A Review and Future Directions of UAV Swarm Communication Architectures

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***Abstract*—The utility of unmanned aerial vehicles (UAVs) has significantly disrupted aviation-related industries. As technology and policy continue to develop, this disruption is likely to continue and become even larger in magnitude. A specific technology poised to disrupt industry is UAV swarm. UAV swarm has the potential to distribute tasks and coordinate operation of many drones with little to no operator intervention. This paper surveys literature regarding UAV swarm and proposes a swarm architecture that will allow for higher levels of swarm autonomy and reliability by utilizing cellular mobile network infrastructure. Additionally, this paper chronicles initial testbed development to meet this proposed architecture. Specific development of higher levels of autonomous swarms with UAV-to-UAV communication and coordination ability is central to advancing the utility of UAV swarms. The use of cellular mobile framework alleviates many limiting factors for UAVs including range of communication, networking challenges, size-weight-and-power (SWaP) considerations, while leveraging a robust and reliable infrastructure for machine to machine (M2M) communication proposed by 5G systems.**

***Index terms*- autonomous systems, UAV swarm, wireless communications**

I. INTRODUCTION

Small unmanned aircraft systems (sUAS) have become an attractive vehicle for a myriad of commercial uses. The ability of sUAS to bring payloads for utility, sensing, and other uses into the sky without a human pilot on board is an attractive proposition. With manned aviation, there is the risk of injury or fatality should a critical error occur in flight. With an unmanned aircraft system, these concerns are alleviated. Additionally, manned aviation is expensive. The price to buy, rent, or use a general aviation aircraft is prohibitive. Additionally, the price to pay a pilot to fly the aircraft, fuel costs, and maintenance are all additionally prohibitive expenses to the use of general aviation aircraft for widespread commercial applications. For these reasons, the utility of sUAS has been an attractive alternative. Additionally, there are many advantages for unmanned aircraft in military applications, though this paper focuses mostly on applications of UAVs in private sector and commercial applications.

A. *State of the industry*

In August of 2016 the regulatory body of aviation in the United States announced the passing of 14 CFR Part 107, a federal code of regulations for the commercial use of sUAS [1].This code established a regulatory framework for the commercial use of sUAS in the United States National Airspace System (NAS). The passing of part 107 was significant in that although it laid foundational regulations for commercial use of sUAS, it also relaxed many regulations and requirements that were in place for the commercial use of sUAS. Since the adoption of part 107 regulations the number of registered commercial sUAS pilots has grown to over 60,000 as of September 2017 [2]. Additionally, the FAA estimated that 600,000 commercial sUAS would fly in the year following the passing of 14 CFR Part 107 in August 2016 [3].

The sUAS industry has oriented itself mostly as a service industry. The actual sUAS themselves are important, but the real value of the sUAS is what type of payloads they can carry and what type of services they can efficiently provide. Some of these use-cases include photography [4], cinematography [4], precision agriculture [5], power line and structure inspection [6], [7] surveillance security [4], surveying [8], Infra-red and multispectral imaging [9]–[12], natural disaster recovery [13], search and rescue operations [14], and many more [4].

B. *Traditional commercial operation*

Currently, as per the regulations of 14 CFR part 107.35, “A person may not operate or act as a remote pilot in command or visual observer in the operation of more than one unmanned aircraft at the same time.” This regulation, coupled with the rest of part 107 currently make the simultaneous commercial operation of UAVs illegal. The current method of commercial operations is for one pilot to control one UAS. Additionally, other crew acting as mission control or visual observers can be present. The hardware involved in a traditional operation includes a handheld transmitter to control a sUAS, an unmanned aircraft, associated payload, and a computer with ground control software acting as a ground control station (GCS) for semi-autonomous control.[1], [4] Fig. 1. shows the current commercial operation and associated hardware.

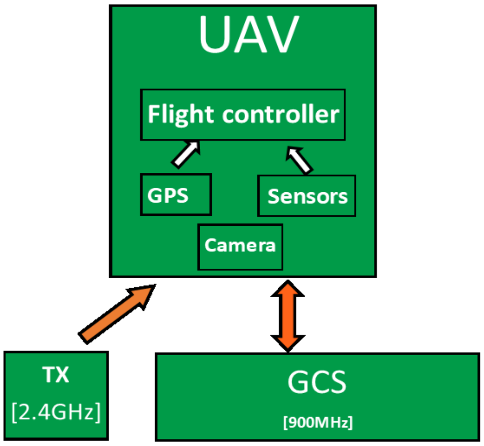

Fig. 1. Block diagram of traditional hardware setup and control of single sUAS

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II. CURRENT STATE OF SWARM

Though the utility of sUAS has budded an industry, the capability of swarms of UAVs is an intriguing development. Limitations of traditional operation of sUAS is that they are small, have a limited payload, have a limited flight time, and require a remote pilot to operate them through a handheld transmitter or computer with appropriate control software. The utility of swarming many UAVs to perform tasks thus becomes attractive because it addresses these limitations of single sUAS while adding more functionality.

A swarm is generally defined as a group of behaving entities that together coordinate to produce a significant or desired result or behavior [15]–[17]. There are several natural examples of swarming behavior in nature. Bees coordinate with one another to complete tasks critical to the survival of their swarm. Flocks of migrating geese coordinate efficient flight patterns to achieve their migration. Similarly, a swarm of UAVs is a coordinated unit of UAVs that perform a desired task or set of tasks. A general architecture for task order in swarm environments is shown in [17]. A UAV swarm is an example of this architecture and could complete tasks relevant to commercial purposes.

A. *Advantages and applications*

Advantages to swarm include time-savings, reduction in man-hours, reduction in labor, and a reduction in other costs. One specific example of a commercial application that would see an increase in efficiency using swarm is the observation of normalized difference vegetation index (NDVI). NDVI is an important observation for precision agriculture. NDVI observation requires flying sUAS over fields of farmland. Cameras equipped with remote sensing equipment record high resolution geo-tagged imagery of crops. These specific NDVI imagery and sensing equipment show what parts of crops in fields are growing correctly or are in the proper stages of crop development. Surveying a farm with hundreds or thousands of acres is time-consuming and lacks efficiency using current methods. The use of a coordinated number of sUAS surveying an entire farmstead with little to no operator intervention would greatly increase efficiency and could potentially revolutionize precision agriculture.

The most notable application of UAV swarm is delivery services. Amazon and United Postal Service have indicated interest us using UAS for package delivery [18],[19]. Using a typical remote pilot and a single sUAS, package delivery would be inefficient. Swarms of drones with coordinated control and communication capabilities would be efficient in this application.

B. *Autonomy in UAS*

There are varying levels of autonomy for autonomous vehicles. Levels of autonomy are based the number of tasks, coordination, or decision making a vehicle can make without input from an operator. In the example of commercial and passenger vehicles, 6 levels have been defined. The six level range from no autonomy, to full autonomy where a steering wheel is optional [20], [21]. Levels of autonomy for UAVs are not yet well defined [22], [23]. A work in [24] proposes five levels of UAV control autonomy, but these levels are not widely accepted and require more research to arrive at a clear consensus [25]. This work defines the highest level of UAV swarm autonomy as the ability to perform a task coordinated among multiple UAVs without intervention of human operator.

The level of autonomy proposed can be theoretically be achieved by a UAV swarm. A UAV swarm is a cyber-physical system (CPS). The most important aspect of an autonomous system is the decision chain that occurs in lieu of human operation. The movement and task completion of a UAV operated traditionally is completely controlled by a human making decisions and controlling the operation of the UAV. In a fully autonomous system, decisions are made by algorithms. An autonomous CPS uses a decision-making paradigm defined by three stages: Data, control, and process. The decision structure of a UAV swarm would follow this paradigm as proposed in [26] and shown in Fig. 2.

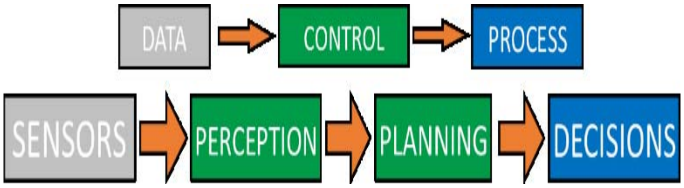

Fig. 2. Decision chain of an autonomous system

Sensors make up the data portion of the paradigm. Sensors acquire raw data pertaining to the environment of operation of a desired task and relay the data to a computer. UAV swarm sensors include GPS, airspeed, acoustic sensors, cameras, and many more depending upon the application. The control stage is comprised of 2 sub-phases perception and planning. Perception is defined by transforming ambiguous data to useful information. Planning refers to the process of using the perceived information to formulate a decision to execute the task. NVIDIA has recently designed specific embedded hardware for autonomous vehicles to meet this need [27], [28] And finally, the process stage is the execution of the decisions made and the completion of the task. The work in [26] surveys and proposes methods centered upon artificial intelligence, machine learning, formal logic, expert systems, and other distributed intelligence methods to ultimately realize full autonomy in distributed CPS.

C. *Current swarm communication architectures*

Swarm is not a new technology. There have been proposed applications and development of UAV swarm, particularly for military applications, dating back to the early 1990's [29]–[31] For general applications, UAV swarm research has just recently started to attract more attention. Notably, a swarm of 300 drones developed by Intel was deployed as a coordinated light show for super bowl 51 as well as the 2018 Winter Olympics [32]. In addition to these examples, there have been other demonstrations of UAV swarm, however, in most demonstrations the level of autonomous operation has been low.

In most cases each individual UAS is simultaneously controlled by a GCS. Traditional UAV swarms use a computer as a GCS running a ground control software. The computers are equipped with a transceiver that sends and receives telemetry data from connected UAVs. Telemetry data traditionally includes GPS information, groundspeed, and other parameters collected from payload sensors. Traditionally these transceivers use unlicensed Radio Frequency (RF) bands such as 900MHz to send and receive the information. Higher levels of autonomy would allow drones to make decisions using on-board processing power. Current demonstrations of UAV swarm utilize one of two general forms of swarm communication architecture. The two forms are an infrastructure-based swarm architecture and ad-hoc network- based architecture.

1) *Infrastructure based swarm architecture*

The infrastructure-based architecture consists of a ground control station (GCS) that receives telemetry information from all drones in the swarm and sends commands back to each UAV individually. In some cases, the GCS communicates back to individual drones in real time, sending commands to the flight controllers on board each UAV. In other cases, a flight operation is pre-programmed aboard each UAV and the individual flight plans of each UAV are simultaneously operated while the GCS is simply used to observe the system. These UAV swarms are considered to be semi-autonomous as they still require direction from a central control to complete the assigned task [33].

Infrastructure based swarm architecture is the most common architecture for UAV swarms [33]. GCS software have already contain basic infrastructure-based swarm capabilities [34]. One advantage of infrastructure-based swarming is that optimization and computations can be conducted in real time by a GCS via a higher performance computer than could reasonably be carried on a sUAS. Additionally, networking between drones does not have be established [33], [35].

Infrastructure-based swarm architectures are dependent upon the GCS for coordination of all drones. This dependency causes a lack of system redundancy. In the event of an attack or failure to any operation of the GCS, the operability of the entire swarm is compromised. Additionally, infrastructure-based methods require all UAVs to be within propagation range of the GCS. A drawback to unlicensed RF communications is that communication may be susceptible to interference.

Due to the light payload capacities of sUAS, the hardware necessary to establish reliable communication with an infrastructure may limit the utility of infrastructure-based swarms. Another drawback is a lack of distributed decision making. In an infrastructure-based architecture, the GCS coordinates the decision making of all UAVs based on computations and algorithms developed in the GCS. Fig. 3. Demonstrates and infrastructure-based swarm architecture.

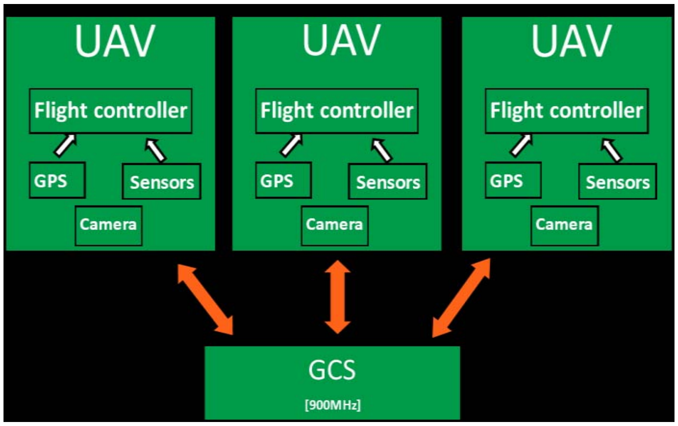

Fig. 3. Example of an infrastructure (GCS) based swarm architecture

2) *Flying ad-hoc network (FANET) architecture*

In [33] the use of Flying Ad-Hoc Networks (FANETs) to coordinate communication between drones all in one network is proposed. A wireless ad-hoc network (WANET) are wireless networks that do not rely on existing infrastructure to establish the network. No routers or access points are needed for an ad-hoc network. Instead, nodes are dynamically assigned and reassigned based on dynamic routing algorithms. Additional works have also proposed various configurations of ad-hoc communication networks in UAV swarms [15], [16], [35]–[39]. In a FANET all UAVs are part of a network of communications that is established between the UAVs. This network allows for real time communications between UAVs.

Direct communication between UAVs forces distributed decision making as is no necessity for an infrastructure-based decision engine. This also provides built in redundancy as the entire swarm is not dependent upon an infrastructure to execute the desired tasks. This is the primary advantage of FANETs. Some drawbacks to FANETs are related to SWaP considerations. To establish a FANET, networking hardware is required on board each UAV. The distance over which UAVs can reliably communicate to one another in a FANET is a limiting factor to its implementation [33], [39]. Additionally, dynamic reconfiguration of routing for UAV swarm applications is a challenging task resulting packet loss [33], [40]. For applications where accurate telemetry of data between UAVs is critical, the establishment of a reliable FANET is a difficult task [33], [39]. A block diagram detailing a FANET is shown in Fig. 4.

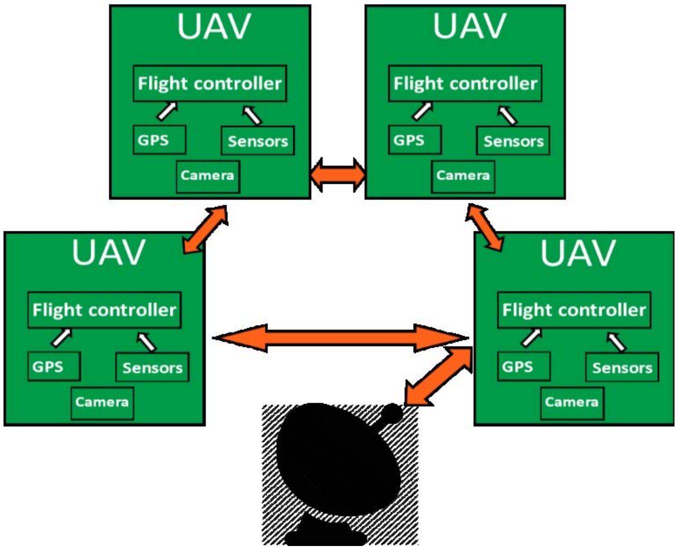

Fig. 4. FANET swarm architecture block diagram

This work proposes a hybrid of an infrastructure-based network making use of cellular network infrastructure but establishing network protocol between drones without intervention of a GCS. This proposed architecture of UAV swarms leverages strengths of both architectures while mitigating some weaknesses.

III. PROPOSED SWARM ARCHITECTURE

The proposed architecture is an adaptation of an ad-hoc network realized through infrastructure support. Specifically, the infrastructure features complete UAV-to-UAV communication, where the telemetry of each UAV is communicated to every other UAV via cellular mobile infrastructure. While it differs from a pure FANET in that communication is relayed through infrastructure, it is like a FANET where the infrastructure does not make any decisions. Rather, decision making is distributed among the UAVs, and the infrastructure is purely used to transmit data. Fig. 5. Showcases a block representation of the proposed architecture.

High levels of autonomy can still be achieved despite the proposed infrastructure-based architecture. UAV payloads containing computational power sufficient to coordinate decisions based on the real-time telemetry data received from connected UAVs must be developed. This allows for distributed decision making based upon formal logic, machine learning, and other distributed control algorithms as proposed in [26]. The command and control of UAVs using cellular network infrastructure has been proposed in [41], [42] and commercial hardware development has been demonstrated by [43].

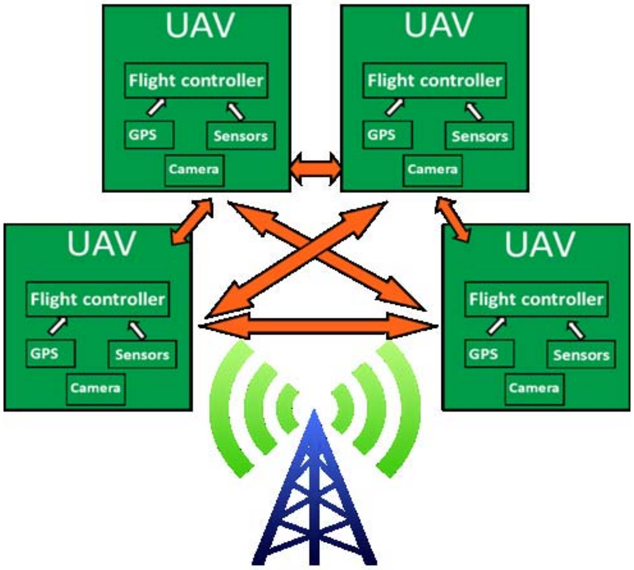

Fig. 5. Proposed cellular network UAV swarm architecture

A. *Machine to Machine (M2M) and 5G networks*

Fourth generation (4G) cellular technology boast maximum download speeds of 1Gbps. [44]. 5G communication systems are expected to boast maximum download speeds of 10Gbps with network latency as low as 1ms. A typical packet size for UAV communications is between 17 and 263 bytes. While 4G speeds are sufficient for these packets, 5G will allow for additional data streaming including data types such as video from payload cameras or data from payload light detection and ranging (LiDAR) systems. The ability to achieve low latency is important for UAV swarm communication. A central objective to 5G communications is machine to machine (M2M) communications [45], [46]. M2M communication capabilities of 5G would provide a natural backbone for UAV swarm environments [47], [48]. The ability to transmit real time telemetry data between all UAVs connected to the cellular network allows for sense and avoid methodologies to be followed. The hardware required to reliably access cellular networks is space and weight efficient. SIM cards or 4G wireless access cards are lightweight and can easily be added to a companion computer or even a companion smart phone [49].

Analysis of communication latency using the proposed infrastructure is a topic of research, however, packet loss and the performance of OFDM for UAV communication have been analyzed and with increased speeds and infrastructure updates of 5G systems, the performance will increase [40], [50].

B. *Strengths of proposed architecture*

The advantages of this architecture are many. First, the range for which the UAVs can communicate is practically unlimited. Nearly the entirety of the United States has 3G or better cellular data coverage. The reliability and redundancy are less of a concern than for traditional infrastructure reliant architecture due to the reliability of cellular base stations. While high levels of autonomy can be achieved through traditional architectures, the redundancy provided by the proposed infrastructure is advantageous.

IV. PRELIMINARY DEVELOPMENT

A recent need for counter autonomous UAV technology has driven development of UAV swarm technology [51], [52]. Preliminary development has focused upon developing a testbed of hardware and software to test UAV swarm architectures, including the proposed cellular network-based architecture. The command and control of a single drone using cellular networks has been demonstrated. Additionally, real time UAV-to-UAV communication including sending of basic commands through an ad-hoc UAV network has also been demonstrated. The use of cellular network for this work is not yet approved, so preliminary development focuses on establishing initial ad-hoc mesh communication using traditional hardware that can easily be updated and extended for the use of cellular network communication between UAVs via the use of virtual machines and software in the loop protocols.

A. *UAV-to-UAV network communication test bed*

The testbed developed uses custom built quadcopters. The quadcopters feature flight controllers interfacing with on-board companion computers and mesh networking hardware. The flight controller communicates with the on-board computer using MavLink communication protocol [53]. The companion computer understands MavLink telemetry through MavProxy software [54]. Fig. 7. displays a functional block diagram of the communication protocol from flight controller and companion computer of one UAV to the flight controller of another UAV.

Fig. 7. UAV-to-UAV communication hardware diagram

V. CONCLUSION

This paper provides a concept level proposal, initial development, and literature review for the use of cellular networks as the communication infrastructure for UAV swarms. It provides an overview of the sUAS industry, the applications of UAV swarm, and in-house development efforts for UAV swarm. The paper reviews preliminary testbed developments and provides direction for future works regarding UAV swarm at UND. Specific development of autonomous swarms with UAV-to-UAV communication and coordination ability is central to advancing the utility of UAV swarms. Though swarm technology has yet to be practically utilized in commercial applications, there exists great potential. The use of cellular mobile framework alleviates limiting factors for traditional UAVs swarm communication approaches. The use of cellular networks for UAV swarm would greatly increase swarm efficiency and commercial utility especially in the presence of upcoming 5G networks with M2M communication capabilities.

VI. ACKNOWLEDGEMENT

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