Implementation of Boids Flocking Algorithm for Efficient Drone Swarm-Based Search and Rescue with Divide and Conquer Approach

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***Abstract*—This paper explores the potential use of drone swarms and the Boids flocking algorithm for search and rescue operations. Indonesia, given its unique geographical and geological conditions that make it prone to natural disasters, might benefit from the usage of UAV swarms in search and rescue operations, which reduces costs and increases efficiency. We propose a solution by incorporating the Boids flocking algorithm and a divide-and-conquer strategy to control individual drones' movement and optimize search space allocation. This approach is implemented in Python using the Pygame library and tested through a 2D simulation to evaluate its ability to achieve effective area coverage and maintain swarm coordination. Test results show that our biologically inspired model for drone swarms searches for victims faster when the drone swarm's size is increased. However, results suggest the need for future improvements for the current implementation, especially on collision avoidance.**

***Keywords*—drone swarm, boids, flocking, search and rescue, divide and conquer**

I. Introduction

Indonesia is located in the Pacific Ring of Fire, which means that it has a lot of different kinds of land and geological activity. Because of this, the country has a lot of natural disasters, like earthquakes, volcanic eruptions, tsunamis, forest fires, and floods. These events often put people in life-threatening situations, such as trapping them under debris, isolating them in remote areas, or preventing them from accessing basic needs, which creates the urgent need for effective search and rescue (SAR) operations. Moreover, due to its tropical climate, Indonesia's forests cover around $51,2\%$ of its whole land territory (according to 2023 data), which adds both physical and visual obstacles that reduce the speed and efficiency of search and rescue efforts. [1] The National Search and Rescue Agency (Badan SAR Nasional, BASARNAS) itself noted that it has performed at least 2.600 SAR operations over the last year. [2]

On increasing the efficiency of search and rescue operations, several previous studies have suggested the use of UAVs (unmanned aerial vehicles), especially for searching. [3] [4] [5] Either not deploying a search and rescue unit to people in distress or deploying them to a place in which they have no need is redundant and inefficient, potentially extending the search and rescue operation's duration and risking the victims' likelihood of survival. The usage of UAVs in disaster management might speed up the search process by scanning through large or inaccessible areas, narrowing the potential locations of the victims, and gathering real-time data from the environment. This provides the search and rescue team an opportunity to focus their efforts effectively and respond faster.

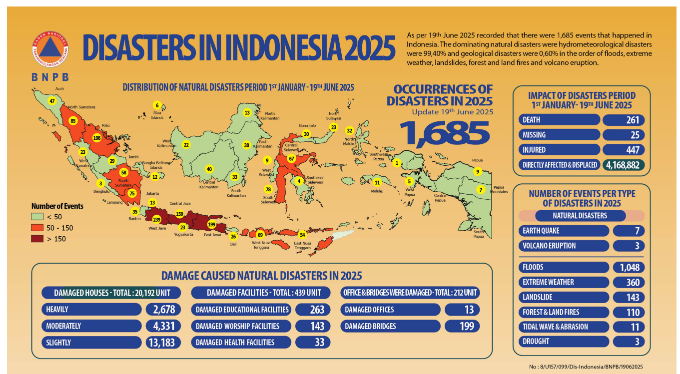

Figure 1. In just the first six months of 2025, 1.685 natural disasters occurred throughout Indonesia, with floods being the most frequent among them. These disaster has caused 261 deaths. Moreover, 25 people went missing and 447 people got injured. (Source: Rangkuman Bencana tahun 2025, National Agency for Disaster Countermeasure/Badan Nasional Penanggulangan Bencana (BNPB) [6]

Not only one drone can be employed in SAR missions. Instead, several drones might be deployed simultaneously, collectively forming a drone swarm that cooperates with each other to handle large areas efficiently. By leveraging swarm intelligence and distributed coordination, these drones can work in parallel to each other and explore complex environments and collaboratively search for victims in a faster and more scalable manner compared to a single UAV.

In order to perform coordinated movement within the drone swarm, many computer scientists has approved the adoption of biologically inspired models such as the Boids flocking algorithm, which mimics the behaviour of bird flocks, animal herds, and fish schools with simple rules. By setting several rules such as aligning with nearby drones, maintaining separation to avoid collisions, and moving together as a group to maintain cohesion in the swarm, each drone can operate individually while moving together in an organized manner.

Lastly, for the sake of optimization in terms of area coverage and to avoid redundancy in the search operation, the search space of the drone swarm can be divided into sectors using a divide-and-conquer approach. This, in turn, will hasten the search process and contribute to its efficiency.

Combining the use of the flocking algorithm and the divide-and-conquer approach might significantly increase the effectiveness, speed, and robustness of the search and rescue operation in complex terrains such as Indonesia's forested or mountainous regions prone to natural disasters.

Since testing with real drones might be expensive, a simulation-based approach will be sufficient for algorithm development and validation purposes. This will provide a baseline for future developments and real-world applications.

In this paper, we will implement a 2D-based simulation for a drone swarm search and rescue mission, utilizing the Boids flocking algorithm and the divide-and-conquer approach. This may provide an opportunity to demonstrate the application of classical algorithmic approaches or paradigms such as divide-and-conquer, and illustrate an example of how informatics concepts can be used to solve real-world problems.

II. Theoretical Foundation

A. Search and Rescue (SAR)

The term "search and rescue" refers to the organized activities that focus on searching for persons in distress during an emergency incident, removing them from any potential danger, treating those who are injured, and transporting them to health facilities for further treatment. [7] This ranges from basic community-level efforts using locally available resources to highly organized national or even international operations that involve special units. Today, SAR has transformed into an extensive system, consisting of several functional components namely:

1) communications network across the SAR region;
2) a rescue coordination center (RCC) for SAR services coordination;
3) SAR facilities;
4) SAR units with specialized equipment and trained personnels;
5) on-scene coordinators (OSCs); and
6) support facilities.

Providing SAR services has been considered as an international humanitarian obligation, which was manifested in UNCLOS 1982, SOLAS 1974, and SAR 1979, but not limited to that. The concept of SAR cannot be separated from its humanitarian nature. [8] A quick response from search and rescue services in the first hour after a disaster occurs is crucial, since this period of time, often referred to as the "Golden Hour," is when the survival rate of victims is at its highest. [8] More broadly, the first 72 hours after the disaster are the most critical moments in SAR. [3] Hence, with quick and proper treatment, we can prevent victims from experiencing more severe injuries or possibly death.

Search and rescue is made up of three steps: size-up, search, and rescue. The size-up step includes evaluating the situation and condition, and then the appropriate course of actions is determined. Search is the next step, which is self-explanatory. In this step, the search and rescue unit attempts to locate the victim(s) and keep track of their position. Lastly, the rescue step involves relocating them to safety.

There are three underlying principles in SAR. These are: [8]

1) Always ensure rescuers safety.
2) Save as many lives as possible in the shortest period of time.
3) Start by rescuing the victims who are not severely trapped.

The existence of obstacles, restricted accessibility, and large search areas often make conventional SAR techniques difficult. For instance, Indonesia's mountainous and forested terrains frequently hinder SAR unit personnel in performing their tasks. Among all factors that influence SAR operations' success, time is the most critical.

This strongly urges the need for an efficient, rapid search strategy that is able to cover large areas without sacrificing safety or accuracy. Therefore, incorporating new technologies such as UAVs, specifically drone swarms, might provide a promising solution to those issues that also adheres to the three aforementioned principles.

B. Unmanned Aerial Vehicles (UAVs) in SAR

Unmanned aerial vehicles, or commonly known as drones, are aircrafts (either fixed wing or rotary) with no human pilot, crew, or passenger onboard. The popularity of UAVs has been seemingly increasing due to their versatility, mobility, and wide applicability in several fields of application, such as in SAR operations, where it improved their effectiveness. [9] UAVs have proven to work successfully for numerous disaster relief efforts in tasks that are previously difficult or infeasible for humans. UAVs are crucial for quickly locating targets and performing necessary follow-up actions within time constraints.

UAVs are useful tools in SAR missions because they enhance the success rate and facilitate more effective and efficient responses, especially in difficult environments. These drones can access dangerous and inaccessible areas, such as tight spots, buildings (or ruins), ravines, and forests, access to which might be hazardous or difficult to humans. They provide real-time monitoring and data collection, including images, videos, and sounds, allowing SAR unit personnel to quickly locate victims or assess disaster situations. These capabilities make UAV beneficial in a geographically and geologically challenging country like Indonesia.

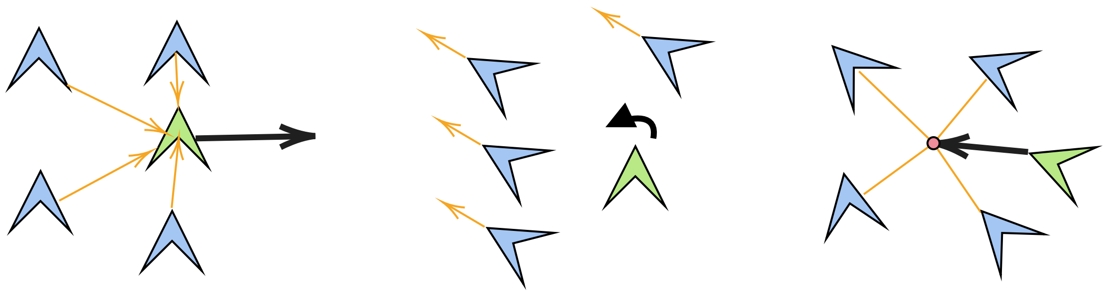

Figure 2. The three rules of Boids flocking algorithm (from left): separation, alignment, and cohesion. Source: own work using TikZ

C. Swarm Intelligence and Drone Swarms

Computer scientists have long admired nature and taken inspiration from it. Among them is the swarm behaviour of bee or ant colonies, bird flocks, animal herds, or even the aggregate movement of schools of fish. [10] The concept of swarm intelligence refers to the collective behaviour of these animals, in which they move cooperatively. [11] This concept is then adopted to the field of robotics, in which it's used to model several robots to work together and mimic the swarm behaviour of animals.

A drone (or UAV) swarm consists of multiple drones that range from tens to thousands. These drones move collectively and perform tasks in parallel to each other, which in turn makes a complex task easier. By developing algorithms that allow the drone swarm to move autonomously, this technique can be utilized for a large-scale search operation for victims. [12] A swarm can cover a search area faster, which in turn makes decision-making and rescue operations planning more efficient.

D. Collision Avoidance

While traversing through a complex terrain, drones are likely to face physical obstacles. Hence, considering collision avoidance is a must. For this paper, we adopt the adaptive artificial potential field method proposed by Zhou and Li (2014) to implement an obstacle avoidance path planning algorithm for robots. [13] Intuitively, this method treats every obstacle as a point that gives a repulsive force towards the moving object that increases inversely proportional to the square of the distance between the obstacle and the object. The object will move towards the direction of the sum of all repulsive forces it experiences. This ensures the object stays away from obstacles. Hence, a simple formula to calculate the repulsive force between a moving drone o with position vector $\vec{p_o} = (\vec{x_o}, \vec{y_o})$ and an obstacle i with position vector $\vec{p_i} = (\vec{x_i}, \vec{y_i})$ would be

$$\overrightarrow{F_{rep,i}} = \begin{cases} \eta\left(\frac{1}{d_{oi}} - \frac{1}{d_T}\right)^2 \cdot \frac{\vec{p_o} - \vec{p_i}}{|\vec{p_o} - \vec{p_i}|}, & d_{oi} \leq d_T \\ 0, & d_{oi} > d_T. \end{cases} \tag{1}$$

where η is a constant real number, d_{oi} is the Euclidean distance between o and i and d_T is the maximum threshold of distance between a drone and an obstacle beyond which the repulsive force is ignored. The total repulsive force can be expressed as

$$\overrightarrow{F_{rep}} = \sum \overrightarrow{F_{rep,i}}. \tag{2}$$

E. Boids Flocking Algorithm

Reynolds (1987) proposed three fundamental rules to simulate flocking behaviour: separation, alignment, and cohesion. [10] We will discuss each of them in depth.

The separation rule prevents every drone from colliding with each other. Given a drone swarm of n drones, this rule can be written mathematically as

$$\vec{v_s} = \sum_{i=1}^{n} \frac{\vec{x_o} - \vec{x_i}}{|\vec{x_o} - \vec{x_i}|^2}. \tag{3}$$

Next, the alignment rule ensures all drones in the swarm are heading towards a common direction. This can be represented as

$$\vec{v_a} = \frac{1}{n}\sum_{i=1}^{n} \vec{v_i}, \tag{4}$$

where $\vec{v_i}$ is the velocity vector of obstacle i.

Lastly, the cohesion rule attempts to keep every drone close to each other, moving a drone towards the swarm's centroid. Mathematically, this can be expressed as

$$\vec{v_c} = \frac{1}{n}\sum_{i=1}^{n} \vec{x_i}. \tag{5}$$

The resultant velocity vector to which the drone heads is

$$\vec{v} = w_s\vec{v_s} + w_a\vec{v_a} + w_c\vec{v_c}, \tag{6}$$

where w_s, w_a, and w_c are constants to be determined by tuning.

F. Divide and Conquer

Divide and conquer is an algorithm design paradigm in which the solution of a problem is acquired by dividing it into smaller parts and then conquering each part. In general, the divide and conquer paradigm consists of three steps: [14]

1) Dividing the problem into subproblems.
2) Solve the sub-solution for each subproblem.

3) Combine the sub-solutions to acquire the complete solution of the whole problem.

Procedurally, the divide and conquer paradigm can be described using the following pseudocode: [15]

Algorithm 1 DIVIDEandCONQUER

procedure DIVIDEANDCONQUER(input P: problem, n: integer)
// Solves problem P using the divide and conquer algorithm
// Input: problem P of size n
// Output: solution to the original problem
    Declaration
    r : integer
    Algorithm
    if $n \leq n_0$ **then** // size of problem P is sufficiently small
        SOLVE this problem P of size n
    else
        DIVIDE into r subproblems, $P_1, P_2, \ldots, P_r$, each of size $n_1, n_2, \ldots, n_r$
        for each P_i, P_2, ..., P_r **do**
            DIVIDEANDCONQUER(P_i, n_i)
        end for
        COMBINE solutions from $P_1, P_2, \ldots, P_r$ into a solution for the original problem
    end if
end procedure

The divide and conquer approach is used in several sorting algorithms, such as merge sort and quick sort, organizing data in trees, and many more.

III. Methodology

In this section, we discuss the methodological approach to simulating a SAR operation using a drone swarm based on the Boids flocking algorithm with a divide-and-conquer approach. Our goal is to incorporate the topics discussed in the previous section into a 2D simulation. We begin by modelling the SAR problem and defining the simulation environment. We then plan the individual drone behavior, swarm coordination, and search strategy. Lastly, we will determine the metrics used to evaluate the simulation performance.

A. Environment Modelling

The simulation is implemented in Python using the Pygame library. The SAR operation is simulated on a 2-dimensional 800×800 grid map with obstacles and victims spread across the map. Each victim is represented as a red stationary point, while each obstacle is drawn on the map as a black rectangle. The map is engulfed by a fog of war representing undiscovered regions. The terrain is randomly generated.

B. Drone Movement

Each drone can perform basic movements such as translation and rotation. They follow the fundamental rules derived from the Boids flocking algorithm and are equipped with an obstacle avoidance mechanism using the artificial potential field mentioned previously. Since the location of the victims is unknown initially, the fog of war gives drones an attractive force that eventually engages them to perform a search in undiscovered areas.

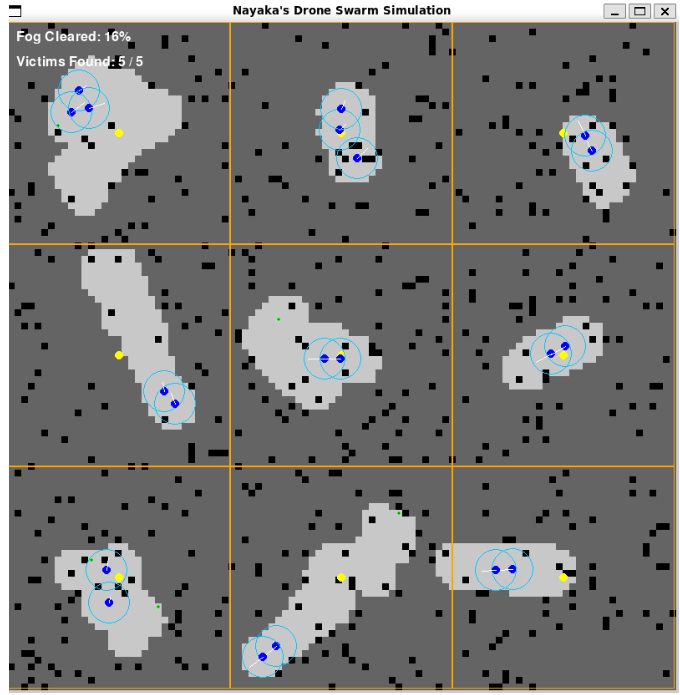

Figure 3. A screenshot of the drone swarm simulation built in Python using the Pygame library. Here, the map is divided into 9 sectors. The drone must discover 5 victims throughout the map. Source: own work

It is worth noting that the artificial potential field method suffers from the problem of local minima. When all of the repulsive forces cancel each other, the total repulsive force will be 0, causing the drone to stop moving. To handle this issue, we compare the drone's previous and next coordinates. If the difference is smaller than a particular threshold, then a local minima problem is occurring. The value of η is then adjusted until the drone is not trapped in the local minima anymore.

C. Divide and Conquer Strategy

The divide and conquer approach is applied by dividing the map into several sectors, to each of which a drone subswarm will be assigned. Once a victim is discovered, the drone will notify the system and continue the search until every victim is discovered. Another strategy is also used in optimizing the calculations used in the Boids flocking algorithm and the artificial potential field method for collision avoidance. Here we use quadtrees to partition the 2-dimensional map efficiently.

D. Performance Metrics

To evaluate the performance of the proposed drone swarm model, especially in searching a large area and maintaining its flocking behaviour, the metrics used are the elapsed time, coverage efficiency, and the number of collisions.

1) **Elapsed time** (t, in seconds): This metric measures the total elapsed time taken to discover all victims.

2) **Coverage efficiency** (r_c, in %): This metric measures the ratio of explored area to the total map area.
3) **Number of collisions**: This metric measures the total number of collisions between drones and obstacles.

IV. Results and Discussion

In this section, we examine the results of the simulations. Four iterations of simulations were performed under the platform specification in Table 1.

Parameter	Specification
Simulator	Pygame 2.6.1
Operating System	Ubuntu 22.04 LTS
Storage	1,5 TB
RAM	16 GB
CPU	Intel(R) Core(TM) i7-10750H CPU @ 2.60 GHz
GPU	NVIDIA GeForce GTX 1660 Ti
Video Memory	5 GB

Table I
Platform specification

The result is presented in Table 2. The variable n represents the drone swarm's size while v denotes the number of victims.

Iteration	n	v	t	r_c	n_c
1	20	5	81.90	60	133
2	30	5	39.42	84	213
3	40	5	18.50	96	469
4	40	10	20.50	71	1058

Table II
Simulation results

The time required for drones to detect every victim decreases proportionately with the drone swarm size, while the coverage rate increases proportionately with it. This suggests that the drone swarm's size corresponds to the coverage rate. As the swarm size increases, redundancy and collisions rise sharply. This might be caused by the imperfection in the tuning of the Boids algorithm's constants. Overall, the data imply a trade-off between speed and stability. On the other hand, it is also possible that the implementation of the collision avoidance might not be good enough, causing collisions to occur frequently.

V. Conclusion

This paper presents a 2D-based simulation of a drone swarm search and rescue (SAR) mission by integrating the Boids flocking algorithm with a divide and conquer approach to search large areas efficiently. The performance of the proposed drone swarm model is evaluated based on elapsed time, coverage efficiency, and the number of collisions. The results indicate that the time required to discover all victims decreases as the drone swarm size increases, with a proportional rise in coverage rate. This suggests a direct correlation between swarm size and coverage efficiency. However, an increase in swarm size also leads to a sharp rise in redundancy and collisions, potentially due to imperfect tuning of the Boids algorithm constants or shortcomings in the collision avoidance implementation. Overall, the data reveal a trade-off between search speed and swarm stability.

VI. Recommendations

In this paper, a 2D-based simulation of a drone swarm search and rescue mission was used. This demonstration provides a simple yet intuitive illustration of how the proposed and implemented algorithm works. However, for a more realistic scenario, a 3D-based simulation is strongly recommended for future research. The author strongly suggests utilizing actual UAV-related software or tools such as Gazebo, ArduPilot, and MAVLink. In this case, instead of using quadtrees, we may use octrees, namely trees in which each node has eight children nodes, to partition the 3D-space efficiently.

VII. Appendix

The GitHub repository containing the source code for the implementation of this paper can be found here. Moreover, the demonstration video can be watched here.

VIII. Acknowledgements

Untaian benang takdir mempersatukan kita,
Teknik Informatika berjiwa kesatria.

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Statement

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Bandung, June, 24th 2025

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