Research Article

Dmitry Gura*, Victor Rukhlinskiy, Valeriy Sharov, and Anatoliy Bogoyavlenskiy

Automated system for dispatching the movement of unmanned aerial vehicles with a distributed survey of flight tasks

<https://doi.org/10.1515/jisys-2021-0026>

received February 03, 2021; accepted April 08, 2021

Abstract: Over the past decade, unmanned aerial vehicles (UAVs) have received increasing attention and are being used in the areas of harvesting, videotaping, and the military industry. In this article, the consideration is focused on areas where video recording is required for ground inspections. This paper describes modern communication technologies and systems that enable interaction and data exchange between UAVs and a ground control station (GCS). This article focuses on different architectures of communication systems, establishing the characteristics of each to identify the preferred architecture that does not require a significant consumption of resources and whose data transmission is reliable. A coherent architecture that includes multiple UAVs, wireless sensor networks, cellular networks, GCSs, and satellite network to duplicate communications for enhanced system security has been offered. Some reliability problems have been discussed, the solution of which was suggested to be a backup connection via satellite, i.e., a second connection. This study focused not only on the communication channels but also on the data exchanged between system components, indicating the purpose of their application. Some of the communication problems and shortcomings of various systems, as well as further focus areas and improvement recommendations were discussed.

Keywords: unmanned aerial vehicle, ground control station, communication system, information flow, wireless networks

MSC: 9405

1 Introduction

Unmanned aerial vehicles (UAVs) are airborne vehicles that can fly without a crew on board and are controlled remotely from the ground [1]. It can operate autonomously, depending on its pre-programmed software, or it can be monitored and controlled remotely from the ground by a system built into a ground control station (GCS). Over the past few decades, the popularity of UAVs has grown steadily. Today, more than 1,000 models of UAVs are developed in many countries around the world, serving as essential

* **Corresponding author: Dmitry Gura**, Department of Cadastre and Geoengineering, Kuban State Technological University, Krasnodar, 350072, Russian Federation; Department of Geodesy, Kuban State Agrarian University, Krasnodar, 350044, Russian Federation, e-mail: d_gura@rambler.ru

Victor Rukhlinskiy: The Interstate Aviation Committee (IAC), Moscow, 119017, Russian Federation, e-mail: vicrukhlinskiy@rambler.ru

Valeriy Sharov: Department of Flight and Life Safety, Moscow State Technical University of Civil Aviation, Moscow, 125993, Russian Federation, e-mail: valersharov@rambler.ru

Anatoliy Bogoyavlenskiy: Metrology Department, State Research Institute of Civil Aviation, Moscow, 125438, Russian Federation, e-mail: anbogoyavlenskiy@rambler.ru

assistants in a wide range of military and civilian applications [2–4]. Accordingly, the use of UAVs is in demand in such industries as detection and monitoring of forest fires [5], meteorological services [2], aerial photography [2,5], mapping [6], parcel delivery [7], video shooting [8], the rescue of people and in precision agriculture [9,10], etc.

Besides, one Facebook project uses drones to deliver the Internet to isolated areas [11]. In addition, UAVs enable searching for missing people [12] since the latest developments of UAVs have been used for search and rescue works [13]. One of the important applications of UAVs is the military sphere. Because of its small size, increased stealth, and ability to receive commands in real-time, UAVs are used to control hostile areas and borders [14]. UAVs can easily be used to fight terrorism without losing human lives in various scenarios as the pilot is secure. In this context, the task of observing and controlling UAV flight in real-time will involve the use of several data types obtained from telemetry and payload subsystems, as well as commands to be sent from a ground station to control the UAV. This exchange of data between the UAV and the GCS requires a reliable, broadband, and high-performance wireless channel for real-time communication and distributed data exchange.

As the scope of UAVs application is expanding every year, and the demand for the use of this technology is increasing, the safety of the data channel between UAVs and GCS is an important and relevant issue, having a great influence on system performance and accuracy of the tasks. Besides, the implementation of new innovative technologies for control systems and autonomous mode is also relevant.

1.1 Literature review

Recently, numerous researching works and projects related to UAV communication have been performed. In ref. [15], the authors investigated the characteristics and requirements of communication networks for UAV civil use and classification specified by the aims of the UAV application, their technical characteristics (built-in sensors), and data transmission speed (depending on the type of data sent and the distance between the two nodes). Currently, the UAV's design includes many sensors and processors that can deliver high-quality, real-time observations and images. Consequently, UAVs are increasingly used for aerial photography [16,17], field mapping [18], and the study of hard-to-reach areas [19]. Furthermore, the use of drones greatly reduces the cost of research, and increased flight time and enhanced capabilities for easy launch can only contribute to expanding their application areas.

In ref. [20], the author proves that because of the multifunctionality and specific features of UAVs, the use of drones is very successful in traffic surveillance. The Airborne Video Surveillance System was aimed to monitor remote rural areas of Florida using a camera-equipped UAV and to identify the potential benefits of using UAVs for monitoring traffic and collecting information on the condition of the highway. In ref. [21], the author focused on the architecture of using multiple UAVs. The relationship between multiple UAVs is the most important task in the system. Using a special network between the UAVs is an ideal solution. For this purpose, the author introduced the concept of the FANET (Flying Ad-Hoc Network).

In ref. [22], the authors implemented the equipment and the implementation of the GCS layout, which controls a semi-automated flight of UAVs. This development using the MAVLink protocol enables the operator to program the flight path, view the current telemetry data, and set the requirements for the flight parameters (direction, altitude, and speed). However, the results of the study showed that the project commercialization requires refinements to optimize the hardware and programming part, including GPS receivers, SQLite database, CSV or XML file, recording and storage of information, etc. The use of the software-defined network (SDN) as on-demand forwarding switches in UAVs can provide efficient management and fast service handover by reducing service handover delay, E2E delay, and service signals [23]. According to the simulations of various service transfer scenarios in a 5G network [24], including various network elements, the SDN-based service transfer scenarios are shown to perform better than existing 4G-LTE service transfer for UAVs.

In ref. [25], the researcher compared also the FANET with another unique network, the role, and transmission of data between different modules. Then, comparing different communication architecture (direct architecture, cellular architecture, and UAANET architecture), as well as mentioning their strengths and weaknesses, the authors suggest that the most appropriate architecture is UAANET (UAV Ad-Hoc NETwork). The characteristics, advantages, and projects involved have been mentioned, and the routing protocols used in UAANET, security problems to be considered, and possible options to improve the security of UAANET routing protocols have been discussed.

In ref. [26], the authors published an overview document on important issues related to UAV communication networks. First, the characteristics of existing special networks such as MANET, VANET, and UAV have been compared. Then, the UAV networks have been classified according to the topology (based on infrastructure or Ad-Hoc), architecture (Star or Grid), and if the UAV act as a server or a client, etc. Afterward, a discussion on the existing routing protocols (which are classified as static, proactive, reactive, and hybrid routing protocols) has been performed to select the most appropriate one for the UAV networks, taking into account several issues such as power consumption, limited UAV lifetime, and network dynamics.

1.2 Task setting

Following the aforementioned, existing research efforts have been focused on the impact of UAV deployment and the relationship between UAVs. However, little information has been provided in the literature on the safety and various approaches to communication between the UAV and the GCS, which is an important aspect for precise and correct use of these technologies in military and civil areas. Therefore, the main objective of this article is to investigate different architectures that provide a reliable and secure link between the UAV and the GCS.

In this regard, the main tasks of the study were:

- (1) to study recent developments and research results of the UAV and GCS communications systems; to describe the system architectures with the various components and the interactions between them;
- (2) to determine the communication channels established between the different components; to consider different communication models that can be used between the UAV and the ground terminal; to examine the information flows between the UAV and the GCS, defining the protocols and structures of the data frame;
- (3) to explore the different network technologies that may be candidates for connectivity in the proposed coherent architecture;

The study results can contribute to establishing some of the communication problems and shortcomings of the systems under study, as well as identify further focus areas and improvement recommendations.

2 Overview of UAV-GCS connection

This section presents main characteristics and properties of the communication system model, routing and communication security features.

Within the wireless network model, the UAV acts as a dynamic object (flying) with great mobility. In addition, in the network model, the UAV can be connected decentrally via UAV-UAV and UAV-GCS wireless communication, where the UAV can be directly controlled.

In the UAV-GCS communication system, the network requirements are highly dependent on the purpose and direction of the drones because of the high mobility and change in the dynamic topology of the drones [27]. For example, in a disaster area, UAVs can be used as repeaters to ensure less communication disruption. When using the system for military purposes, the drones should move unpredictably for the

enemy, and the UAVs are controlled centrally through the GCS [28]. For this purpose, a secure communication protocol shall be provided in this network.

Routing protocols in the UAV-GCS network are divided into three main subcategories, depending on the routing methods used [29]:

- (1) topology-based routing protocols,
- (2) swarm-based routing protocols,
- (3) position-based routing protocols.

High mobility rate and dynamic changes in UAV's topology make it difficult to design a routing protocol, resulting in high package loss and low package delivery ratio. In such a network, each UAV must be provided with global knowledge of the dynamic network topology in real-time.

The risk of a routing attack in the system is also unavoidable and can lead to a broken drone trajectory or other consequences. Therefore, a security mechanism based on authentication and identification of objects and users in the control system is required [30]. In addition, a secure authentication mechanism can be used to detect any type of attack.

3 The UAV-GCS system communication architecture

The observation task requires synchronization and interaction between the UAV network and the wireless sensor network (WSN). Thus, the multi-system communication architecture, as shown in Figure 1, has been examined. Depending on the different tasks, the architecture will contain three networks:

- Air Ad-Hoc network for communication between drones;
- Ground-based WSN representing an interactive set of sensors installed in the geographical area at ground level for monitoring and collection of various data, such as humidity, temperature, and pressure, in autonomous mode.
- Mobile network that provides communication between the base station (BS) and the UAV or the GCS command center. This network acts as a transponder between the GCS and UAV networks.

The architecture includes the GCS, also known as the Flight Planning and Control Station [31,32], and is the operational command center for the UAV. The GCS allows the user to create a mission and administer the drone flight, which facilitates the observation of the UAV as the station collects and displays all the data on the drone status, the current command, and telemetry data.

Figure 1: The monitoring architecture of several UAVs [20].

To date, a great variety of GCSs that can be used for different purposes is available worldwide as civil and military applications [33]. Moreover, GCS can be software and have open source such as Mission Planner (Windows, Mac OS X, Linux), APM Planner 2, and MAVProxy [34]. Moreover, there are autopilots (such as Ardupilot) with their own Control Station software (Ardupilot Mega Planner) [35,36]. This surveillance system combines six communication lines (Figure 1):

- L1 is a communication line between multiple UAVs, usually based on IEEE 802.11.
- L2 is responsible for communication between the BS and the UAV.
- L3 communication line between wireless sensor network and BS.
- L4 channel of communication between two nodes of WSN.
- L5 communication line between BS.
- L6 communication lines between GCS and BS.

The information must be continuously transmitted from the UAV to the GCS to control the UAV, i.e., there must be a bi-directional communication between them, providing telemetry, and sending commands in real-time. The communication line from the UAV to the GCS is intended for telemetry. It contains flight data collected by the drone, such as geographic location and streaming video captured by the camera during the flight. The communication line from the GCS to the UAV sends the UAV control commands (e.g., changing the UAV direction).

3.1 The UAV signal processing architecture

As the tasks (targets) in which drones are used are important, the communication between the UAV and the GCS must work in the protected spectrum. Besides, a backup satellite communication line should be created. The main link is implemented via LTE or 5G, which is preferable because of low latency reasons. However, a reserve connection increases reliability. Advanced security mechanisms should also be used to avoid a situation when unauthorized users intercept control of the UAV. Figure 2 illustrates the architecture of multiple UAV controls.

Figure 2: Scheme of the UAV signal processing architecture [33].

There are different communication architectures (network topologies) for establishing communication between UAVs and ground terminals [33,37], which can be divided into two categories: star and grid [38,39] (see Figure 3).

Figure 3: Different communication architectures [39].

The “star” topology is based on an infrastructure where each UAV is directly connected to a central hub, which is usually a fifth-generation BS (see Figure 3). Thus, all flows are centralized, but the BS cannot exchange data with an UAV out of range. In addition, the UAVs are not directly connected, even though their actions must be synchronous to avoid collisions.

For this purpose, the connection between several UAVs passes through the BS, which in this case leads to a long delay in signal transmission. A network topology integrating two or more “star” communication architectures is called an “extended star.” In this architecture, several groups of UAVs are interconnected, and for each group, there is a node CGS, which is responsible for data exchange and is directly connected to the BS and. To exchange data between multiple groups of UAVs, the data must pass through the BS. The problems of this network topology are high latency and high bandwidth requirements for the communication line. Besides, if the BS fails, the entire network also breaks down.

Another type of communication architecture is a cellular topology. In this network topology, there is no centralized communication with the BS, i.e., each UAV can act as a transponder and can transmit data between other UAVs without passing through the BS. This topology is based on Ad Hoc (Figure 3), i.e., there is only one UAV, called mainstream, directly connected to the BS, which acts as a gateway between the BS and other UAVs. It collects data from the UAV and transfers them to the BS, simultaneously sending commands and information from the GCS to the UAV.

The specifics of this network topology are the presence of a single connection between the BS and all the UAVs. Another topology, similar to the “extended star” is an extended grid network, which also contains several groups, but all of them can transmit data to each other directly, without the need to connect through the BS, and, as mentioned earlier, there is only one gateway to the UAV in direct connection with the BS (Figure 3). The advantages of grid topology are the support of communication between the UAV, even when the BS failed, and less bandwidth for data transmission for the communication line between the UAV and the BS. As already mentioned, a huge amount of information is transmitted between the UAV and the GCS, which can be divided into service data and measured data.

Service data are the information exchanged between the UAV and GCS, including control commands, status, reports, as well as all data for the UAV management. The details collected by sensors onboard during the flight are classified as data that can be presented in various forms [40]. The main data are images and videos taken by different types of cameras (optical, thermal, etc.). Because of the high speed and stability of the network, these images and videos are transmitted to the NSU in real-time and displayed to the pilot allowing for a correction of UAV actions. In addition, UAV transmits other information such as its speed, battery charge level, altitude, and current flight mode.

4 Discussion on security of routing protocol

The exchange of data between the GCS and UAV is determined by various protocols, such as the MAVLink protocol (Micro Air Vehicle Link), which is the most standardized communication protocol used in the data channel for the UAV, or STANAG 4586 protocol. The MAVLink is an open-source protocol used to exchange messages between autopilot and GCS [41,42], i.e., it receives telemetry data from the UAV and transmits control and navigation commands.

The MAVLink [43] presents a list of the available common MAVLink messages set, executed by the majority of GCSs and autopilots. MAVLink is a simple protocol tested on several platforms of the UAV and numerous software for the GCS. It can communicate between 255 UAVs controlled by only one UAV. The minimum package length in the MAVLink protocol is 8 bytes, and the maximum – 263 bytes at full payload. Figure 4 shows the structure of the MAVLink command, and Table 1 shows a detailed description of this MAVLink package.

Figure 4: The structure of MAVLink command.

Table 1: Details of the MAVLink package

Region	Meaning	Target
STX	0xFE	Indicates the beginning of a new package
LEN	0–255	Specifies the length of payload
SEQ	0–255	Includes package loss detection
SYSID	1–255	Includes package loss detection
COMP	0–255	Defines the number of interacting UAVs
MSG	0–255	Defines the message to be sent
PAYLOAD	0–255	Messages data
CKA, CKB		CRC options

Security is crucial for any communication protocol to guarantee the reliable and safe transmission of data between network components. However, the MAVLink protocols have security gaps, and the researchers are addressing these problems [44–46]. The previous section focused on the architecture of communication between the UAV and GCS. The various network topologies available for different application purposes were presented, followed by mentioning a data exchange. As follows from the architecture presented in Figure 1, numerous network technologies can be applied in the communication system between the UAV and GCS. Table 2 highlights the principal characteristics of different communication technologies, which allows classifying them by range and speed of data transmission. Thus, for short-distance communication, the WIFI (802.11) or ZigBee is suitable, i.e., cellular network, WiMAX, or satellite communication is preferable to cover a large area. In addition, the bandwidth requirements for video and images are not the same as for commands or GPS data. Therefore, when selecting network technologies, the purposes of UAV usage should be taken into account.

This article discussed the standard architecture and the interactions between GCS and UAV. However, some issues are disabling their successful practical use, namely: *Ubiquity*: users must control the UAV and access the UAV system at any time from any device. *Limited resources*: A surveillance task requires a lot of data, while the UAV has limited storage and power capacity. Therefore, an architecture that does not

Table 2: Comparison of technologies for communication channels

Technology	Theoretical speed	Range	Advantages	Restrictions	Data traffic
Satellite [1,47]	10 Mbps output; 1 Gbps reception	All over the earth	Broad coverage provides communication in all areas	Limited bandwidth; high delays; low data transfer rates; high cost	Real-time processing
IEEE 802.11(a,g)	54 Mbps	30 m	High speed	Limited range; limited user support	Control commands; telemetry data from UAV sensors
IEEE 802.11(b)	Up to 11 Mbps	75–100 m			
IEEE 802.11(n)	Up to 300 Mbps	75 m			
IEEE 802.11(ac)	Up to 866.7 Mbps	35 m			
[1,48,49]					
GSM	Up to 9.6 kbps	Depends on the BS	Extended coverage duplication	High cost	Control commands; telemetry data from UAV sensors (pictures and video)
GPRS	Up to 144 kbps	(from 1 to several km)	One infrastructure for multiple UAVs		
UMTS	Up to 2 Mbps		High bandwidth and mobility		
LTE	1 Gbps				
5G [1,50]	10 Gbps or more				
WiMAX [50,51]	70 Mbps	Up to 50 km	High bandwidth Low cost Easy to use High mobility	Interference issues	Control commands; telemetry data from UAV sensors (pictures and video)
ZigBee [52]	250 kbps	Up to 30 m	Low cost	Low data transfer rate; short range coverage	Control commands
Bluetooth	1 Mbps	Up to 30 m	Low cost	Low data transfer rate; short range; low safety	Data transfer between UAVs
IEEE 802.15 [1]					

consume their resources is preferable. *Real-time management*: UAV task allocation, mission status monitoring, and flight path must be provided in real-time. Moreover, unmanned aircraft require real-time communication with each other to indicate their location and status to provide common work and complete the mission. *Reliable connection*: drones require a permanent connection and a reliable communication channel.

However, the communication network may not be available, especially in remote areas. Besides, data must be transmitted securely and protected from external attacks. *Scalability*: adding a new component to the system must be safe and easy. Therefore, in urgent cases, a new UAV be attached to the mission directly in real time, if needed. It has been established that this architecture must be improved to meet the requirements. On the other hand, new concepts such as the Internet of Things (IoT) [53], Cloud [51], and SDN [52] have gained popularity recently as they have become applicable in many industries, including the UAV network, because of their extended functionality.

In fact, IoT is responsible for establishing and facilitating communication between things via the Internet. The Cloud provides flexibility and accessibility from any place at any time, as well as storage and computation of data collected from devices over the Internet. Finally, the SDN, which is responsible for managing the heterogeneous environment, ensures synchronization in the network. Therefore, future research will focus on these concepts, which are becoming more and more complicated to solve the restrictions and problems of a UAV network system.

5 Conclusion

The paper presented the analysis results on the features of communication system architecture for UAV control using GCS. It was shown that an effective and autonomous drone control system from the ground terminal requires a minimum of six communication lines. The analysis of different communication topologies revealed that the communication configuration can vary from “star” to “grid” topology depending on the purpose and the security level of data transmitted. Some reliability problems were discussed, the solution of which can be the use a backup connection via satellite, that is, a second connection. The study of the basic characteristics of different communication technologies showed that for short-range communication, the WIFI (802.11) or ZigBee cellular communication are suitable, while WiMAX or satellite communication is preferable for covering a large area. However, some problems hindered the successful practical use of UAV control systems, such as limited access to the UAV system, limited resources, real-time control possibility, and reliable connectivity. These problems can be solved by applying SDN and IoT technologies in future research.

Funding information: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest: The authors declare that they have no conflict of interests.

References

- [1] Jawhar I, Mohamed N, Al-Jaroodi J, Agrawal DP, Zhang S. Communication and networking of UAV-based systems: classification and associated architectures. *J Netw Comput Appl.* 2017;84:93–108.
- [2] Hoffer NV, Coopmans C, Jensen AM, Chen Y. A survey and categorization of small low-cost unmanned aerial vehicle system identification. *J Intell Robot Syst.* 2014;74:129–45.
- [3] Gatteschi V, Lamberti F, Paravati G, Sanna A, Demartini C, Lisanti A, et al. New frontiers of delivery services using drones: a prototype system exploiting a quadcopter for autonomous drug shipments. In *2015 IEEE 39th Annual Computer Software and Applications Conference*. Vol. 2. Piscataway: IEEE; 2015. p. 920–7.

- [4] Borsuk GM, Coffey T. Moore's Law: a department of defense perspective (No. 30). Washington, DC: Center for Technology and National Security Policy, National Defense University; 2003.
- [5] Torresan C, Berton A, Carotenuto F, Di Gennaro SF, Gioli B, Matese A, et al. Forestry applications of UAVs in Europe: a review. *Int J Remote Sens.* 2017;38:2427–47.
- [6] Eisenbeiss H. The autonomous mini helicopter: a powerful platform for mobile mapping. *Int Arch Photogramm Remote Sens Spat Inf Sci.* 2008;37(B1):977–83.
- [7] Barr A. Amazon testing delivery by drone, CEO Bezos says. USA: USA TODAY; 2013. Available from: <https://www.usatoday.com/story/tech/2013/12/01/amazon-bezos-drone-delivery/3799021/>. Accessed September 26, 2020.
- [8] Chamberlain P. Drones and journalism. Vol. 4, London: Taylor & Francis; 2017.
- [9] Costa FG, Ueyama J, Braun T, Pessin G, Osório FS, Vargas PA. The use of unmanned aerial vehicles and wireless sensor network in agricultural applications. In 2012 IEEE International Geoscience and Remote Sensing Symposium. Piscataway: IEEE; 2012. p. 5045–8.
- [10] Matese A, Toscano P, Di Gennaro SF, Genesio L, Vaccari FP, Primicerio J, et al. Intercomparison of UAV, aircraft and satellite remote sensing platforms for precision viticulture. *Remote Sens.* 2015;7:2971–90.
- [11] Dockrill P. Facebook is preparing its Internet-beaming drone for maiden launch. Sciencealert; 2016. Available from: <https://www.sciencealert.com/facebook-is-preparing-its-internet-beaming-drone-for-maiden-launch>. Accessed September 26, 2020.
- [12] Wang Y, Zhang MX, Zheng YJ. A hyper-heuristic method for UAV search planning. *International Conference on Swarm Intelligence.* Cham: Springer; 2017. p. 454–64.
- [13] Chaves AN, Cugnasca PS, Jose J. Adaptive search control applied to search and rescue operations using unmanned aerial vehicles (UAVs). *IEEE Lat Am Trans.* 2014;12:1278–83.
- [14] Berrahal S, Kim JH, Rekhis S, Boudriga N, Wilkins D, Acevedo J. Border surveillance monitoring using quadcopter UAV-aided wireless sensor networks. *J Commun Softw Syst.* 2016;12:67–82.
- [15] Mozaffari M, Saad W, Bennis M, Nam YH, Debbah M. A tutorial on UAVs for wireless networks: applications, challenges, and open problems. *IEEE Commun Surv Tutor.* 2019;21:2334–60.
- [16] Koh LP, Wich SA. Dawn of drone ecology: low-cost autonomous aerial vehicles for conservation. *Trop Conserv Sci.* 2012;5:121–32.
- [17] Vermeulen C, Lejeune P, Lisein J, Sawadogo P, Bouche P. Unmanned aerial survey of elephants. *PLoS One.* 2013;8:e54700.
- [18] Sweeney KL, Helker VT, Perryman WL, LeRoï DJ, Fritz LW, Gelatt TS, et al. Flying beneath the clouds at the edge of the world: using a hexacopter to supplement abundance surveys of Steller sea lions (*Eumetopias jubatus*) in Alaska. *J Unmanned Veh Syst.* 2016;4:70–81.
- [19] Goebel ME, Perryman WL, Hinke JT, Krause DJ, Hann NA, Gardner S, et al. A small unmanned aerial system for estimating abundance and size of Antarctic predators. *Polar Biol.* 2015;38(5):619–30.
- [20] Guido G, Gallelli V, Rogano D, Vitale A. Evaluating the accuracy of vehicle tracking data obtained from unmanned aerial vehicles. *Int J Sustain Transp Technol.* 2016;5:136–51.
- [21] Bekmezci I, Sahingoz OK, Temel Ş. Flying ad-hoc networks (FANETs): a survey. *Ad Hoc Netw.* 2013;11:1254–70.
- [22] Walendziuk W, Oldziej D, Binczyk DP, Slowik M. Ground control station software design for micro aerial vehicles. In *Photonics applications in astronomy, communications, industry, and high energy physics experiments 2017*. Vol. 10445. Wilga, Poland: International Society for Optics and Photonics; 2017. p. 1044564.
- [23] Barritt B, Kichkaylo T, Mandke K, Zalcman A, Lin V. Operating a UAV mesh & internet backhaul network using temporospatial SDN. In 2017 IEEE Aerospace Conference. Big Sky, MT, USA: IEEE; 2017. p. 1–7.
- [24] Sharma V, Song F, You I, Chao HC. Efficient management and fast handovers in software defined wireless networks using UAVs. *IEEE Network.* 2017;31(6):78–85.
- [25] Maxa JA, Mahmoud MSB, Larrieu N. Survey on UANET routing protocols and network security challenges. *PKP Publishing Services Network*; 2017. Available from: <https://hal-enac.archives-ouvertes.fr/hal-01465993/document>. Accessed September 26, 2020.
- [26] Li B, Jiang Y, Sun J, Cai L, Wen CY. Development and testing of a two-UAV communication relay system. *Sensors.* 2016;16:1696.
- [27] Gupta L, Jain R, Vaszkun G. Survey of important issues in UAV communication networks. *IEEE Commun Surv Tutor.* 2015;18(2):1123–52.
- [28] Xiong F, Li A, Wang H, Tang L. An SDN-MQTT based communication system for battlefield UAV swarms. *IEEE Commun Mag.* 2019;57(8):41–7.
- [29] Oubbati OS, Lakas A, Zhou F, Güneş M, Lagraa N, Yagoubi MB. Intelligent UAV-assisted routing protocol for urban VANETs. *Comput Commun.* 2017;107:93–111.
- [30] Atoev S, Kwon OJ, Kim CY, Lee SH, Choi YR, Kwon KR. The secure UAV communication link based on OTP encryption technique. In 2019 Eleventh International Conference on Ubiquitous and Future Networks (ICUFN). Zagreb, Croatia: IEEE; 2019. p. 1–3.
- [31] Krichen L, Fourati M, Fourati LC. Communication architecture for unmanned aerial vehicle system. In *International Conference on Ad-Hoc Networks and Wireless.* Cham: Springer; 2018. p. 213–25.

- [32] Bulat PV, Zasukhin ON, Upyrev VV, Silnikov MV, Chernyshov MV. Base pressure oscillations and safety of load launching into orbit. *Acta Astronautica*. 2017;135:150–60.
- [33] Lissandrini N, Michieletto G, Antonello R, Galvan M, Franco A, Cenedese A. Cooperative optimization of UAVs formation visual tracking. *Robotics*. 2019;8:52.
- [34] Zaheer Z, Usmani A, Khan E, Qadeer MA. Aerial surveillance system using UAV. In 2016 Thirteenth International Conference on Wireless and Optical Communications Networks (WOCN). Piscataway: IEEE; 2016. p. 1–7.
- [35] Mission Planner Ground Control Station; 2018. Available from: <https://ardupilot.org/planner/docs/mission-planner-ground-control-station.html>. Accessed September 26, 2020.
- [36] Bulat PV, Volkov KN, Ilyina TY. Interaction of a shock wave with a cloud of particles. *Math Edu*. 2016;11(8):2949–62.
- [37] Schalk LM. Communication links for unmanned aircraft systems in very low-level airspace. In 2017 Integrated Communications, Navigation and Surveillance Conference (ICNS). Piscataway: IEEE; 2017. p. 6B2–1.
- [38] Frew EW, Brown TX. Airborne communication networks for small unmanned aircraft systems. *Proceedings of the IEEE*. 2008;96:10401570.
- [39] Khan MA, Qureshi IM, Khanzada F. A hybrid communication scheme for efficient and low-cost deployment of future flying ad-hoc network (FANET). *Drones*. 2019;3:16.
- [40] Andre T, Hummel KA, Schoellig AP, Yanmaz E, Asadpour M, Bettstetter C, et al. Application-driven design of aerial communication networks. *IEEE Commun Magaz*. 2014;52:129–37.
- [41] Del Arco JC, Alejo D, Arrue BC, Cobano JA, Heredia G, Ollero A. Multi-UAV ground control station for gliding aircraft. In 2015 23rd Mediterranean Conference on Control and Automation (MED). Piscataway: IEEE; 2015. p. 36–43.
- [42] Santos N, Raimundo A, Peres D, Sebastião P, Souto N. Development of a software platform to control squads of unmanned vehicles in real-time. In 2017 International Conference on Unmanned Aircraft Systems (ICUAS). Piscataway: IEEE; 2017. p. 1–5.
- [43] MAVLink. MAVLink common message set; 2020. Available from: <https://mavlink.io/en/messages/common.html>. Accessed September 26, 2020.
- [44] Rivas A, Chamoso P, González-Briones A, Corchado JM. Detection of cattle using drones and convolutional neural networks. *Sensors*. 2018;18:2048.
- [45] Kwon YM, Yu J, Cho BM, Eun Y, Park KJ. Empirical analysis of MAVLink protocol vulnerability for attacking unmanned aerial vehicles. *IEEE Access*. 2018;6:43203–12.
- [46] Ostrikov A, Ospanov A, Vasilenko V, Muslimov N, Timurbekova A, Jumabekova G. Melt flow of biopolymer through the cavities of an extruder die: mathematical modelling. *Math Biosci Eng*. 2019;16(4):2875–905.
- [47] Sánchez-García J, García-Campos JM, Arzamendia M, Reina DG, Toral SL, Gregor D. A survey on unmanned aerial and aquatic vehicle multi-hop networks: wireless communications, evaluation tools and applications. *Comp Commun*. 2018;119:43–65.
- [48] Pareek D. *The business of WiMAX*. New York: John Wiley; 2006.
- [49] Kiran K, Vaishnavi K, Shenoy PD, Venugopal KR. Throughput analysis in an infrastructure-based mesh network using BeeHive algorithm. *Int J Appl Inform Syst*. 2017;11:1–9.
- [50] Šulaj P, Haluška R, Ovseník L, Marchevský S, Pulli P, Kramar V. UAV Management system for the smart city. Piscataway: IEEE; 2018.
- [51] Chaâri R, Ellouze F, Koubâa A, Qureshi B, Pereira N, Youssef H, et al. Cyber-physical systems clouds: a survey. *Comp Networks*. 2016;108:260–78.
- [52] Zhang X, Wang H, Zhao H. An SDN framework for UAV backbone network towards knowledge centric networking. In IEEE INFOCOM 2018-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS). Piscataway: IEEE; 2018. p. 456–61.
- [53] Shaikh Z, Baidya S, Levorato M. Robust multi-path communications for UAVs in the urban IoT. In 2018 IEEE International Conference on Sensing, Communication and Networking (SECON workshops). Piscataway: IEEE; 2018. p. 1–5.