.00), Avoids: 62, Battery: 39.99%
Drone 1: Real Distance: 430.12 cm, Travel Distance: 442.12 cm, Travel Time: 17.50 s, Real Time: 17.03 s
Drone 2: Real Distance: 308.22 cm, Travel Distance: 340.22 cm, Travel Time: 12.90 s, Real Time: 11.69 s
Drone 3: Real Distance: 320.16 cm, Travel Distance: 320.16 cm, Travel Time: 13.90 s, Real Time: 13.90 s
Drone 4: Real Distance: 502.49 cm, Travel Distance: 502.49 cm, Travel Time: 21.30 s, Real Time: 21.30 s
Drone 5: Real Distance: 430.12 cm, Travel Distance: 554.12 cm, Travel Time: 17.40 s, Real Time: 13.51 s
```

Figure 22. simulation data of the Modified Flocking Method Simulation

The following data shows:

- Real Time : The time required for the drone to reach the target without collision avoidance.
- Travel Time : The time required for the drone to reach the target after making several collision avoidance attempts.
- Real Distance : The distance from the drone's starting point to its destination if no path changes are made.
- Travel Distance : The distance from the drone's starting point to its destination after making several collision avoidance attempts, which results in changes to the flight path.

Table 4. Distance and Time Data in Simulation of the Modified Flocking Method Simulation

Drone	**Real Distance**	**Real Time**	**Travel Distance**	**Travel Time**
Drone1	430.12 cm	17.03 s	442.12 cm	17.5 s
Drone2	308.22 cm	11.69 s	340.22 cm	12.9 s
Drone3	320.16 cm	13.9 s	320.16 cm	13.9 s
Drone4	502.49 cm	21.3 s	502.49 cm	21.3 s
Drone5	430.12 cm	13.51 s	554.12 cm	17.4 s

Table (4) data follows indicates how long it takes for drones using the modified flocking method to reach their destination.

D. Difference Between Travel Time and Real Time

Based on the conducted simulations, the difference between the real time and the travel time required for the drone to reach the target can be determined as in table (5).

Table 5. Travel Time and Real Time Data in Simulation of the Modified Flocking Method Simulation

Drone	**Real Time**	**Travel Time**
Drone1	17.03 s	17.5 s
Drone2	11.69 s	12.9 s
Drone3	13.9 s	13.9 s
Drone4	21.3 s	21.3 s
Drone5	13.51 s	17.4 s

Based on the table above, the following graph can be derived:

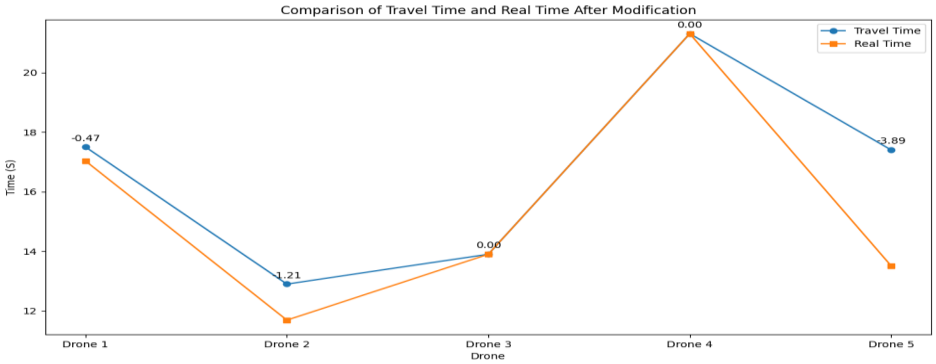


Figure 23. graph of the difference between travel time and real time of the Modified Flocking Method Simulation

From figure (23), it can be observed that there are several differences in time between the real time, when the drone did not attempt any collision avoidance, and the arrival time after the drone made several collision avoidance attempts. In the prioritized flocking method, there are drones that did not experience a change in time due to their priority. Here is the time difference for each drone:

- Drone 1: 0.47 s
- Drone 2: 1.21 s
- Drone 3: 0 s
- Drone 4: 0 s
- Drone 5: 3.89 s

E. Difference Between Travel Distance and Real Distance

Based on the simulations performed, the difference between the real distance and the travel distance needed by the drone to reach the target point can be determined as in table (6).

Table 6. Travel Distance and Real Distance Data in Simulation of the Modified Flocking Method Simulation

Drone	**Real Distance**	**Travel Distance**
Drone1	430.12 cm	442.12 cm
Drone2	308.22 cm	340.22 cm
Drone3	320.16 cm	320.16 cm
Drone4	502.49 cm	502.49 cm
Drone5	430.12 cm	554.12 cm

Based on the table above, the following graph is obtained:

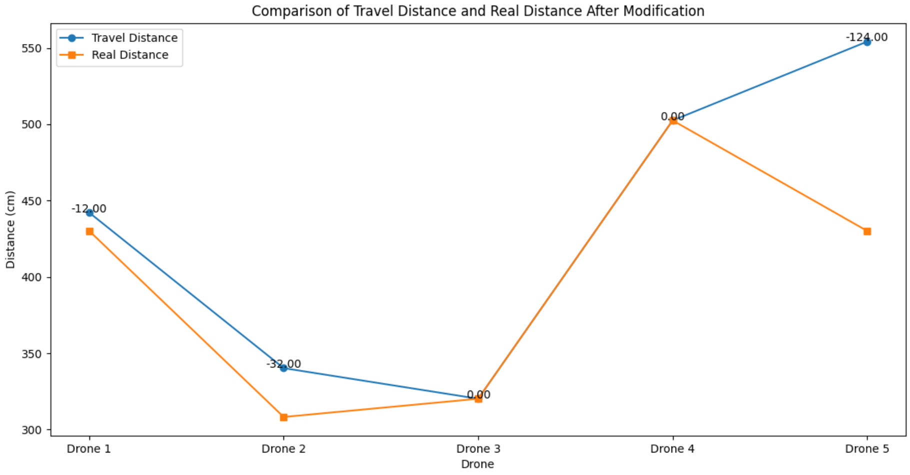


Figure 24. graph of the difference between travel distance and real distance of the Modified Flocking Method Simulation

In Figure (24) it is known that there is a difference in the distance traveled by the drones compared to the real distance based on the predefined drone paths. However, some high-priority drones do not show changes in the length of their paths. This occurs because high-priority drones do not perform collision avoidance. The results are as follows:

- Drone 1: 12 cm
- Drone 2: 32 cm
- Drone 3: 0 cm
- Drone 4: 0 cm
- Drone 5: 124 cm

Evaluation of Simulation: Pre-Modification Flocking Method vs. Modified Flocking Method

A. Distance Evaluation

Based on the simulations conducted, a comparison will be made between the travel distances of the pre-modification flocking method and the modified flocking method. This evaluation will reveal the difference in distances and determine which method makes the drone's travel more efficient. The results of the simulation are as in table (7) below.

Table 7. Distance Evaluation Data

Drone	**Real Distance**	**Travel Distance Unmodified**	**Travel Distance Modified**
Drone1	430.12 cm	464.12 cm	442.12 cm
Drone2	308.22 cm	356.22 cm	340.22 cm
Drone3	320.16 cm	388.16 cm	320.16 cm
Drone4	502.49 cm	548.49 cm	502.49 cm
Drone5	430.12 cm	518.12 cm	554.12 cm

Based on the data above, the following graph is obtained:

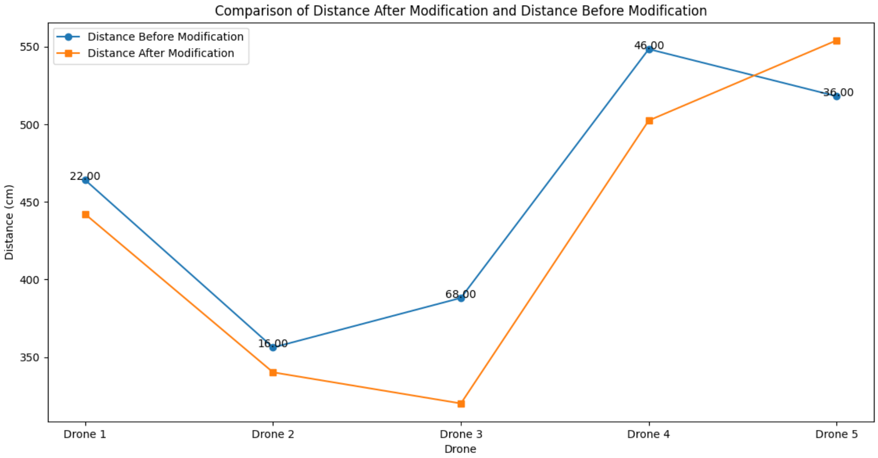


Figure 25. graph distance evaluation

In figure (25) it is known that there is a difference in the distance traveled by drones using the flocking method before modification compared to the distance traveled by drones using the modified flocking method. After modification, the distances traveled by drone 1, drone 2, drone 3, and drone 4 are shorter compared to before modification. However, there is one drone, drone 5, that has a longer distance traveled after modification compared to before modification. This is because drone 5 is the one that frequently performs collision avoidance maneuvers. The results are as follows:

- Drone 1: 22 cm
- Drone 2: 16 cm
- Drone 3: 68 cm
- Drone 4: 46 cm
- Drone 5: -36 cm

B. Evaluation of Time

In addition to evaluating distance, time evaluation was also conducted. Based on the simulations carried out, there is a difference in travel time between the simulation using the flocking method before modification and the simulation using the flocking method after modificationas in table 8 below.

Table 8. Time Evaluation Data

Drone	**Time Taken Before Modification**	**Time Taken Modification**
Drone1	21.5 s	17.03 s
Drone2	14.8 s	11.69 s
Drone3	15 s	13.9 s
Drone4	25 s	21.3 s
Drone5	20.3s	13.51 s

Based on the data above, the following graph is obtained:

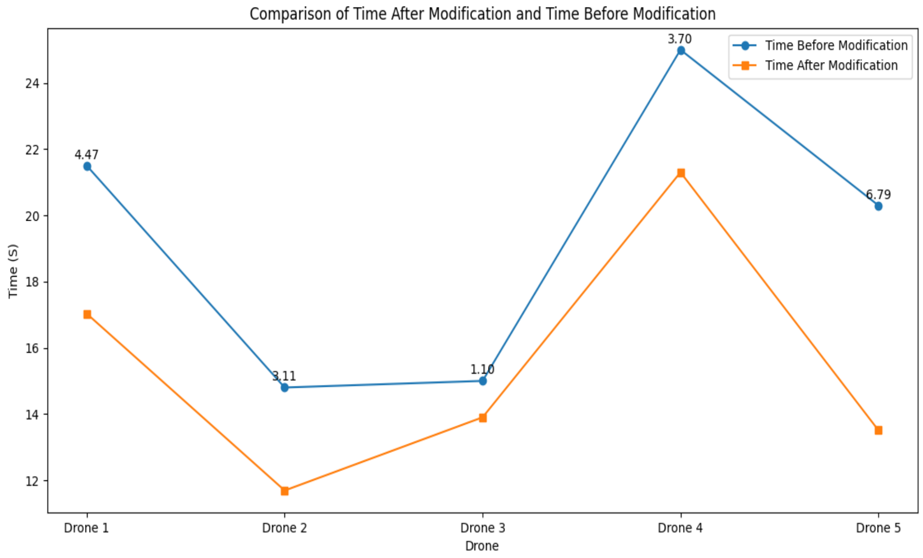


Figure 26. graph time evaluation

In figure (16) it is known that there is a difference in arrival time between drones using the flocking method before modification and drones using the flocking method after priority modification. In the distance evaluation for drone 5 (green), the travel distance for the flocking method after modification is longer than that before modification. However, in the time evaluation, it is found that the travel time after modification for drone 5 (green) is faster by 2.9 seconds compared to the travel time of the flocking method before modification. Thus, the results are as follows:

- Drone 1 : 4.45 S
- Drone 2 : 1.9 S
- Drone 3 : 1.1 S
- Drone 4 : 3.7 S
- Drone 5 : 2.9 S

C. Obstacle Avoidance Movement Evaluation

In addition to conducting distance evaluations to determine which method results in a more effective distance and time evaluations to see which method improves drone travel time, the next evaluation conducted is the collision avoidance movement evaluation. This is done to assess which method allows the drone to avoid collisions more efficiently.

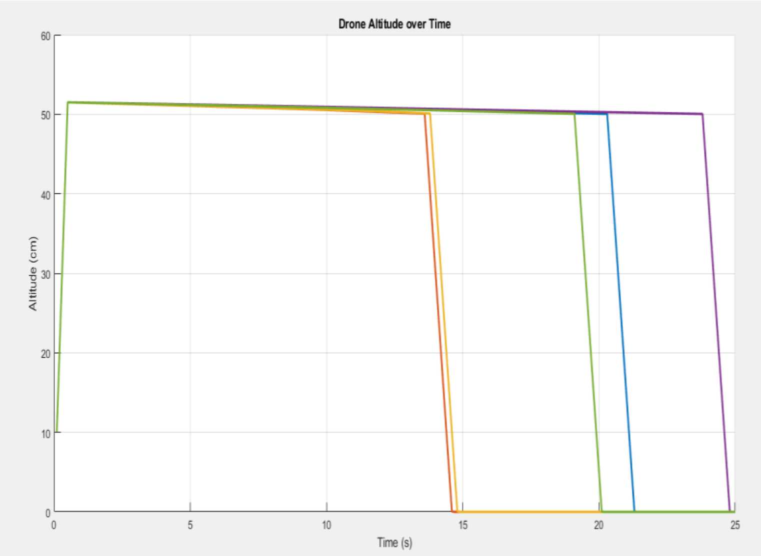


Figure 27. Elevation Graph of the Unmodified Flocking Method Simulation

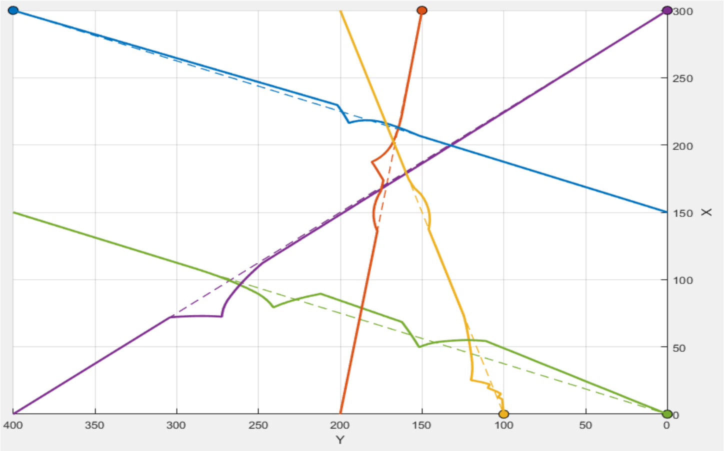


Figure 28. Two-Dimensional Graph of Unmodified Flocking Method

In the method before modification, there is no height adjustment for collision avoidance. Therefore, it can be said that the pre-modification method can only avoid collisions by moving in 2D, to the right and left. Additionally, in the pre-modification flocking method, there is no priority assigned to drones, so each drone at risk of collision will attempt to avoid one another. This results in less effective distance and travel time for the drones.

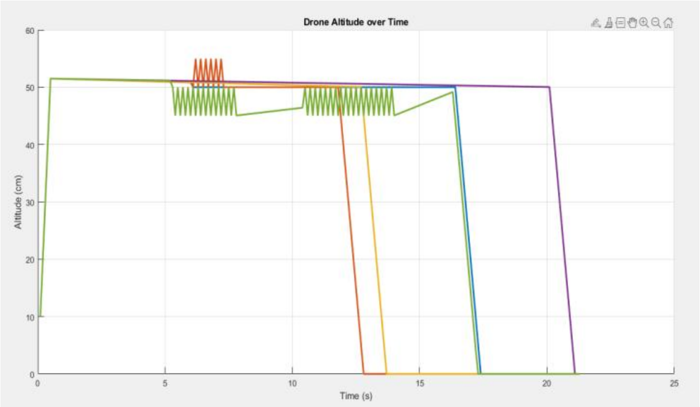


Figure 29. Elevation Graph of the Modified Flocking Method Simulation

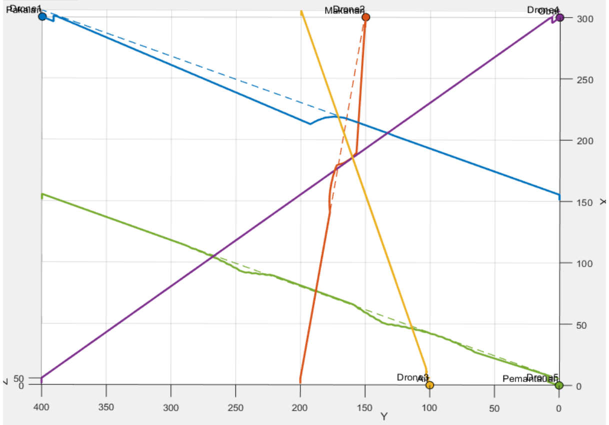


Figure 30. Two-Dimensional Graph of Modified Flocking Method

In the modified flocking method with prioritization, there is a change in altitude for collision avoidance. This indicates that, in addition to avoiding collisions by moving to the right and left, the drones are also avoiding collisions by moving in three dimensions to change altitude. Furthermore, it can be observed that some drones do not change their flight path, as they are high-priority drones. When these drones are about to collide, they will remain on their designated path, while lower-priority drones will be the ones to avoid the collision.

CONCLUSION

Based on the experiments conducted with the same scenario using two different methods—pre-modification flocking and post-modification flocking—the following conclusions were drawn:

1. In the distance evaluation, it was found that using the modified flocking method resulted in four out of five drones having a shorter travel distance to the target compared to using the unmodified flocking method.
2. In the time evaluation, it was observed that using the modified flocking method resulted in all five drones having shorter travel times compared to the travel times when using the unmodified flocking method.
3. In the altitude evaluation, it was noted that the experiment using the unmodified flocking method did not cause the drones to avoid collisions by changing altitude, whereas in the experiment using the modified flocking method, the drones changed altitude to avoid collisions.

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