Applications, Challenges, and Research Issues for Enabling a UAV Swarm

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Abstract

Unmanned aerial vehicle (UAV) swarms have the potential to be useful in numerous applications due to their versatility and ability to operate without human intervention. However, this promising technology still requires further investigation, research, and testing before UAV swarms can be implemented extensively. The level of human intervention needed to control the system determines the differing levels of autonomy for UAV swarms. For swarms to become more independent, efficient algorithms for task and path planning are essential. In addition, accurate communication is essential for swarms to be able to coordinate and accomplish tasks successfully. This paper seeks to provide a review on the architecture, communication, applications, and challenges associated with UAV swarms. Furthermore, this paper discusses the types of communication that have been used or proposed for UAV swarms. Lastly, this paper provides a review of the potential applications of UAV swarms, as well as the research issues which still exist surrounding this technology.

Keywords: *UAV swarms, swarm intelligence, autonomy, communication systems*

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UAV swarms rely on intercommunication among individual UAVs. Typically, a UAV swarm system consists of a ground control station (GCS), transmitter, individual UAV units, and occasionally payloads or cargo. UAVs communicate wirelessly through specific networks called UAV Swarm Networks (USNETs) (Chen et al., 2020a). UAV swarms are unique because they possess different levels of autonomy; the highest level is complete autonomy where the swarm operates without human intervention. To facilitate communication for this level of autonomy, ad-hoc networks are often used, which enable communication between devices without relying on fixed infrastructure. This allows UAVs to communicate and coordinate with each other without a pre-established connection point, thus increasing the flexibility of their usage. In addition to a robust communication system, sensors are needed to detect aerial positions and proximity to the other UAVs in the swarm and to detect obstructive objects. Furthermore, UAV swarms can be equipped with sensors such as GPS, thermal sensors, cameras, and light detection and ranging sensors depending on the application.

The ability to have multiple UAVs operating together to accomplish a common purpose opens possibilities for operations that would be impossible with just one UAV. The benefits of a UAV swarm include decreased costs, increase in safety due to the reduction in manpower, and increased efficiency. In military applications, for example, UAV swarms have the potential to be a highly efficient and deadly weapon since they can perform coordinated attacks from multiple angles. The use of a UAV swarm in military attacks can potentially reduce the number of casualties, as it eliminates the need for human presence on the battlefield. In a civilian context, UAV swarms offer promising applications in fields such as natural disaster response, agriculture, delivery services, surveillance and security, and infrastructure monitoring, including power line, railway, and road inspections. For example, equipping UAVs with thermal imaging could enhance their effectiveness in search and rescue missions. Having multiple UAVs active in search missions would allow for more ground to be covered concurrently, thus reducing rescue times. This could be accomplished using an algorithm that assigns certain areas of the search location to each UAV, which would then communicate any discoveries with the other UAVs, processing the data to match with the given search information.

This paper seeks to provide a review of the technology of UAV swarms and of the ways in which the technology can be improved and developed for practical applications. This paper covers the architecture types of UAV swarms, the communication styles that the swarms can use, the potential applications of UAV swarms, and the current research issues that exist on this topic. The primary focus of this discussion is on the communication and control of UAV swarms.

Architecture

Drone Structure and Features

The general mechanical structure of individual UAVs utilizes structures and styles typical of manned aircraft. UAV structures are generally divided into the categories of rotary-wing and fixed-wing, as is typical for most aircraft (Khalil et al., 2022). As expected, rotary-wing UAVs are maneuvered with rotating blades, while fixed-wing UAVs are maneuvered with stationery wings. The rotary-wing structure allows for better maneuverability, while the fixed-wing structures tend to be more stable. However, the type of UAV structure is chosen based on requirements for hovering capabilities, take-off and landing, endurance length, loading capacity, and operating radius (Khalil et al., 2022). Rotary-wing UAVs have been used frequently in a range of applications because of their ability to hover in place, fly in any direction, and take off and land vertically, thus providing a wide range of motion and high level of maneuverability (Yang et al., 2023).

While the overall structure of an individual UAV may be similar to a manned aircraft, the high levels of communication necessary to make a UAV swarm operational differentiate UAV swarms from manned aircraft and from singular UAVs. Specifically, UAV swarms are unique in the fact that each individual UAV must be able to communicate with the others in the swarm. This feature enables UAVs to accomplish tasks previously impossible or inefficient with one UAV. However, the technology involved in a swarm of UAVs as opposed to a single UAV has much different complications and architecture considerations due to the advanced communication required among all the UAVs.

Components

Sensors are some of the most important components in the design of a UAV swarm, as they provide UAVs with the means to collect essential data from their environments. Depending on the specific function of the UAV, different sensors will be utilized. Some types of sensors utilized in UAV swarms are GPS, air-speed sensors, acoustic sensors, and cameras (Campion et al., 2019). Sensors send the raw data they have gathered to the processors. Processors are essentially the brain of the UAV because the algorithm is implemented within the processors. They take the raw data from the sensors and make decisions accordingly. In addition to sensors, transmitters and receivers are also essential components of a UAV swarm. Communication among the UAVs and or with the GCS is of the utmost importance to the functionality of the swarm. Thus, the correct transmitters and receivers for the swarm's communication type are essential to ensuring successful communication among the UAVs.

Levels of Autonomy

UAVs communicate with each other through varying wireless technologies. The style of a swarm's communication determines its level of autonomy. The two main communication architectures include operation with a connection to a ground control station (GCS) or base station (BS) and operation independent of a ground link. UAV swarms that are connected to a GCS are considered the least autonomous, while UAVs which can effectively communicate with each other without the use of a GCS, or any human intervention, are considered the most autonomous. Enabling a UAV swarm to operate without communication with a GCS allows a greater level of autonomy because the swarm is not connected to a stationary link controlled by an operator. Being independent of a link to a stationary control center allows the swarm to have a much greater range for performing tasks. When UAV communication is not directed through a ground control station, an ad hoc network may be used, where the UAVs communicate with each other without a node to link them all. When a UAV swarm is at the highest level of autonomy, each UAV will "adjust its behaviors autonomously according to certain principles when needed based on its storage, communication, computing, positioning, and mobility capabilities" (Chen et al., 2020a). Ad hoc networks allow for the system to perform these behaviors independent of a GCS.

When the UAV swarm is connected to a GCS, the individual UAVs do not need very high-functioning computing units as most of the computing is performed by the GCS. This paradigm where UAVs are implemented without computing units is called edge computing-assisted UAV swarm networks (Wu et al., 2022). Another name for this type of architecture is centralized communication architecture because the GCS is the central node controlling each UAV in the swarm (Chen et al., 2020b). In this variation of swarm architecture, the computing is done at a nearby server with which the individual UAVs communicate due to their limited size and uses a two-hop architecture (Wu et al., 2022). While centralized communication architecture is generally implemented with a ground-based control center, another version of this architecture consists of one UAV sending data to multiple access points and one UAV serving as a flying base station, gathering data from ground nodes (Yang et al., 2023). One benefit to the centralized communication architecture is the fact that each UAV does not need high-level computational hardware. If the UAVs are small or their weight plays a crucial factor in their task completion, eliminating the need for extra hardware on each UAV can be extremely beneficial. However, the need to remain in proximity to the GCS limits the reach of a swarm using the centralized communication architecture. Furthermore, the use of this architecture requires a ground control operator, which limits the autonomy of the swarm. In addition, one important disadvantage to this system is the fact that the GCS becomes a Single Point of Failure (SPOF): if the GCS were to be destroyed or disconnected from the swarm, all swarm communication would fail (Chen et al., 2020b). The existence of a SPOF poses a huge disadvantage, especially in military applications: the GCS becomes a target for the annihilation of the entire swarm.

For a UAV swarm to have a greater area of operation and increased autonomy, the UAVs need to be able to communicate and make decisions without the use of a GCS. The paradigm where individual UAVs are equipped with computing units is called UAV swarm-assisted edge computing (Wu et al., 2022). In this variation of swarm architecture, individual UAVs are equipped with computing elements and can perform local data-processing, often using a flying ad-hoc network (FANET) (Wu et al., 2022). Swarm-assisted edge computing is considered the most autonomous architecture because the UAVs are independent from a GCS, providing more mobility to the swarm. Furthermore, locating the main processing units on individual UAVs allows the UAVs to make collective decisions. One drawback to this architecture is the added weight on each UAV caused by the computational hardware needed for the extra processing capabilities. In addition, complex and efficient algorithms are needed for such high-level functionality to occur. In short, completely autonomous UAV swarms are the most complex type of UAV swarm and are a more demanding technology to produce effectively. However, the independence from a GCS poses a huge advantage by eliminating the single point of failure. Thus, swarms equipped with swarm-assisted edge computing are much better equipped to deal with damage to the swarm than swarms using centralized communication architecture: communication and task planning can be readjusted to account for specific UAVs which were destroyed or lost connection.

Unique Technical Features

Autonomy

As mentioned previously, UAV swarms are unique in their ability to achieve varying levels of autonomy. According to Campion et al. (2019), "the highest level of UAV swarm autonomy is defined as the ability to perform a task coordinated among multiple UAVs without intervention of a human operator." The potential to achieve this level of autonomy in UAV swarms is a highly attractive aspect of the UAV swarm technology. High levels of autonomy require sophisticated decision-making structures. A decision structure for a UAV swarm involves three stages: data collection, control planning, and process implementation (Campion et al., 2019). Data collection is carried out by sensors, which gather data from the UAV's environment, such as temperature, position, obstacles, or proximity to other UAVs. The control stage involves perception and planning: the transforming of data to useful information (Campion et al., 2019). Perception is "the act of transforming ambiguous data to useful information," and planning is "the process of using the perceived information to formulate a decision to execute a task"

(Campion et al., 2019). Achieving autonomy in UAV swarms requires an efficient and successful algorithm for the perception and planning process of the decision structure. Finally, the process stage involves the execution of the decisions that are made by the algorithm (Campion et al., 2019). For high levels of autonomy to be implemented in UAV swarms, efficient and reliable algorithms are essential for information to be processed and decisions made successfully.

Decision-Making capabilities

The capability to make decisions based on sensor data, independent of a human operator, is another unique technical feature of UAV swarms. Successful algorithms are necessary for UAV swarms to become completely autonomous. Eliminating the need for an operator requires the system to independently adapt and process received data based on algorithms. These algorithms need to be computationally sophisticated as well as power efficient. The following section discusses two broad types of algorithms used in UAV swarms.

Necessary Algorithms

Swarm Intelligence Algorithms. Studying swarms in nature led to the development of swarm intelligence algorithms (Lei et al., 2021). Ant colony optimization, particle swarm optimization, artificial fish swarm, bacterial foraging optimization, and artificial bee colony algorithm are all examples of algorithms developed from observations in nature (Tang et al., 2021). As would be expected, types of swarm intelligence algorithms are often used in UAV swarms. The strengths of these algorithms are demonstrated in their “relatively higher scalability, excellent exploration and exploitation capability, simple individuals and collective intelligence, [and] good robustness;” however, the limitations of these algorithms include “temporal complexity, stagnation situation/local optimum, [and] possible slower feedback” (Tang et al., 2021). The possibility of slower feedback could be a major drawback for the use of swarm intelligence algorithms due to the importance of low latency and quick reactions in UAV swarms. In addition, "…the performance of such algorithms degrades drastically in large-scale complex applications" (Lei et al., 2021). Furthermore, "swarm intelligence algorithms are generally time-consuming processes…directly affect[ing] the efficiency…relative to the size of relevant applications (Tang et al.,2021)," which further demonstrates that these algorithms may be useless when certain factors are large. The swarm intelligence algorithm may be useful for UAV swarms that have fewer individual UAVs; however, when the number of UAVs increases, these algorithms may not be as effective.

Machine Learning Algorithms. An alternative to swarm intelligence algorithms is machine learning algorithms. "These algorithms train agents to learn the correlation of past empirical data and predict future trends for challenging tasks" (Lei et al., 2021). The downside of these algorithms is that they require high computational and storage capabilities (Lei et al., 2021). One proposed machine learning type that can be used in UAV swarms is reinforced learning (RL), whose goal in the application of UAV swarms is to "optimize the behavior of an agent according to the evaluative feedback received from the environment" (Arranz et al., 2023). With an RL algorithm, the agent attempts to learn optimal actions based on the environmental inputs, and it adjusts based on levels of success (Arranz et al., 2023). Having an algorithm that is adaptable and responsive to environmental factors is extremely beneficial in the case of a UAV swarm due to its constantly changing environment and need for adaptation. Swarm intelligence algorithms are not adaptive to the environment like machine learning algorithms are, thus machine learning algorithms may be a better candidate for UAV swarm algorithms. However, important drawbacks to machine learning algorithms include their expensive computational processes and the fact that training a UAV swarm system for a new scenario may not be quickly achievable (Arranz et al., 2023). Such a drawback could affect military applications, for example, where a new and important mission may be determined and need to be accomplished within a small window of time.

Task Allocation

Another important aspect of decision making in UAV swarms is task allocation. Task allocation is an essential aspect of communication for UAV swarms because tasks must be efficiently sorted based on priority. Especially with urgent tasks, UAVs must be able to accomplish the necessary task with maximum accuracy and minimal time. An optimized task allocation algorithm is needed for every UAV swarm to be effective. Three determinants of effective task allocation processes are time, collaborative load, and cost (Duan et al., 2023). This is especially important with urgent tasks, to ensure that each task is executed in a minimal amount of time.

In 2020, authors Duan, Wang, Wang, Chen, and Li published an article titled "Dynamic Tasks Scheduling Model of UAV Cluster based on Flexible Network Architecture" where they proposed the flexible dynamic scheduling algorithm (FDSA) and proposed a flexible network architecture supporting a dynamic fault-tolerant task scheduling model (DSM-FNA) (Duan et al., 2020). Their research concluded that the FDSA algorithm can reduce the communication load and time to schedule tasks as compared to other algorithms (Duan et al., 2020). Another proposed algorithm for task allocation is the dynamic reconstruction algorithm (DRA-M) (Duan et al., 2023). In this algorithm, capabilities of the swarm are organized into clusters to form a matrix; a combination of these capability clusters represents a task (Duan et al., 2023). In the article "A Task Planning Method for UAV Swarm Reconstruction Based on a Fourth-Order Motif," previous authors Duan, Wang, Wang, along with Huang and Zhou, tested a swarm of ten virtual UAVs using the DRAM-M algorithm, the Max-Min algorithm, and FDSA (Duan et al., 2023). They concluded that the DRAM-M algorithm was more capable than the FDSA algorithm in accomplishing tasks (Duan et al., 2023). As suggested in the proposed task-scheduling model DSM-FNA, a UAV system should be fault-tolerant, able to remain functional if one or more of the UAVs in the system were to experience malfunction. In addition, the motivation for determining a better task allocation algorithm is to find an algorithm best optimized to plan tasks for a specific swarm.

UAVs in a swarm can either always be assigned to the same roles or be able to perform needed roles based on autonomous decision making (Yao et al., 2021). According to Khalil et al. (2022), a UAV swarm formation could be formed in such a way that leading UAVs can work as data acquisition terminals, while others can be assigned to carry out tasks, such as payload drops. In this structure, each UAV is assigned to its specific task, without variation from its assignment. Overall, due to the changing environment or task, the role of a UAV may not always stay stationary, but instead become dynamic (Yao et al., 2021). Having the ability to assign roles to certain UAVs depending on tasks needed, the environment, or unforeseen obstacles can increase productivity and efficiency in the swarm. However, such a high level of functioning would require strong computational abilities.

Path Planning

Whereas task allocation is the instructions to the UAV swarm regarding decisions to make based on processed information, path planning is the instructions to the UAV swarm regarding the path taken to accomplish its tasks. Path planning is the process of calculating a trajectory from an origin to an endpoint (Arranz et al., 2023). For applications such as search and rescue, UAV swarms need to be able to plan their flight paths in real-time, determining efficient paths as the swarm is in flight. However, for applications such as delivery, a UAV swarm can have its path predetermined, but still can account for interruptions in the path. Online path planning may become a necessity to ensure the execution of specific tasks is feasible (Wu et al., 2022). In the case of UAV swarms, each individual UAV needs to calculate the best path to accomplish its assigned task. Path planning often considers an independent path for each individual UAV in the swarm (Arranz et al., 2023). Path planning algorithms can be classified as combinational, sampling based, biologically inspired, and reinforced learning based (Arranz et al., 2023). These algorithms may use variations of Dijkstra’s algorithm, an algorithm used to find the shortest path between a source node and other nodes (Arranz et al., 2023). Path planning algorithms should be paired with real-time planning algorithms to ensure that unforeseen obstacles are dealt with when they arise in the swarm’s operation (Arranz et al., 2023). This real-time aspect of path planning is especially important in UAV swarm missions where the environment is volatile, such as in military missions or in disaster relief missions.

Communication

Infrastructure-based Communication System

The most common type of UAV swarm communication architecture consists of a ground control station (GCS) which receives communication from each UAV in the swarm and sends commands to the individual UAVs (Campion et al., 2019). Although this is the least autonomous architecture of UAV swarms, it still has benefits in the fact that each UAV requires less computational power, and an operator is able to monitor the system for errors or failures. However, some of the drawbacks to this system include the UAVs’ need to maintain a certain range with a stationary GCS, thus limiting the reach of the particular UAV swarm, and the use of unlicensed radio frequencies could leave the swarms open to interference (Campion et al., 2019).

Regardless of these drawbacks, this type of UAV system is much simpler to implement than a fully autonomous UAV system. Cellular networks are often the communication system used to implement this type of UAV system. Cellular networks operate using fixed transmitters and receivers which are part of an existing infrastructure. Using cellular networks allows for UAVs to utilize the licensed frequency spectrum (Yang et al., 2023). This allows for greater information security and reliability.

Another type of infrastructure-based system utilizes the single-group swarm ad hoc network; with this network, a specific UAV called the gateway communicates between the swarm and the existing infrastructure (Chen et al., 2020b). This gateway UAV is equipped with two transceivers: one to communicate with the individual UAVs and one to communicate with the existing infrastructure (Chen et al., 2020b). Although the autonomy of this system is increased because no GCS is necessary, the gateway UAV still becomes a single point of failure to the system. Another type of infrastructure-based communication is a multi-group ad hoc network, where multiple gateway UAVs communicate with certain groups of UAVs and the gateway UAVs communicate through the infrastructure (Chen et al., 2020b). In addition, a multi-layer swarm ad hoc network is a network where the UAVs can communicate directly with each other and only the gateway UAV closest to the infrastructure communicates with the infrastructure for the entire system (Chen et al., 2020b). Since there is not one GCS or gateway UAV with which the entire system is dependent, this last network system for a UAV swarm is more resilient to damage.

FANET Communication System

In a FANET (flying ad hoc network) communication system, the UAVs communicate among each other, while only one of the UAVs is connected to a GCS (Campion et al., 2019).

Such a network can be used to increase autonomy in UAV swarms. According to Campion et al. (2019), “A wireless ad-hoc network is a wireless network that does not rely on existing infrastructure to establish the network. No routers or access points are needed for an ad hoc network.” A FANET uses embedded processors for communication to link each UAV in the swarm. One of the limitations to this system would include the fact that each UAV needs to be supplied with the hardware for networking and the UAVs need to remain within reasonable proximity to each other (Campion et al., 2019). Another potential drawback to the FANET system is that the transmission of data may not be as accurate as an infrastructure-based system (Campion et al., 2019). To support the extra hardware needed for networking, each UAV will have to be strong and large enough for the extra weight. In applications where each UAV is carrying a payload, the extra weight needed for hardware could decrease the weight limit of the payload. However, the benefit of increased autonomy and processing capabilities can outweigh the downside of increased weight and complexity. In addition, proper hardware selection can ensure that the increase in weight is not significant enough to eliminate the benefits of using a FANET. Furthermore, one of the benefits to a FANET system is that distributed decision making is used instead of the decisions being made by the GCS (Campion et al., 2019).

In addition, in a FANET system, the UAVs need to send acknowledgement messages to each other periodically to detect breaks in the links or to detect new devices being added to the swarm (Ayub et al., 2022). The time interval between these acknowledgments needs to be fast enough to allow for quick detection of breaks in the communication but also needs to not be too fast for energy to be conserved (Ayub et al., 2022). In some cases, individual UAVs may need to periodically send out more information than just an acknowledgement; this could include the position and velocity, status of task being performed, and certain sensor readings (Arranz et al., 2023). In a UAV swarm operating on a FANET, the UAVs in the swarm must determine the location of and maintain communication with the other UAVs in the swarm to establish efficient paths (Ayub et al., 2022). This is one of the reasons that operations with a FANET are more computation intensive than the operations with a system controlled by a GCS. The GCS can monitor the location of each UAV and send the necessary commands, thus reducing the computational requirements for each UAV. However, dependence on a GCS takes away the autonomy of a UAV system.

SDR and 5G combined communication systems

Because the infrastructure for a 5G connection is not always available where UAV swarms are intended to be used, Zeeshan et al. (2022) proposed a hybrid connectivity module (HCM) to allow UAV swarms to connect to 5G when it is available, but to use other means of connectivity when 5G is not available. Furthermore, his article suggests combining 5G infrastructure with satellite communication and adaptive multiband multimode SDR waveforms with cooperative communication support (Zeeshan et al., 2022). The HCM module is used to determine which connectivity method to use based on the swarm’s current communication needs and circumstances. Such a model would provide the benefits of utilizing existing infrastructure, while also addressing the issue of connectivity losses due to the need for proximity to the infrastructure. Campion et al. (2019) also suggests the use of 5G networks for UAV swarm architecture: UAV-to-UAV communication can happen through existing cellular mobile infrastructure, and the ad-hoc network can be combined with existing infrastructure. One of the benefits of this proposed system is the fact that the hardware needed to support cellular communication, such as SIM cards or wireless access cards, is generally small and lightweight (Campion et al., 2019).

Routing protocols

UAV swarms need routing protocols to manage the amount of information being transferred among so many aerial vehicles at once. UAVs need a method for locating the nodes in the network with which to communicate and for successfully sending the needed information to these nodes. Chen et al. (2020b) lists six common routing protocols for UAV swarms: store-carry-forward, greedy forward, path discovery, single path, multi-path, and predictive routing. In general, routing protocols can be divided into three main categories: topology-based routing protocols, geographic/position-based routing protocols, and SI (Swarm Intelligence)-based routing protocols (Chen et al., 2020b). Topology-based routing protocols use a device's IP address to send information packets and to define the nodes in the swarm; this type of protocol can be further broken down into the categories of static, proactive, reactive, and hybrid routing protocols (Chen et al., 2020b). The second general category, geographic/position-based routing protocols use location services to locate the nodes in the network before sending information packets; this type of routing protocol is suited for UAV swarms due to their highly dynamic nature (Chen et al., 2020b). On example of a geographic routing protocol algorithm is the Distance Routing Effect Algorithm for Mobility (DREAM), which stores the location of nodes in the network in a location table, thus utilizing lesser bandwidth (Chen et al., 2020b). The third category of general routing protocols, the SI-based routing protocols use the swarm intelligence algorithms to determine where the information packets are being sent (Chen et al., 2020b). Routing protocols in an ad hoc network and especially in a UAV swarm are essential to ensuring that information is being delivered accurately and efficiently. With such high levels of time-sensitive information being continuously transferred among UAVs in a swarm, the routing protocols are essential in ensuring that the swarm communicates properly.

Non-Line of Sight Capabilities

UAV swarms must have non-line of sight (NLoS) capabilities because obstacles and obstructions will eventually come between individual UAVs or between the UAVs and the GCS. The UAVs in a swarm must have the ability to maintain communication with the swarm, despite possible obstructions to the communication signals. Line-of-sight (LoS) channel mode has been generally used by UAV communications, whether it be UAV-to-UAV communication or UAV to ground (Wu et al., 2022). When flying at high altitudes, the likelihood of obstructions to LoS is relatively low; however, when operating close to the ground, UAVs are very likely to run into obstacles and experience interference (Wu et al., 2022). Thus, NLoS capabilities should be considered when a UAV swarm communication system is designed. For a UAV swarm to remain functional while carrying out its tasks, it is imperative that the communication between the UAVs is not lost or broken. Therefore, ensuring NLoS capabilities in a UAV swarm adds robustness to the system.

Device to Device Technology

Device to device (D2D) communication technology allows for devices on a cellular network to communicate directly with each other without being linked to a base station, given the devices are in proximity with each other (Kar & Sanyal, 2018). D2D can use either the same spectrum that the cellular network is using, or it can use an unlicensed spectrum which is different from the spectrum that the cellular network uses (Kar & Sanyal, 2018). D2D can be useful in UAV swarms as it can offer another level of autonomy to swarms which are using cellular networks. One benefit of using D2D technology is the very low latency due to the proximity of the devices (Kar & Sanyal, 2018). Using D2D technology could be a viable way to save power in a UAV swarm if it were used when devices were within a certain proximity.

Applications

Military

The real-time data processing of UAV swarms creates potential for use in military intelligence and can greatly increase situational awareness on the battlefield (Wu et al., 2022). Being able to receive and process information from distinct locations at the same time can provide faster information on details such as enemy location and where to allocate resources. In addition, a UAV swarm can be beneficial in spotting far-off enemy ships and taking note of their number and formation or in finding hidden enemies where it would have been fatal for soldiers on foot to enter (Wu et al., 2022). Having UAVs perform dangerous military tasks could potentially save countless lives. In addition, the future of UAV swarms in military applications will also lead to the need for developing technology to counteract military UAV swarms.

Delivery

One of the commonly anticipated applications of UAV swarms is delivery services. Companies such as DroneUp have already begun to develop systems for drone delivery (DroneUp, n.d.). The use of a single delivery UAV controlled by an operator would not be efficient because a person is still directly in control of each delivery and the load carrying capabilities of a UAV are significantly less than those of a delivery truck. Using a coordinated swarm of UAVs would greatly increase efficiency in delivery services (Campion et al., 2019). Multiple deliveries can be made at a time with minimal manpower necessary. In addition, UAV swarms can be utilized to make deliveries to inaccessible locations.

Agriculture

In the agriculture industry, UAV swarms can be beneficial by spraying pesticides or monitoring crops where it is too expensive for farmers to implement the infrastructure for efficient completion of these tasks (Wu et al., 2022). In addition, having UAVs spraying pesticides can reduce direct human exposure to these chemicals. Furthermore, UAV swarms can use hyper spectral imagery to gather data about crops as they are growing (Wu et al., 2022). UAV swarms can be used to determine the normalized difference vegetation index (NDVI) of crops by using remote sensing equipment, determining the stages of crop development (Campion et al., 2019).

Search and Rescue

In the wake of a disaster, speed and efficiency are crucial to the saving of lives. UAV swarms can decrease the time it takes to find victims or assess situations because each UAV can cover its own unique area and send data to the other UAVs and back to the ground control. In addition, UAVs could be used to provide a means of communication between rescuers and isolated humans (Wu et al., 2022). UAV swarms can provide night illumination to aid individuals in search and rescue (Khalil et al., 2022). In addition, swarms could be equipped with infrared sensors or thermal imaging to detect the presence of life within a disaster zone or to find missing individuals. Such technology has the potential to save lives through the greatly decreased time in performing searches or other such life-saving tasks.

Existing drone swarms

ICARUS

The French company ICARUS has developed drone swarms, specifically in coordinated light displays, and is working on developing swarms for military applications (Jackson, 2021). ICARUS tends to use UAVs from the company Parrot (Jackson, 2021). The main product that ICARUS sells is a case of twenty UAVs which are ready to be programmed for specific purposes

(Jackson, 2021). Instead of using a GCS or a version of an ad hoc network, ICARUS has designed their swarms with algorithms for predetermined actions (Jackson, 2021).

BlueBear

BlueBear Systems Research is a branch of Saab UK Ltd. They developed a test swarm of about twenty UAVs carrying multiple payloads and controlled by a single operator (Bbsr.com, n.d.). The company's focus is on the design of AI-enabled autonomous swarm systems, including swarm systems which operate on the ground as well as in the air (Bbsr.com, n.d.).

Research Issues

Spectrum sharing

Among the frequency spectrum, there are certain bandwidths that are restricted and tightly controlled. Thus, the more open bandwidths can become clogged with the amount of communication flowing at any given moment; UAV communication is generally within the unrestricted spectrum (Shang et al., 2020). One of the issues in the usage of UAV swarms is the potential for the overcrowding of bandwidths due to the copious amounts of information that must be transmitted and received among the UAVs themselves and with the ground station. According to Feng et al. (2019), one possible solution to the problem of bandwidth overcrowding is millimeter wave technology. Using millimeter waves to transmit the information among the UAVs can enable a greater amount of data to be transmitted. In addition, Shang et al. (2020) suggests using spatial spectrum sensing "which enables devices to sense spatial spectrum opportunities and reuse them aggressively and efficiently by controlling the SSS radius." Using this sensing, a UAV swarm would be able to determine open opportunities for use within the spectrum. When considering the design of a UAV swarm, the decision of whether to use the licensed or unlicensed spectrum should come with considerations for privacy and security, which are decreased in the unlicensed spectrum, and with consideration for where the UAV swarm would experience the least interference. Spectrum sharing is not an issue unique to UAV swarms but is a consideration for all technologies using wireless communications.

Information security

The issue of privacy and security in relation to UAV swarms has two approaches: the concern that the communications between the UAVs may be hacked and that UAV swarms may be used for unethical surveillance. UAV swarms automatically collect data about the environment to process for decision making and task planning. One main privacy concern with UAV swarms is whether these data collection capabilities will be utilized for nefarious purposes. A concern that is often present with the use of UAV swarms is that the UAVs will collect personal information and use the information without consent. In addition, individuals may feel that UAV swarms can become an invasion of privacy through captured footage or recorded audio without the individual’s knowledge. One way to keep this issue in check would be to put regulations in place for the use of such data automatically gathered by UAV swarms. In addition, regulations for zones where UAV swarms may not be allowed is a possibility for preventing the unethical collection and use of data. On the other hand, information security could be a concern if a UAV swarm were operating in an information-sensitive mission, such as military surveillance. The transfer of data in the swarm would have to remain secure to prevent hacking into the information the UAV swarm is gathering and transmitting.

Limitations

Weather resistance

Due to the relatively small size of the individual UAVs in a swarm, UAVs are more sensitive to adverse weather conditions than manned aircraft. Determining ways to develop resistance to harsh weather conditions in UAV swarms would be extremely beneficial in enabling the use of UAV swarms under many conditions. If UAV swarms were equipped to deal with adverse weather conditions, they could be used for tasks that would normally require humans to venture out into unsafe weather conditions.

Battery and Power

Power consumption and power supplied continue to be prominent considerations in most electrical systems. In the case of UAV swarms, optimizing control and communication cannot happen without considering the power that is being drawn through specific operations such as data transmission or length of flight route, as well as the power drawn from the system as whole (Yao et al., 2021). As battery power is likely the chosen mode of power for most UAV swarms, the length of time a battery will last before it needs a recharge or replacement is a limitation placed on UAV swarms. Each mission of a UAV swarm needs to be optimized to perform the most functions using the least amount of power. Thus, not only does task allocation and path planning need to be optimized for fastest communication and task completion, but it also needs to be optimized to efficiently utilize the power supplied to the system. One proposed solution to the problem of battery life, proposed by Zeeshan et al. (2022), is to reserve UAVs to replace ones that have dead batteries, thus allowing a number of the UAVs to always be charged and ready for integration into the swarm.

Regulations

According to the United States Government Accountability Office (GAO), current regulations “do not permit a person to operate more than one drone at the same time;” currently, for operators to use a UAV swarm, they must obtain a waiver (U.S. Government Accountability Office, 2023). For UAV swarms to be utilized regularly in commercial applications, regulations must be sufficiently lenient to allow the use of UAV swarms to be feasible. However, certain regulations should be in place to deter the nefarious use of UAV swarms. Thus, for the regular operation of UAV swarms to become realistic, policy makers should find a balance between the allowance of the technology and the prevention of the technology from being used for harm.

Damage Response

In applications such as military and search and rescue, where the UAV swarm is in a potentially harsh environment, it has the potential to experience damage or loss of individual UAVs. Thus, a method needs to be in place for dealing with damage and lost links to UAVs. The system needs to be fault-tolerant for the swarm to keep operating despite losses. In the article "SIDR: A swarm intelligence-based damage-resilient mechanism for UAV swarm networks," the authors propose a Swarm Intelligence-based Damage-resilient (SIDR) mechanism for dealing with a damaged UAV network (Chen et al., 2020a). This proposed mechanism would constantly communicate with the UAVs and adapt the network based on which UAVs are still functioning within the network; the SIDR mechanism would utilize the computational power of the UAV swarm to determine the best ways to reconstruct the network and adjust each UAV's tasks accordingly (Chen et al., 2020a). Such a mechanism is important for increased robustness to the system. Future work regarding UAV swarms should continue to develop ways to deal with loss of UAVs and damage to a swarm to keep the swarm functional until it has accomplished its tasks.

Ethical considerations

As with any emerging technology or research, ethical considerations are necessary to ensure safety and respect for human life is maintained. Ethical considerations are often linked to privacy and security issues. Gathering and using data without permission can become an issue with technology that is well equipped for such tasks. Thus, with the emergence of UAV swarms in practical applications should come standards for what happens to data collected intentionally or automatically by UAV swarms. In addition to data collection concerns are concerns similar to those associated with artificial intelligence, such as the implications of algorithms making decisions rather than human minds. For instance, in his article "Autonomous Swarm Drones New Face of Warfare," Robert Cheek, a developer of high-performance drones, brings up the issues of UAV swarms and their algorithms making decisions in warfare that were once made by directly by humans (Cheek, 2023). Algorithms cannot make decisions outside of the capabilities they were programmed for, thus removing the ability for the potential of last-minute human considerations to be made. For example, a UAV swarm sent to attack an enemy army is not capable of making ethical decisions spontaneously. Thus, placing the power of decision making with an algorithm must be carefully considered ethically before full implementation happens.

Conclusion

UAV swarms have the potential to bring improvements to many industries by increasing efficiency and decreasing manpower. Making improvements to the technology of UAV swarms and enabling them in commercial and defense applications has the potential to lower costs, increase safety, and provide benefits for a wide range of companies and services. Due to the promising benefits of UAV swarms, advances in their technology will continue to be developed and tested. This paper has provided a review of the architectures of UAV swarms, the computational capabilities of such swarms, the communication necessary for UAV swarm functioning, and algorithms necessary for task and path planning. In addition, this paper has provided a review of the challenges and research issues that come with enabling a UAV swarm, as well as the promising applications providing incentive to overcome these challenges. Due to the high functionality of a fully independent UAV swarm, many factors such as planning algorithms, communication methods, and architectures must be carefully considered, tested, and analyzed to create effective UAV swarms. The research and development of UAV swarm technology is still a topic that needs further exploration. However, the progress and potential thus far is promising for the implementation of UAV swarms in future applications.

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