Visually Detecting Drones in Drone Swarm Formations Topologies

Nisha Kumari, Kevin Lee, Chathurika Ranaweera, and Jan Carlo Barca

Abstract In drone swarm network, the topology is an important characteristic of the swarm and the level of bonding with each node is strongly influenced by the communication links between drones. Understanding the network structure of a swarm by recognising, monitoring, and intervening with nodes is important to understand the behaviour and intention of the swarms. Current methods for understanding drone organisation generally require access to the swarm network which is not practical, therefore, passive approaches for network topology estimation are needed. The research presented in this paper proposes an approach using computer vision to detect drones in distinct swarm formations. The approach is evaluated by simulation using multiple different drone formations. It is anticipated that the results of this study will lead to approaches for detecting and understanding different drone formations.

Keywords Drone swarm · Network topology · Computer vision

1 Introduction

Drones are a type of unmanned aerial vehicle (UAV) that were initially flown by a single operator (Sharma et al. 2020). In various applications ranging from defence to firefighting and disaster response, multiple connected drones frequently work together to complete critical tasks. The term "drone swarm topology" pertains to the arrangement and intercommunication of a small group of drones for the purpose of

N. Kumari (✉) · K. Lee · C. Ranaweera · J. C. Barca
School of Information Technology, Deakin University, Geelong, VIC, Australia
e-mail: kumarinis@deakin.edu.au

K. Lee
e-mail: kevin.lee@deakin.edu.au

C. Ranaweera
e-mail: chathu.ranaweera@deakin.edu.au

J. C. Barca
e-mail: jan.barca@deakin.edu.au

A. Ullah et al. (eds.), *Proceedings of International Conference on Information Technology and Applications*, Lecture Notes in Networks and Systems 839,
https://doi.org/10.1007/978-981-99-8324-7_3

executing a designated objective or operation. The topology of the network can be conceptualised as the arrangement of the drones, where each individual drone serves as a distinct node within the network. In these circumstances, communication within drones is a crucial part. Therefore, it is essential to have a deep understanding of the various characteristics of drone communication.

The components of drone (Gupta et al. 2016) communication networks present complex and demanding challenges that require solutions. In contrast to many other wireless networks, the architecture of drone networks stays flexible despite changes in the number of nodes and links as well as their relative placements. The velocity of drones may fluctuate based on their intended use, resulting in the intermittent establishment of links. The physical and dynamic nature of drone swarms can impact communications networks, leading to the need for dynamic topologies.

The swarm's network topology is the logical structure that depicts the connections between individuals based on information sharing. Depending on the input from the controller and the rate of progress towards an objective, this topology is dynamic and evolves over time. Each link in the topology represents an interaction between two nodes, which may take the form of an explicit information transfer or an implicit challenge that conveys a response from the other node in the topology. Network topologies are often represented in the form of a graph (Vasquez et al. 2018).

In order to complete challenging tasks like coordinated reconnaissance, defence, and offence, the drone swarm can adopt a variety of formations. The typically used formations are diamond, wedge, and mesh (Ouyang et al. 2023; Bi and Huang 2018). Each formation shape possesses distinct characteristics that are appropriate for tasks. The design of a formation that is reasonable and effective has the potential to decrease fuel consumption, increase the flight range of drones, and enhance the flexibility of formations. This can significantly improve the safety and success rate of missions carried out by drone swarms.

Tracking each node in various swarm formations can help to identify the network structure of the drone swarm. The importance of tracking swarms is best demonstrated by the importance of trying to disrupt them. Once the swarm is dispersed, it would be possible to use the information gathered to identify the network structure and communication links among them. The aim of the research presented in this paper is to evaluate the viability of computer vision techniques to detect and track drones in distinct swarm formations. The main contributions of this paper are (i) Implementation of various formation shapes of drone swarms, (ii) The framework for the identification of drones in various formations, and (iii) An experimental analysis of the proposed approach.

The remainder of the paper is organised as follows. Section 2 is describing the background that justifies the creation of details of the previous work on the different formations of swarms of drones. Section 3 describes a proposed framework for the detection and tracking of drone swarms. Section 4 presents a practical implementation and experimental evaluation of the drones in a simulation environment of the gazebo simulator. Finally, Sect. 5 presents some conclusions and future work.

2 Background and Context

Connectivity and cooperation among UAVs are made feasible by the network of communications between them. The following subsections provide an overview of drone swarm topologies and techniques used for detecting drone swarm topologies which support understanding the networking concept in drone swarms.

2.1 Drone Swarm Topologies

A network consists of nodes and the communications between them. The topology of the network depicts the architecture or network architecture. In Social Network Analysis (SNA) and Dark Networks (DN), centrality determines the significance of network nodes (Everton 2008) which can be used to represent the topology of the network. The performance of complex networks is often influenced by collaborative communication among nodes. Consequently, several earlier studies have concentrated on altering the efficacy of complicated networks by recognising, monitoring, and intervening with main nodes that play a vital role in network communication.

Topologies are used to describe the spatial arrangements and formations of drone swarms, which are made up of several UAVs. The topologies determine how the drones interact with one another, how they share information, and how they behave as a group. For efficient swarm coordination and mission planning, it is crucial to have a firm grasp of the various possible swarm topologies. Typical topologies for drone swarms are outlined, including:

The line formation involves the arrangement of drones in a linear configuration, where each drone is positioned in a consistent manner, maintaining a uniform distance from its adjacent drone. When multiple drones need to move together, search an area, or keep watch over a vast area, this network design is frequently utilised (Yasin 2020).

Drones flying in a circular formation are evenly spaced around the outside of the circle. This topology is well-suited for uses like perimeter security and environmental monitoring because of its efficient 360° monitoring and surveillance capabilities (Hernndez et al. 2021).

The diamond formation is a configuration of drones that is arranged in a shape resembling a diamond. The formation consists of a foremost drone serving as the lead, while the other drones are arranged to form the sides and rear of the diamond. The aforementioned topology is frequently utilised in collaborative endeavours that necessitate a hierarchical arrangement, such as safeguarding a convoy or conducting search-and-rescue missions (Alkouz and Bouguettaya 2020).

With the wedge formation, drones are arranged in a V-shape, with one drone in the front and the others spreading out behind it. This configuration allows for comprehensive sensor coverage and a wide field of view. It is frequently used in missions requiring observation, target tracking, or reconnaissance (Gao et al. 2022).

Drones in a mesh structure are arranged in a dispersed and interconnected network, improving the swarm's capacity for coordination and information sharing. Collaboration tasks that benefit from robustness, redundancy, and decentralised decision-making are well-suited to mesh formations (Ferranti et al. 2019).

Drones are arranged in certain ways for these formations to accomplish a variety of goals, such as avoiding obstacles, maximising communication, or meeting other specific operational requirements. It's also worth noting that these topologies are not incompatible with one another and that different configurations can be used for different missions. For optimal swarm behaviour, coordination and mission effectiveness, selecting the proper swarm topology is crucial.

2.2 Techniques for Detecting Drone Swarm Topologies

Various technologies are available for detecting or monitoring drones, including radar, radio frequency (RF) signal detection, video sensor, and acoustic sensor (Brust 2021; Shi et al. 2018). The utilisation of radar as a means of detecting and locating drones is a well-established technique, however, it is not without significant obstacles, as evidenced by existing literature (Guvenc et al. 2018). One of the primary obstacles is that drones possess a limited radar cross-section (RCS) and consistently operate at a low speed and height during flight. According to the literature, the utilisation of RF scanners has been proven effective in detecting drones through the interception of radio signals emitted by UAVs (Shi et al. 2018). An AI-based classification algorithm is utilised for detection purposes, whereby the spectrum of signals transmitted by drones is extracted and analysed. RF scanners are subject to a significant likelihood of producing false alarms and are incapable of detecting self-governing drones in the absence of communication. The drone's sounds can be recorded by acoustic sensors. Drones may be detected, categorised, and localised using only their auditory signatures, which can be analysed in both the temporal and frequency domains (Salvati et al. 2019). However, the detection range is constrained by noise sensitivity and the requirement of environment-specific calibration.

The identification and tracking of drones can be achieved through the utilisation of computer vision and pattern recognition technology which recognises the unique appearance features and motion patterns of these drones. Several proposed techniques have successfully achieved the task of tracking mobile drones in a challenging and constantly changing environment (Hu et al. 2017). Several factors make vision-based methods and cameras, in particular, useful for determining the network topology of drone swarms:

- Drones can self-organise into a specified network architecture using vision-based techniques. Drones can make smart decisions about their positioning and connectivity within the swarm by analysing visual inputs.
- Unforeseeable factors such as obstacles, alterations in terrain or other dynamic elements could disrupt the operation of drones. The utilisation of vision-based

methodologies facilitates the capability of UAVs to flexibly adjust their network topology in reaction to such alterations. Drones can enhance their operational efficiency and achieve their objectives by utilising cameras to consistently monitor their surroundings, thereby enabling them to adapt their positions and connections as required.

- The integration of cameras into sensing network topologies offers redundancy. The integration of camera data with Global Positioning System (GPS) or proximity sensor data enhances the robustness of the system. In the event of a sensor malfunction, cameras have the potential to provide significant insights into the network architecture of a swarm. The main idea to use cameras for tracking purposes is that they are passive sensors and using this will therefore not alert the swarm in case of targeted elimination.

3 Proposed Approach

The aim of this study is to evaluate the ability of a computer vision approach to observe different drone swarm topologies. The proposed approach utilises a deep learning-

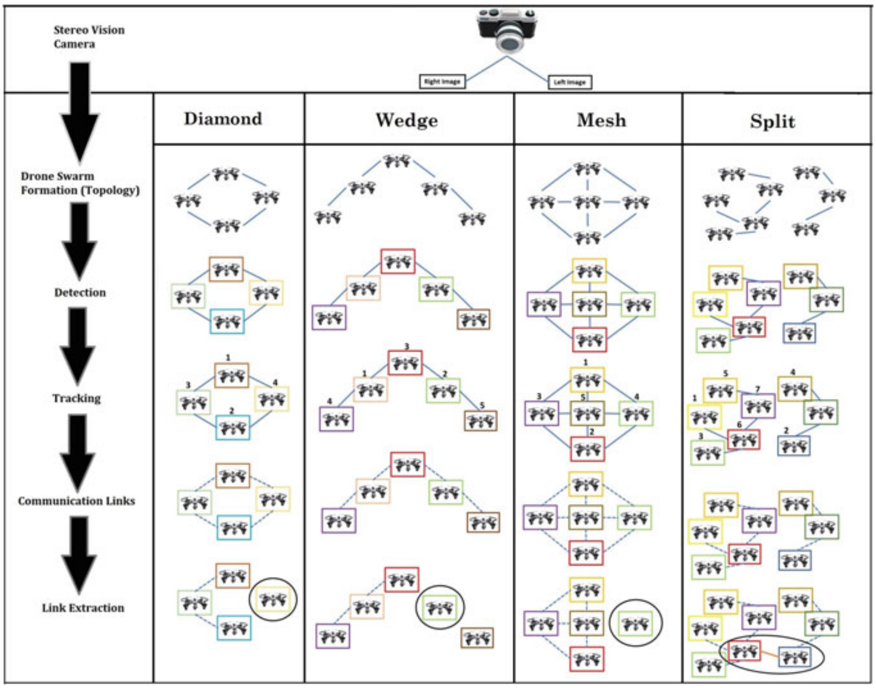


Fig. 1 Observing drone swarm topology formations

based you only look once (YOLO) algorithm for detection purpose and Kalman filter for tacking each drone in distinct formations over time. The experiments are conducted in a gazebo simulator and robot operating system (ROS) used for drones as an interface. It is implemented in Python language. The images processed are taken by linking OpenCV and ROS together in the same environment.

Figure 1 illustrates how the proposed approach will use computer vision techniques to observe and analyse different formations. The following are the drone formations chosen for this study, as identified by Ouyang et al. (2023).

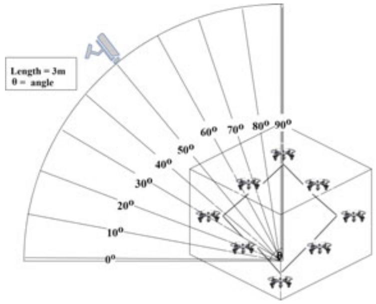
- **Diamond Formation**: Protecting significant targets that are located in the diamond's centre is the primary goal of this formation (Junlei et al. 2017). The shape protects the most critical targets and aims to exit the battlefield with the centre nodes intact.
- **Wedge Formation**: Drones are arranged in a wedge design and positioned diagonally behind the two edges of the leading drone. The wedge formation is widely used for the purpose of surveillance and bombing missions.
- **Mesh Formation**: A mesh is characterised by the direct connections between its nodes. The absence of a central or critical link, as observed in a diamond topology, is avoided by the interconnectivity of the system. The routing method used will depend on a variety of conditions and will be crucial for the mesh network's operation (E. Cai et al. 2019).
- **Split Swarm**: An additional approach is using split topology formation, which aims to confuse the observer into believing a single swarm is split.

4 Evaluation

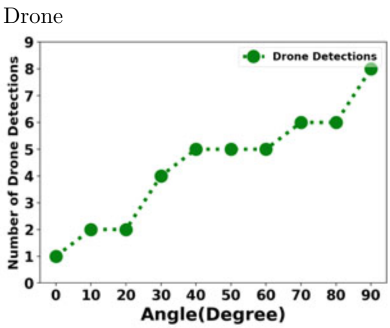
This section presents an evaluation of the proposed approach to detect drones in three different formation types. The aim is to investigate the effectiveness of the approach in detecting and tracking different drone formations.

4.1 Experiment 1: Drone Detection in Diamond Formation

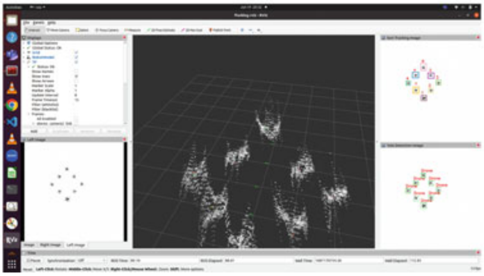
This experiment evaluates the accuracy of tracking a diamond formation of a drone swarm. The aim is to show how a vision-based approach can track this type of formation over time with different observation angles of stereo-vision camera. This experiment used a stereo-vision camera to observe the flat diamond at different observer angles as shown in Fig. 2a. Initially, a YOLO detection algorithm is used to detect and then tracking takes place to track each drone over time, as illustrated in Fig. 2c. Tracking a flat diamond is a challenging task as drones are hidden behind each other. Figure 2b illustrates the results of the experiment, with the observer at different



(a) Detection for Diamond Formation



(b) Detection for Diamond Formation



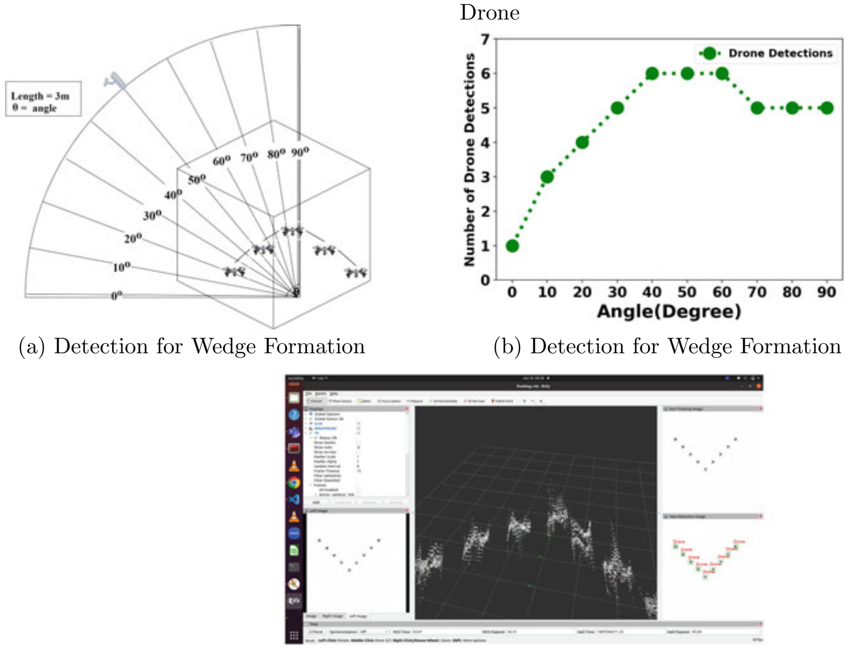
(c) Diamond Shape Tracking

Fig. 2 Experiment 1 setup and results

angles. At 0°, all drones are not tracked properly because the drones located at the front and back corners of the diamond are occluded by the drones in the middle. As the observer angle changes from 20° to 80° the detection gradually increases. Finally, at 90° all eight drones are visible since they are in the camera field of view.

4.2 Experiment 2: Drone Detection in Wedge Formation

Experiment 2 evaluates the proposed approach for a drone swarm in a wedge formation. In this experiment, stereo-vision camera angles as shown in Fig. 3a are used to demonstrate how a vision-based technique can keep track of flying drones in a wedge configuration over time as depicted in Fig. 3c. After being detected with a YOLO detection algorithm, each drone is then tracked individually over time. Keeping up with a flying flat wedge form presents a significant challenge. As can be seen in Fig. 3c a wedge is captured flat using a stereo-vision camera. It can be seen that the swarm is placed on the horizontal plane and therefore line graph in Fig. 3b shows that at 0° only one drone's coverage area falls within the angle range hence only one drone is spotted within this region. The detection of drones rises steadily as we



(a) Detection for Wedge Formation (b) Detection for Wedge Formation

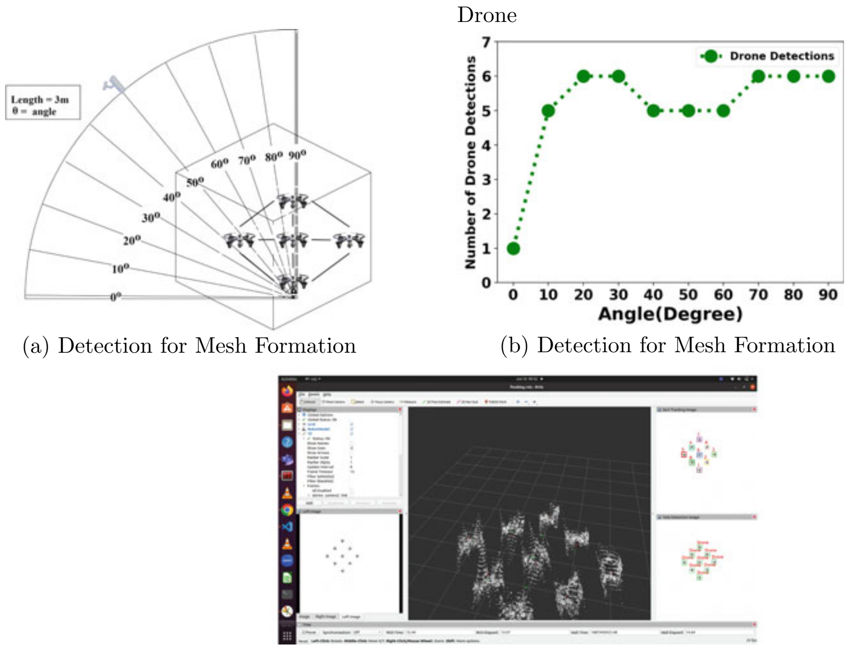
(c) Wedge Shape Tracking

Fig. 3 Experiment 2 setup and results

progress deeper into the wedge. At 30° five drones are detected and this pattern stays all the way to the widest point of the wedge. From 60° to 70° detection of drones fluctuates because drones are overlapped or hidden at these angles and are not visible to camera field of view. Finally, at 90° the number of detected drones drops to five as the angle to the end of the wedge is approached because the coverage of just five neighbouring drones overlaps with this angle range.

4.3 Experiment 3: Drone Detection in Mesh Formation

Experiment 3 examines drone swarm mesh formation tracking accuracy. The aim is to show how a vision-based technique can track numerous drones for mesh construction utilising stereo-vision camera angles as shown in Fig. 4a. This study examined the structure and behaviour of a drone swarm using the flat mesh scenario as shown in Fig. 4c. This experiment uses a stereo-vision camera to randomly positioned drones in a mesh shape. A YOLO detection algorithm detects and tracks each drone over time. Tracking a flat mesh shape is challenging because of the range of cameras from different angles. As can be seen in Fig. 4c a mesh shape drone swarm is captured flat



(a) Detection for Mesh Formation (b) Detection for Mesh Formation

(c) Mesh Shape Tracking

Fig. 4 Experiment 3 setup and results

using a stereo-vision camera. It can be seen that the swarm is placed on the horizontal plane and therefore line graph in Fig. 4b depicts that at 0°, only one drone's coverage area falls within the angle range hence only one drone is spotted within this region. The detection of drones rises steadily as we progress deeper into the mesh. At 20° to 40° six drones are detected then again detection reduces to five from 50° to 70° because only five drones fall into the field of view. Finally at 90° detection rises to six as the one-sixth portion of mesh is visible to the camera range.

5 Conclusion

This paper presented a computer vision-based approach and evaluation for tracking different drone swarm formations (i.e. diamond, wedge, mesh). A deep learning-based detection method YOLO is employed to detect the drone swarms, and then, each detected drone swarm is tracked using the Kalman filter technique. The performance of the proposal was evaluated by varying the position of the stereo-vision camera from 0° to 90° angle. The findings show conclusively that the proposed approach is capable of identifying and tracking drones in a range of swarm formations.

Although stereo-vision cameras have difficulty following complicated swarm formations, advances in computer vision, sensor fusion, and machine learning offer potential ways to overcome this problem. Improved swarm tracking and analysis can be achieved by more investigation into different sensor modalities, the creation of cutting-edge algorithms for multi-object tracking and data association, and the use of machine-learning techniques.

References

Alkouz B, Bouguettaya A (2020) Formation-based selection of drone swarm services. In: MobiQuitous 2020-17th EAI international conference on mobile and ubiquitous systems: computing, networking and services, pp 386–394

Bi Q, Huang Y (2018) A self-organized shape formation method for swarm controlling. In: 2018 37th Chinese control conference (CCC), pp 7205–7209

Brust Matthias R et al (2021) Swarm-based counter UAV defense system. Discover Internet of Things 1:1–19

Cai E et al (2019) Dynamic mesh network for telemetry propagation and communications in coordinated drone swarms. In: University of California, Irvine

Everton SS (2008) Tracking, destabilizing and disrupting dark networks with social networks analysis. In: Naval post graduate school

Ferranti L et al (2019) Hiro-net: self-organized robotic mesh networking for internet sharing in disaster scenarios. In: 2019 IEEE 20th international symposium on a world of wireless, mobile and multimedia networks (WoWMoM). IEEE, pp 1-9

Gao H, Li W, Cai H (2022) Fully distributed robust formation flying control of drones swarm based on minimal virtual leader information. In: Drones 6.10, p 266

Gupta L, Jain R, Vaszkun G (2016) Survey of important issues in uav communication networks. In: IEEE communications surveys and tutorials 18(2)

Guvenc I et al (2018) Detection, tracking, and interdiction for amateur drones. In: IEEE communications magazine 56(4):75–81

Hernndez D et al (2021) The kuhn-munkres algorithm for efficient vertical takeoff of UAV swarms. In: 2021 IEEE 93rd vehicular technology conference (VTC2021-Spring). IEEE, pp 1–5

Hu S, Geoffrey HG, Christoph CB-D (2017) Detection of unmanned aerial vehicles using a visible camera system. In: Appl Opt 56(3):B214–B221

Junlei S et al (2017) The conceptual design and aerodynamic characteristics analysis of the diamond joined-wing configuration UAV. In: 2017 5th international conference on mechanical, automotive and materials engineering (CMAME). IEEE, pp 275–279

Ouyang Q et al (2023) Formation control of unmanned aerial vehicle swarms: a comprehensive review. Asian J Cont 25(1):570–593

Salvati D et al (2019) Acoustic source localization from multirotor UAVs. IEEE Transactions Ind Electron 67(10):8618–8628

Sharma A et al (2020) Communication and networking technologies for UAVs: a survey. J Netw Comput Appl 168:102739

Shi X et al (2018) Anti-drone system with multiple surveillance technologies: architecture, implementation, and challenges. IEEE Commun Magaz 56(4):68–74

Vasquez BLM, Barca JC(2018) Network topology inference in swarm robotics. In: 2018 IEEE international conference on robotics and automation (ICRA). IEEE, pp 7660–7666

Yasin JN et al (2020) Energy-efficient formation morphing for collision avoidance in a swarm of drones. IEEE Access 8:170681–170695