Computer Communications 119 (2018) 43–65

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

A survey on unmanned aerial and aquatic vehicle multi-hop networks: Wireless communications, evaluation tools and applications

J. Sánchez-García[a], J.M. García-Campos[a], M. Arzamendia[a], D.G. Reina[b], S.L. Toral[a,*], D. Gregor[c]

[a] Electronic Engineering Department, University of Seville. Camino de los Descubrimientos S/N, 41092 Seville, Spain
[b] Engineering Department, Loyola Andalucía University, Energía Solar, E, Seville, 41014 Spain
[c] Engineering Faculty of the National University of Asunción (FIUNA), National University of Asuncion (UNA). Campo Vía y, San Antonio, Paraguay

ARTICLE INFO

Keywords:
Unmanned aerial networks
Aquatic networks
Wireless communications
Simulation tools
Bibliometric analysis

ABSTRACT

Unmanned aerial and aquatic vehicle networks have attracted the attention of the wireless communication research community in the last decade. The low manufacturing costs for developing small unmanned vehicles and the notable developments on wireless communication technologies have made possible the design of co-operative applications involving multiple unmanned aerial and aquatic vehicles. However, the design of wireless networks, which include very dynamic and complex entities like unmanned vehicles, poses many challenges. Fortunately, unmanned aerial vehicle networks applications usually resemble those of unmanned aquatic vehicle networks such as military missions, or environmental monitoring among others. With the exception of the obvious differences in the lower layers of the wireless communications protocols, valid approaches used in the aerial medium could be easily adapted to the aquatic medium. This survey presents together the main features to take into account for designing unmanned aerial and aquatic vehicle networks with the aim to help the reader to transfer valid approaches and techniques between aerial and aquatic applications. We survey the results of more than 100 references on this topic published in international conferences and journals, and we also include the results of several bibliometric analyses in order to better present the status of the art and research directions on this scientific area.

1. Introduction

The advances in electronics, robotics, communications and other areas have made a reality the fact of building networks with unmanned vehicles for a variety of applications. On the one side, Unmanned Aerial Vehicle (UAV) networks have experienced a rapid development lately [1–3]. These networks are usually known as Aerial Ad hoc Networks (AANETs) [4]. On the other side, unmanned aquatic vehicles have also attracted the attention of the research community. Unmanned aquatic vehicles, either Unmanned Surface Vehicles (USV) [5] or Unmanned Underwater Vehicles (UUV) [6,5], have been also used to build up networks of unmanned aquatic vehicles. There is not a specific name assigned to unmanned aquatic vehicles, and therefore, we name them after Aquatic Ad hoc Networks (AQNETs) in this paper. Both networks, AANETs and AQNETs follow the ad hoc networking paradigm [10] and that is one of the main reasons for using these names. Some application examples for AANETs and AQNETs are disaster relief operations [4,11,20], detection and tracking of toxic plumes [12], monitoring and surveillance [13,11], logistics [14], agriculture [15], environmental monitoring [16], among others. These applications present complex scenarios with highly dynamic features and it has been demonstrated that multi-robot systems outperform single robot missions in terms of reliability, robustness and efficiency [1,17,21].

Although AANETs and AQNETs belong to different mediums, i.e. the air (AANETs) and the water (AQNETs), it is usual to find related works in the literature using similar approaches when building AANETs and AQNETs applications. Obviously, the main difference between both AANETs and AQNETs comes from the fact that underwater applications cannot use the same wireless technologies as surface AQNETs and AANETs. The main reason is that the communication channel, the water, makes underwater networks to change the technologies used in the lower layers of the communication protocols stack (mainly the physical and MAC layers). However, important features such as routing techniques, vehicles mobility and applications of AANETs and AQNETs may present important similarities. Also, there are multiple scenarios formed by a combination of both AANETs and AQNETs [17].

In this survey, we present AANETs and AQNETs together. The term UAAV network is used for addressing those common characteristics of

---

* Corresponding author.

E-mail addresses: jsanchez73@us.es (J. Sánchez-García), josgarcam@etsi.us.es (J.M. García-Campos), marzamendia@ing.una.py (M. Arzamendia), dgutierrez@uloyola.es (D.G. Reina), storal@us.es (S.L. Toral), dgregor@ing.una.py (D. Gregor).

https://doi.org/10.1016/j.comcom.2018.02.002
Received 12 October 2016; Received in revised form 22 June 2017; Accepted 4 February 2018

Table 1
Summary of existing surveys on AANETs and AQNETs.

Survey	Aerial				Aquatic			
	Network architecture	Wireless comm. and tech.	Evaluation tools	Applications	Network architecture	Wireless comm. and tech.	Evaluation tools	Applications
[1]	Yes	Yes	No	No	No	No	No	No
[2]	Yes	Yes	No	Civil Applications	No	No	No	No
[3]	Yes	Yes	No	Yes	No	No	No	No
[6]	No	No	No	No	Yes	Yes	No	No
[7]	No	No	No	No	Yes	No	No	No
[8]	No	No	No	No	Yes	Yes	No	No
[17]	No	No	No	No	No	No	No	Yes
[18]	Yes	No	No	Disaster Scenarios	No	No	No	No
[19]	Yes	No	Yes (mobility models)	Yes	No	No	No	No

both aerial and aquatic networks. On the contrary, when presenting specific characteristics, which are not shared by both AANETs and AQNETs, the terms AANET or AQNET will be used. In this survey, we review the existing literature organized in the following areas: i) UAAV networks, ii) wireless communications (between node peers and also between a node and a ground base station), iii) evaluation tools (mobility models, simulators, and testbeds), and iv) applications. To the best of the authors' knowledge, this survey covers aspects that have not been reviewed by previous surveys like evaluation tools for UAAV networks. Table 1 shows the most relevant surveys on both AANETs and AQNETs that can be found in the literature. Table 1 shows that previous surveys did not cover simultaneously aerial and aquatic networks, which is an interesting way of transferring knowledge among two related scientific areas. Some surveys focused only on UAVs networks such as [1,3], or [2], while others only focused on aquatic ones [22]. Clearly, there is lack of surveys on evaluation tools like the one presented. Regarding the applications and scenarios, there are some surveys that cover specific scenarios such as civil applications [17] and disaster scenarios [18].

In contrast to previous works, in this survey we provide two main contributions:

- We present together the state of the art of both AANETs and AQNETs, which can be useful for raising awareness about the similarities among these two types of networks, and leverage the fact of applying valid approaches used in AANETs to an AQNETs, or vice versa.
- We present one of the most completed and updated survey on both AANETs and AQNETs, including some aspects that have not been covered deeply such as the evaluation tools and a bibliometric study like the one included in Section 6.

The rest of this paper is organized as follows. Section 2 introduces UAAV networks as multi-hop networks. Section 3 reviews the existing work on wireless communications used in UAAV networks. In Section 4, the evaluation tools available for working with UAAV networks are presented. Section 5 includes the main applications of UAAV networks nowadays. In Section 6, the lessons learned and open challenges regarding UAAV networks are presented. Finally, Section 7 concludes this paper.

2. UAAV networks

One of the main aspects to consider when developing an UAAV network is the networking approach that should be used. Wireless multi-hop ad hoc is a communication paradigm that suits the main requirements of UAAV systems, which are: i) node mobility and ii) adaptive network topologies. This section describes the different wireless multi-hop ad hoc approaches used in UAAV networks and their main characteristics.

2.1. Multi-hop ad hoc networks

The most generic and firstly studied wireless multi-hop ad hoc networks receive the name of Mobile Ad Hoc Networks (MANETs) [22]. MANETs were conceived originally as a way to connect wirelessly different portable devices such as smartphones, laptops, and tablets located close to each other. As an evolution of MANETs, Delay Tolerant Networks (DTNs) [23] are low density networks with very high mobility. DTNs aim to transmit data packets in disconnection-prone environments and with non-guaranteed end-to-end connections. The communication strategy in DTNs is the well-known *store-carry-forward* policy. Under such communication paradigm, when a node receives a message, it keeps the message in memory until it finds a different node to forward the message with. Both aerial and aquatic vehicles can work under sparse connectivity scenarios, where DTN paradigm can be seen an interesting solution to allow communications among nodes. Wireless Sensor Networks (WSNs) [10] are another type of ad hoc networks in which nodes are sensing devices capable of communicating wirelessly. The common architecture in WSNs is characterized by numerous sensing nodes and a small group of higher-capabilities nodes called sinks. The sink nodes are responsible for gathering the sensed data and sending the information to a command station for further processing. However, nowadays sensors are being embedded in mobile robots like aerial and aquatic vehicles. Thus, currently WSNs are starting to have mobile capabilities and dynamic topologies. Furthermore, Wireless Mesh Networks (WMNs) [10] are multi-hop networks designed to extend the Internet connectivity at a lower cost. The nodes in WMNs are called mesh routers. In the first designs, the mobility of mesh routers was considered to be low or inexistent [24]. However, recent WMNs integrate the routers in mobile robots thus having higher mobility [4]. Under some critical circumstances, aerial vehicles have been proposed as wireless mesh routers to provide communication services to ground nodes [25].

The wireless multi-hop ad hoc networks can also be classified according to the type of vehicle that represents the network nodes. Node speed in MANETs ranges from low to medium values as these nodes represent walking people carrying portable devices like smartphones. When referring to ground vehicles, and more specifically to common cars, the term Vehicular Ad Hoc Networks (VANETs) [26] is used. Clearly, autonomous vehicles will need a communication approach that specifically addresses its requirements, and therefore, VANET communications will play an important role in this area. For this aim, specific wireless technologies for vehicular scenarios such as IEEE 802.11p and CALM architecture [27] have been developed.

In the last decade there has been an incredible advancement on the development of smaller and cheaper Unmanned Aerial Vehicles (UAVs), which are also called drones. When UAVs are used to form a wireless multi-robot network they are called Aerial Ad Hoc Networks (AANETs) [28]. AANET nodes have the ability to move at high speeds or, on the

Table 2
Wireless multi-hop network classification.

	MANET/ DTN	WSN	WMN	VANET	AANET	AQNET
Type of vehicle	Person, robot	Things	Things	Car, motorbike	Aerial	Aquatic
Vehicle name	Node	N/A	N/A	Node, car	UAV	Surface: USV, ASV Underwater: AUV, UUV
Mobility	Mainly free	Static	Static	Limited to road layout	Free	Limited (e.g. lakes, rivers) or free (e.g. sea, ocean).
Speed	Low to medium	Static	Static	Low to High	Low (multirotors can hover) to High	Low to High
Main wireless technology	IEEE 802.11	IEEE 802.15.4	IEEE 802.11	IEEE 802.11p	IEEE 802.11 (a, ac, b, n, s…), IEEE 802.15.4	IEEE 802.11, IEEE 802.15.4 Acoustic
Main Application	Generic purpose	Sensing environment	Extending Internet Connectivity	Safety, traffic management, entertainment…	Military, disaster, environmental, construction, agriculture, logistics…	Military, disaster, environmental

contrary, to maintain specific positions when it is needed (e.g. when the UAVs have a helicopter-like architecture). Also, AANETs make advantage of the fact that air-to-air communications usually are less affected by disruptions than ground-to-ground communication links. These advantages make AANETs a very flexible and efficient multi-robot system.

Furthermore, Aquatic Ad Hoc Networks (AQNETs) are networks able to be deployed in aquatic environments. AQNETs can be divided into two main categories: i) surface AQNETs, and ii) underwater AQNETs. In surface AQNETs [29], the nodes only move over the water surface (e.g. robotic boats). Usually, these vehicles are called Unmanned Surface Vehicles (USVs) [30] or Autonomous Surface Vehicles (ASVs) [31]. In underwater AQNETs, the nodes are able to dive and move underwater. These latest are usually called Underwater Wireless Sensor Networks (UWSNs) [21]. Underwater vehicles can be found in the literature under the name of Autonomous Underwater Vehicles (AUVs) [32] or Unmanned Underwater Vehicles (UUVs) [33].

Table 2 shows a classification of wireless multi-hop ad hoc networks, including important features such as type of vehicle, mobility, speed, wireless technology and the main applications for each multi-hop network. These characteristics are described in more detail later on in the paper.

2.2. Aerial vehicle networks

Aerial vehicle networks are multi-hop ad hoc networks in which nodes are UAVs. To refer to these networks the term AANET [4] is normally used. The term FANET (Flying Ad hoc NETwork) can also be found in the literature [3]. There are two main types of UAVs depending on the vehicle architecture: i) fixed-wing and ii) rotary-wing UAVs [34]. Fixed-wing UAVs are airplane-like vehicles (Fig. 1a). These UAVs are characterized for performing Conventional Takeoff and Landing (CTOL) operations like passenger planes. On the contrary, rotary-wing UAVs (Fig. 1b) are able to perform Vertical Takeoff and Landing (VTOL). They can hover in specific locations during flight.

Due to their flying properties, AANETs have the advantage of avoiding most of the obstacles that other terrestrial robots might find on the ground. This characteristic makes AANETs to be less affected by obstacles in many of their applications. Consequently, communication links suffer less from fading, multi-path propagation and other ground-like disturbances [2]. However, there are some applications that may require low altitude flights in difficult scenarios. As an example, assembly and construction applications [35] using UAVs require precise obstacle avoidance strategies in order to perform crash-free flights.

In general, AANETs are based on communication links established among UAVs and other links with other higher level networks and/or ground base stations or command centers (Fig. 2). Therefore, it is common to find UAVs-to-ground communication links in order to transmit data from the AANET nodes to ground stations and vice versa. For example, in disaster relief operations, the AANET is usually controlled from a ground station such as the mission control center mentioned in [12]. When we refer to a control or command base station, it is important to clarify that we focus on networks consisting of unmanned vehicles, thus the kind of commands that may appear in these applications are high-level. An example would be a “come-back-home” command, for making the unmanned vehicles return to their mission ground base station. UAVs may also establish links with satellites. Global Navigation Satellite Systems (GNSS), such as American Global Positioning System (GPS) or the European Galileo [36], can be considered the simplest satellite centralized system used in AANETs. In other cases, satellites act as relay nodes controlling the UAV mission in a centralized manner [37]. This is a common approach when there is a need for transmitting the information collected by the AANET to a ground command station located far apart. A generic application

a) E500 fixed-wing UAV by ELIMCO
(©ELIMCO SOLUCIONES INTEGRALES S.A.)

b) Rotary-wing UAV used by ACE-TI research group (University of Seville)

Fig. 1. Examples of fixed-wing and rotary-wing UAVs.

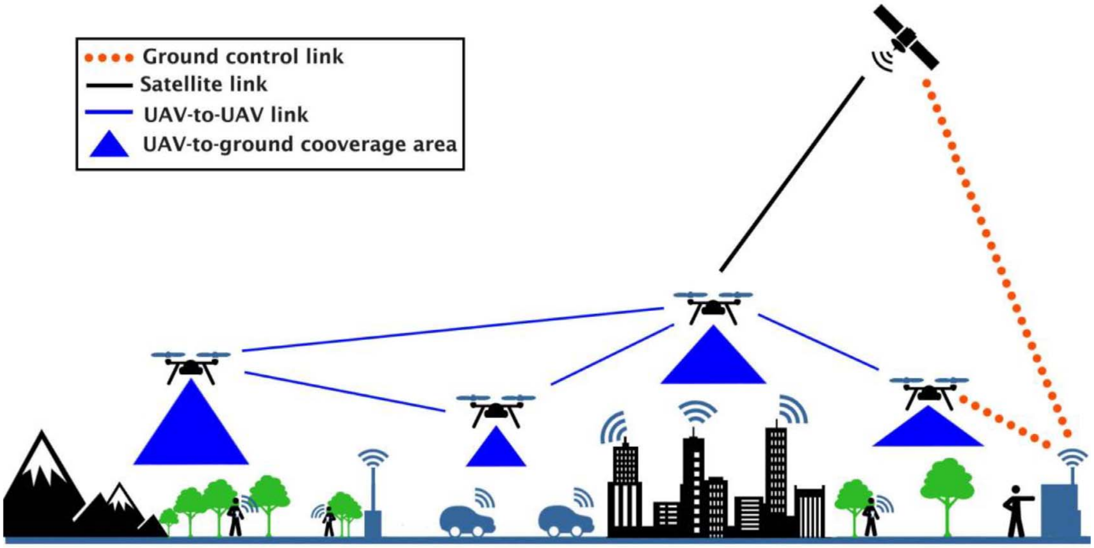

Fig. 2. A potential application scenario for an AANET.

scenario for an AANET is depicted in Fig. 2.

Due to the ad hoc nature of AANETs, the topology of the network may change over time. Also, AANETs can consist on different types of UAVs organized in different hierarchies [3]. For example, in an AANET, a sub-group of UAVs may be equipped for long range communications in order to communicate with external networks. Another sub-group of UAVs may be focused in sensing tasks, thus carrying specific sensors. The latest would share the sensed information with their equals within the sub-group, but they also can send the information to long-range communication capable UAVs for them to forward the data to reach external networks. This flexibility, in terms of topology and hierarchy, allows AANETs to adapt to very different applications.

2.3. Aquatic vehicle networks

Aquatic vehicle networks (AQNETs) are multi-hop networks that are formed by aquatic nodes. Differently from the AANETs, aquatic networks are mainly composed of two clearly different groups of vehicles, the Unmanned Underwater Vehicles (UUVs) and the Unmanned Surface Vehicles (USVs). Although these vehicles are in condition to operate as standalone, they can cooperate in a work team, in which the tasks are analogous to the hierarchy mentioned in the previous section. For instance, UUVs are more oriented to sensing and relaying data, and ASV can act as gateway to reach long range communications with the ground center.

Fig. 3a shows an example of an UUV, the GUANAY II [5,9] developed by the Polytechnic University of Catalonia, which has the capability of navigating in the surface like an USV. However, at certain points the GUANAY II is able to dive vertically to obtain a profile of a water column. On the right side of Fig. 3, the ROAZ-II [5] is shown, an USV developed by the School of Engineering of the Polytechnic of Porto. It is based on a catamaran, which is the most common type of USV found in the literature due to its stability. Additional types are based on kayak or trimaran architectures. A good summary of USV prototypes can be found in [38].

2.3.1. Underwater vehicle networks

The main objective of the UUV based networks is to perform surveillance and monitoring tasks. The development of this is plenty justified by the fact that 71% of the earth is covered by oceans [39] and that three out of four people on earth depends on surface water for their survival [40]. The UUV is focused on expanding the functionalities of ROV (Remote Operated Vehicles), which are high-cost tethered vehicles. It is the most straightforward way to implement certain underwater tasks, because the ROV does not require an intelligence to carry out the tasks, instead it is controlled by a tele-operator. However, the ROV applications are limited. The UUV has advantages over the ROV. It does not have a single-point of failure like the ROV, which is the cable that connects with the tele-operator. In case of damage of this cable, the vehicle might be lost. Additionally, swarms of UUVs are investigated to perform tasks better and faster when the exploration area is vast [41]. In order to achieve their target objectives in a distributed fashion, coordination between the nodes of the network is required.

Regarding the wireless technology used to exchange information, RF (radio frequency) communication is not an option for underwater environments due to the electromagnetic absorption of the aqueous medium. Consequently, acoustic communication is used for underwater scenarios. However, underwater acoustic channels suffer from large propagation delay, limited available bandwidth, and high error probability. The acoustic signal propagation speed in underwater environments is five orders of magnitude lower than the radio propagation speed (3×10^8 m/s vs. 1.5×10^3 m/s), and most acoustic systems operate below 30 kHz [21]. The frequency band is very narrow, with a maximum reported of 1 MHz at the range of 60 m. Also, the link capacity is very variable and with a short-range system operating over several tens of meters it may have several tens of kbps [42]. Consequently, acoustic technology is a limitation when compared with wireless links used in UAV applications.

Another alternative to acoustic communications in underwater environments is shown in [43]. Considering that no single underwater communication system is currently capable of achieving good performance in all the communication aspects such as transmission range and bandwidth, among others; they present the CoCoro Lily robot, which is equipped with multiple communication systems. For global communications, an Omni-directional low-bandwidth SONAR system is used. And for local communications, a directional high-bandwidth blue light system, which is a pair of high-power blue LED (Light Emitting Diode) and a photodiode that uses the same modulation of IrDA (Infrared Data Association). In addition, it uses a RF system for short distance underwater communication or for air links.

2.3.2. Surface vehicle networks

Considering that an UUV needs in some degree a remote command center, which most probably is not underwater, a conversion of the

a) GUANAY-II UUV

b) ROAZ-II USV

Fig. 3. Examples of a UUV (a) and a USV (b).

communications technologies between the two mediums (water and air) is required. An USV may provide support by operating as a gateway between these two mediums. For example, in [44] the authors describe the research of real-time cooperative localization of multiple autonomous underwater vehicles by using undersea acoustic modems. Tests involving two USVs and an UUV demonstrate the successful data transfers from the USVs to the UUV. Other implementation examples are described in [46], where they use a USV based on the LiquidRobotics Wave Glider SV2 that extends the capabilities of a REMUS UUV. In [46], functionalities such as data caching, link discovery, monitoring acoustic communication link performance, acoustic modem rate, among others, are verified. In [50], the authors also describe field experiments between an UAV and an UUV (REMUS 100) being both at the surface. The design of the communication relay payload, network configuration, optimal flight conditions and UAV antenna mounting, and other experimental results are presented. The tests are carried out under no ideal conditions, and the main limitation identified is the low capacity of the wireless system of the UUV. Finally, in [22] the authors describe the case of using a USV as a coordination station between the Command Center (CC) and an UUV. This allows the use of cheaper technologies based on UMTS (Universal Mobile Telecommunications System) and Wi-Fi protocols instead of satellite communications. Being a gateway is not the only function that USVs can provide to UUVs. GPS it is not available underwater, so an USV can act as a reference for a swarm of UUVs. This is described in [51], where a swam of UUVs named MONSUN II is presented, and one of the vehicles stays at the surface for saving energy purposes and for acting as a relay between the GPS satellites and the submerged vehicles.

USVs can also operate in groups as the UUVs. However, the movement is limited to a 2D plane, i.e. the water surface. They can interact with static buoys, like the study presented in [52] where they propose the USV SCOUT to operate as a self-position buoy, with the ability to track mobile or periodic events. They suggest a heterogeneous network with moored buoys that offers some advantages such as rough weather resistance, large power storage capacity, and reliable communications to and from land-base stations. Particularly, they recommend a single moored buoyed acting as a dock for multiple low-cost mobile vehicles. Whenever the USVs are off the dock, they recommend the use of the DTN paradigm as the communication model between the mobile vehicles. DTNs are adequate for the use in maritime environment since they are used in noisy and loss-prone scenarios. The DTN-based approach operates as a network overlay, meaning that it can provide data forwarding service over heterogeneous networks, and uses persistent storage available in the network to store data while the destination network is not available. Another hybrid network is described in [40], where they describe the architecture called MARTA (Multilevel Autonomy Robot Tele-supervision Architecture). MARTA is an example of architecture for supervisory control of a heterogeneous fleet of networked USV vessels with environmental sensor capabilities. In [40], the heterogeneous fleet consists of two types of vehicles. One named OASIS (Ocean Atmosphere Sensor Integration Systems), which is a long duration solar-powered USV. The second is the RSB (Robotic Sensor Board), which is a smaller and relatively inexpensive USV. Another work that investigates a fleet of USV is shown in [53], where the authors present the CORATAM and HANCAD projects, which focus on the fundamental challenges related to communication and control of USV swarms. They propose the adoption of a heterogeneous communication system and the use of decentralized control to facilitate robustness and scalability. This allows keeping the USVs simple and inexpensive.

3. Wireless communications in UAAV networks

Wireless communication technologies are the cornerstone of UAAV networks. These technologies enable the cooperation between aerial and/or aquatic robots. Depending on the specific application for which UAAV networks are implemented, the wireless technologies used may vary. Also, these technologies may be different depending on the wireless channel characteristics. The communication channel is not equal when the link is established between two UAAV in the same environment, e.g. two UAVs in the air; or between an UAV and a ground node, e.g. between an UAV and a ground command station. We provide in this section a description of the most important wireless technologies used, organized according to the channel characteristics.

3.1. *UAAV–UAAV communications*

We refer to UAAV–UAAV communications as the wireless communication links established between two UAAVs network vehicles, for example, between two UAVs forming an AANET, or two unmanned aquatic vehicles forming an AQNET. As we are considering unmanned aerial and aquatic vehicles, we classify the UAAV-UAAV communications in two main groups: i) AANET communications, and ii) AQNET communications. There may be applications in which an AANET communicates with an AQNET.

3.1.1. *AANET communications*

The most common wireless technologies used for UAV–UAV communication links are IEEE 802.11 standards, IEEE 802.115.4 communications and infrared technologies, among others.

IEEE 802.11 communications: IEEE 802.11 is a family of standard protocols defined by the Institute of Electrical and Electronics Engineers (IEEE) [59] . IEEE 802.11 standards, commonly known as Wi-Fi, define the specifications for creating Wireless Local Area Networks (WLANs). This standard family consists of several versions, some of which have been used widely for AANETs. The first versions of IEEE 802.11 standards, such as IEEE 802.11b, are mainly aiming at static scenarios, i.e. where the network nodes have a very low or inexistent mobility. An example of this situation is a desktop computer connecting to a fixed Wi-Fi access point. With time, new versions of IEEE 802.11 family appeared such as IEEE 802.11a, IEEE 802.11g, IEEE 802.11n, and IEEE 802.11ac [59]. With the increase of IEEE 802.11 compliant portable devices, such as smartphones, some of these versions started to consider higher mobility nodes. Examples of these mobility-aware standard versions are IEEE802.11a and IEEE 802.11p. This situation favored the usage of IEEE 802.11 technologies in AANETs.

In [55], IEEE 802.11ac and IEEE 802.11n standards are studied as wireless technologies for communicating several UAVs with each other, and also with ground base stations. IEEE 802.11n is studied in previous works such as [56,57]. These works provide results of IEEE 802.11n performance in terms of throughput and transmission range. However, the work developed in [55] demonstrates that IEEE 802.11n can reach higher throughput, possibly due to the usage of an optimized omnidirectional antenna consisting on three dipole antennas forming an equilateral triangle [60]. This new results about IEEE 802.11n performance are based on experimental analyses for both single-hop (i.e. infrastructure) and multi-hop (i.e. mesh) configurations. Several configurations are tested: i) direct communications between one UAV and the ground station, ii) one UAV acting as a bridge (access point) between another UAV and the ground station, and iii) two UAVs and a ground station, being all of them nodes of a mesh network. For the IEEE 802.11n mesh configuration, the standard IEEE 802.11s mesh implementation is used. IEEE 802.11s is a standard amendment that extends the lower layers of other IEEE 802.11 versions in order to support mesh topology configurations. Regarding IEEE 802.11ac, [55] is probably the first implementation of this technology in UAV networks. This technology shows higher data rates and a better throughput in comparison with IEEE 802.11n for indoor scenarios. In outdoor scenarios, with higher mobility characteristics, IEEE 802.11ac shows a considerable decrease in throughput in the case of the UAVs moving away from the base station. Thus, the need for further research on the usage of IEEE 802.11ac in AANETs is highlighted in [55].

In [61], the IEEE 802.11b standard is used in an AANET. Two main scenarios are tested. In the first one, UAVs are used to connect two disconnected halves of a ground network. In the second scenario, the UAVs create an AANET for providing communications from a ground base station to far locations. This means that the AANET creates a multi-hop ad hoc network through relaying operations. The IEEE 802.11b standard is used in both scenarios and all the nodes in the network use the same mesh network radio, either they are ground nodes or aerial ones. Six experiments are designed and run in each of the scenarios, these are: i) throughput, ii) connectivity, iii) network congestion, iv) quality of service perceived by the user, v) node failure, and vi) range. These experiments, together with the two scenarios, provide a comprehensive study of IEEE 802.11b communications used in UAV networks. Therefore, the results included in [61] highlight that the performance of the network highly depends on factors such as the specific scenario, the UAVs location with respect to other UAVs and ground nodes, and the antennas used, among others.

In [62], a network made of UAVs is used to provide connectivity to end systems located far from each other. The UAVs establish a wireless mesh network acting as ground node relays. The UAVs have two wireless interfaces. The first one is implemented by using IEEE 802.11s where each node acts as an access point. This interface is used for connecting UAVs to each other. The second interface is implemented with IEEE 802.11g and allows the ground nodes to connect to the UAVs. Two scenarios are described in [62]: i) an airborne relay scenario with a single UAV, and ii) an airborne relay scenario with multiple UAVs. The UAVs have also the capability of finding the ground nodes that need to establish a communication link.

In [58], the IEEE 802.11a standard is used to carry out a performance analysis in terms of throughput and link quality. The IEEE 802.11a family works in the 5.2 GHz band and the aim is to reach higher data rates and lower interference with respect to IEEE 802.11b/g. In [58], the network is composed of two UAVs and one ground base station. Several configurations are tested in a similar way as in [55]: i) infrastructure (one UAV acts as an access point bridge between another UAV and the ground station), ii) and mesh (where two UAVs and the ground station are mesh nodes). All the experiments are carried out in an outdoor scenario. A single-hop configuration is used as a reference for comparison purposes. When comparing the access point and the mesh setup, the results show that the mesh configuration uses the direct link between the UAVs and the ground station as far as it is available. This means that when an UAV gets separated from the ground station and the direct link is still available but intermittent, the mesh configuration will prefer the direct link over the two-hop path, thus causing lower throughput. This is due to the fact that the mesh configuration, which is implemented by using IEEE 802.11s, prefers available paths with fewer hops, no matter the throughput or the link quality. In this situation, the two-hop with the infrastructure (access point UAV) configuration performs better in terms of throughput. In Table 3, a summary of the different wireless technologies used in AANETs are presented.

IEEE 802.15.4 communications: IEEE 802.15.4 is a standard that defines the lower layers of Wireless Personal Area Networks (WPANs). Specifically, IEEE 802.15.4 focuses on low rate networks, which are closely related to WSNs. Some well-known technologies such as ZigBee [63] use this standard to build WSN applications. Also, XBee [64] is a commercial implementation similar to ZigBee and also based on IEEE 802.15.4 standard. As an example, in [54] an aerial network uses the IEEE 802.15.4 standard. Five UAVs are used as sensing devices, thus the network can be considered an aerial WSN. The UAVs are equipped with XBee Pro ZigBee class 2.4 GHz radios. Several experiments are carried out in order to characterize the wireless communications based on IEEE 802.15.4. Among these experiments, the metrics measured are the Received Signal Strength Indicator (RSSI), the path information, the packet loss and the throughput. The main idea behind is to understand the wireless network built among UAVs in order to control their mobility. This will allow carrying out specific missions, such as taking measurements of gases concentrations in the air or measuring weather conditions in a specific area. In order to understand the metrics, the effect of several parameters on the RSSI is studied, being the most important ones: i) distance (path loss), and ii) antenna orientation. Also, a thorough characterization of the packet loss is carried out.

The main issue for the use of IEEE 802.15.4 standard in an AANET is its low data rate. This communication technology is intended for WSNs that are normally focused on saving energy consumption. Also, this technology's transmission range is generally in the order of tens of meters up to 100 m, which can be considered a limitation for applications that need the UAVs performing tasks separated by higher distances. For this reason, the IEEE 802.15.4 technology can be used only for applications in which the UAVs are separated from each other by distances below 100 m.

Infrared communications: Infrared wireless communications [65] were one of the first optical communications used widely. They present some important advantages: i) they are low cost communication systems, ii) the infrared spectral band is unregulated worldwide (which may enable international compatibility), iii) per-link bit rate and aggregate system capacity may be maximized in comparison with radio frequency technologies. Also, there are several disadvantages such as: i) the inability to penetrate opaque objects (e.g. walls), ii) the existence of many sources of thermal noise (such as the sunlight, lighting devices, etc.), and iii) the need for employing high transmission power. The Infrared Data Association (IrDA) [66] is an organism that has standardized several communication systems based on infrared light.

Infrared communications have been widely used for multi-robot navigation systems. As an example, in [67] a communication based

Table 3
Technologies used in communications for AANETs and AQNETs.

Network	Technology	Ref.	Communication device	Computing platform	Usage
AANET	IEEE 802.11s	[62]	OM1P from Open-Mesh[a](universal 802.11b/g interface)	PC Engines Alix boards[b]	- Connect separated ground nodes multi-hop relaying mesh network
	IEEE 802.11b	[61]	- 2.4 GHz 802.11b card Fidelity-Comtech bidirectional amplifier	Soekris single board computer	- UAVs and ground nodes in several configurations ○connecting ground nodes multi-hop mesh network
	IEEE 802.11n	[55]	Compex WLE300NX 802.11abgn mini-PCIe	Intel Atom 1.6 GHz CPU with 1 GB RAM	- AANET single-hop and two hop performance analysis with the ground station ○Infrastructure Mesh
	IEEE 802.11ac	[55]	- Compex WLE900N5-18 miniPCIe Doodle Labs ACM–5500–1 802.11ac 5 GHz miniPCIe		
	IEEE 802.11a	[58]	Compex WLE300NX 802.11abgn mini-PCIe modules	Intel Atom 1.6 GHz CPU with 1 GB RAM	- Two hop analysis - Infrastructure and mesh configurations Connections with the ground station
	IEEE 802.15.4	[54]	XBee Pro Zigbee class 2.4 GHz radios (Maxstream)	CUPIC avionics board (Microchip PIC18F8722 8-bit)	- Generic monitoring tasks: ○Temperature ○Gases Other
	Infrared	[35]	VICON system[c]	Intel Atom Processor Z530	Collaborative assembly and construction tasks
AQNET	IEEE 802.15.4	[29]	- XBee DigiMesh 2.4	- Raspberry Pi 2 mod. B	- Generic monitoring tasks: ○Sea-border patrolling ○Environmental monitoring
	IEEE 802.11g	[11]	- TP-Link TL-WN722N high-gain 150 Mbps wireless dongle	- Raspberry Pi 2 mod. B	- Environmental monitoring
		[74]	- Not specified. Communications equipment integrated in the following UUVs: ○GaviaDefence (by GaviaDefence) ○Iver2 (by OceanServer) ○LAUV SeaCon ○Isurus (REMUS class UUV)	- Not specified	- Various tasks: ○Mine-warfare ○Environmental assessment
	RF	[77]	- 3 different RF modems: ○FGR-115RCFreeWave ○XTend-PKG-UMaxStream ○EH900 Nova Engineering	- Laptops running Fedora Core 5 Linux	- Performance analysis of RF modems
	SONAR	[72]	- Generic SONAR system (simulation)	- Not specified	- Networking protocols and standards experimentation
		[73]	- Benthos ATM-885 acoustic modem	- PC-104 system with a 100 MHz ZFx86 CPU - Slackware Linux OS	- Simulation experimentation - Generic monitoring tasks: ○Path planning ○Area monitoring
		[74]	- Not specified. Communications equipment integrated in the following UUVs: ○GaviaDefence (by GaviaDefence[d]) ○Iver2 (by OceanServer[e]) ○LAUV SeaCon ○Isurus (REMUS class UUV)	- Not specified	- Main tasks: ○Mine-warfare ○Environmental assessment

[a] http://www.open-mesh.com/index.php/professional/professional-mini-router-usplugs.html.
[b] http://www.pcengines.ch/.
[c] http://www.vicon.com/.
[d] http://www.teledynegavia.com/product_dashboard/auvs.
[e] http://www.iver-auv.com/index.html.

navigation algorithm for a ground robotics swarm is presented. An infrared range-and-bearing (IrRB) communication system is implemented, for the robot-to-robot communication links. Regarding aerial robots, infrared communications are normally used for indoor positioning of UAVs. In [35], a group of 2–5 UAVs performs assembly and construction tasks in an indoor environment. Each UAV has several infrared passive markers stuck in different points of its frame. A system of 20 VICON infrared cameras is used to detect the position and heading of each UAV. This information is then fed to a central controller which calculates and controls the trajectories of each UAV. Although the UAVs are passive in this communication system, the infrared technology makes possible the indoor navigation of UAVs. Other UAV applications use infrared cameras in order to acquire thermal-infrared imaging of areas of interest [68,69].

Infrared communications are commonly used as sensing devices rather than a communication technology for multi-robot systems. However, indoor scenarios have been highlighted as proper spaces for using infrared communication technologies [65]. It is also known that UAV networks have important applications in indoor environments, such as the one described in [35,70]. Notice that GPS-based systems are not suitable for indoor scenarios. For this reason, the usage of infrared communication technologies for indoor UAVs networks is yet a potential research line to explore.

3.1.2. AQNET communications

Communications for aquatic networks may be divided into two different groups such as i) USV–USV communications, and ii) UUV–UUV communications. Communications between the surface and the underwater environment is also possible, i.e. USVs to UUVs communication links area also usual. These communications can be carried out by gateway-like nodes [71], such as buoys or vehicles equipped with transceivers suited for both underwater and air communications. Other approaches to connect underwater and surface aquatic networks were already mentioned in Section 2.3.2. In this section, we describe the communications used in AQNET networks according to the different technologies used. These technologies are strongly dependent on the communication medium and thus we will highlight that feature in the description provided.

It is also important to mention that the majority of AQNETs are aquatic WSNs. The reason for this is that most of the applications are related to sensing different variables or processes for different purposes. AQNET applications are classified into two main groups [29]: i) monitoring, and ii) mission-oriented applications. Examples of monitoring applications are sea-border patrolling, environmental monitoring (e.g. temperature, pH, water depth, salinity, etc.) and water movement tracking, among others. Examples of mission-oriented applications are marine oil spill clean-up, or search and rescue. As almost all AQNET applications are considered as WSNs, the amount of data to be transmitted over the network is not very high, i.e. a data rate of 250 kbps offered by XBee and ZigBee may be enough in most situations [29]. It is not the case of AANETs, which in some applications need higher data rates for transmitting high resolution images or video to other UAVs or to a ground/surface base station. We focus in this section on the communication among aquatic vehicles, commonly called short-range communications. The main characteristics of these communications are summarized in Table 3.

Acoustic communications: Underwater communications present some specific characteristics to consider when designing UUV networks. The water, as a communication channel, presents different features in comparison to the air. The most common signals used for underwater communications are acoustic waves. Underwater acoustic communications are also known as Sound Navigation and Ranging (SONAR). Although SONAR is widely used, it is important to highlight that this communication is affected by large propagation delays and high bit error rate [39]. Also, SONAR communication cannot be used for crossing the interface water-air [71].

The Woods Hole Oceanographic Institution (WHOI) has developed an acoustic micro-modem that can be found in different works such as [45,46] and [47]. The device has the capability of performing low-rate frequency-hopping, frequency shift keying (FH-FSK) in five different bands, and variable rate phase-coherent keying (PSK). Field tests have shown that a maximum range of 11 kms has been achieved with a data rate of 208 bps in a 2000 Hz channel bandwidth. On the other hand, a maximum data rate of 5380 bps has been achieved with a 5000 kHz for a 4 kms range [48]. One way to improve the underwater acoustic operation is by using multi-hop communications, like the ones described in [47]. An architecture named CAPTURE (Communications Architecture that delivers arbitrary science data using Progressive Transmission, via multiple Underwater Relays and Eavesdropping) provides end-to-end communications for compressed scientific data and supports multi-hop communications through underwater acoustic relays.

SONAR communication systems may be: i) passive, and ii) active. Passive SONAR systems are only capable of receiving acoustic waves. On the contrary, active SONAR systems are able to send and receive acoustic waves. Usual frequency ranges for SONAR applications are from 50 Hz up to 20 kHz, which are audible frequencies to the human. Some SONAR applications may use higher frequencies reaching up to several MHz [71]. Also, for deep under water communication Extremely Low Frequency (ELF) waves are used, reaching to frequencies in the order of tens of Hz. However, powerful SONAR waves in the ELF band used during long time periods may cause harm to the underwater life.

In [72], a group of UUVs is used for building an underwater ad hoc network. The UUVs use acoustic communication devices, i.e. SONAR for communicating with each other. The aim is to create a simulation environment for testing real underwater missions, i.e. search and survey applications. Specifically, the potential application considered is to perform data collection tasks over an area of interest. This application is very similar to the usage of fleets of UUVs for locating the sunken black boxes of crashed airplanes. A follow-up of [72] is presented in [73]. Specifically, in [73] several UUVs are tested in real water scenarios. The UUVs used are equipped with a FreeWave RF modem, a Benthos ATM-855 acoustic modem and an Iridium satellite modem. The acoustic modem is used for the communication among the UUVs when they are underwater. The RF and satellite modems are used for exchanging information between the UUVs and buoys, or other surface or ground stations, when the UUVs are on the water surface.

In [74], a group of 9 autonomous UUVs of four different types are deployed on real water conditions. The aim is to develop mission planning and inter-communication experiments with this set of heterogeneous UUVs. The experiments are designed to demonstrate the feasibility of using a network of UUVs in mine-warfare and rapid environmental assessment missions. All the UUVs are equipped with acoustic modems for underwater communications, and also with IEEE 802.11g devices for communicating when they are on the water surface. Some of them also have HSDPA/GSM compliant devices and satellite transceivers (e.g. Iridium). Several buoys acting as gateways for communicating the underwater vehicles with surface nodes are also used. The findings of the experiments show that integrating heterogeneous UUVs in mission oriented networks is not a trivial task. The success of this type of missions highly depends on the development of inter-operable standards, for communicating different UUVs more efficiently.

Electromagnetic communications: USVs usually use the same wireless communication technologies as those used in AANETs. The reason is that the communication channel is also the air. However, there are some specific characteristics that may be taken into account in water surface communications. For example, in AANETs, as UAVs are usually flying between 50 up to 120 m from the ground, wireless signal reflections with the ground may be disregarded. However, in water surface communications, the signal reflection on the water surface cannot be disregarded so easily.

In [29], a set of USVs are used as a platform for analyzing the wireless communication capabilities of surface AQNETs. This is part of the HANCAD project [75], which stands for “Heterogeneous Ad-hoc Network for the Coordination of Aquatic Drones”. Each USV has short-range communication devices, but only a few of them have long-range communication devices. Short-range communications are used for coordination tasks among the USVs. Long-range communications are used for establishing communication links with ground stations, i.e. acting as gateways. The scenarios considered for this project are two: i) a set of buoys with long-range communication capabilities acting as gateways to the base station, and ii) a set of buoys with short-range

Table 4
Routing algorithms used in UAAV networks.

Network		Type	Routing protocol		Technology	References
Aerial		Broadcasting	Flooding		IEEE 802.15.4	[54]
		Proactive	OLSR	Pure OLSR	IEEE 802.11n	[87,85]
				P-OLSR	IEEE 802.11n	[85]
			BATMAN		IEEE 802.11n	[87]
			GPSR	Pure GPSR	IEEE 802.11a	[88]
				MPGR		
		Reactive	AODV	HWMP	IEEE 802.11s	[55,58]
				Pure AODV	IEEE 802.11n	[87]
				RGR	IEEE 802.11	[90]
			GGF		IEEE 802.11	[90]
			DSR		IEEE 802.11b	[61]
		Geographic	Greedy Geographical Routing		IEEE 802.11n	[87]
			A-GR		IEEE 802.11	[92]
		Not specified	Not specified		IEEE 802.11g	[62]
Aquatic	Surface	Static	Static		RF 900 MHz ISM	[77]
		Broadcasting	–		IEEE 802.11g	[11]
		Reactive	AODV	Pure AODV	RF 900 MHz ISM	[77]
				DigiMesh	IEEE 802.15.4	[29]
		Not specified	Not specified		IEEE 802.11g	[53]
	Underwater	Reactive	DSR		SONAR	[72]
			QUELAR		SONAR	[93]
		Not specified	Not specified		SONAR	[73]

communication devices and autonomous and mobile vessels with long-range communication devices. In this second scenario, the objective consists of gathering information from the buoys and sending it to the base station. Although for short-range communications Wi-Fi is mentioned, this work's preliminary results have been obtained using IEEE 802.15.4, specifically using XBee.

In [11], a complete design of a small USV is provided. Ten units of this USV are produced in order to create a swarm. The main aim is to carry out experiments with different swarm controllers. These experiments consist of validating several common features of swarms: i) homing, ii) dispersion, iii) clustering, and iv) area monitoring. The testing scenario is a real aquatic scenario, which presents the characteristics of uncontrolled events. Evolutionary algorithms [76] are used in order to synthetize controllers for the USV based swarm. After the evolution process of the controllers, the best ones are selected and tested in real aquatic scenarios. For this purpose, a reliable short-range communication infrastructure is needed for establishing collaboration between the USVs. The communication technology selected is the IEEE 802.11g standard.

A similar approach to [11] is described in [53], where a swarm of USVs is designed and developed as a platform for studying communications and control strategies. Regarding the communications strategies, the IEEE 802.11g standard is also used. This work emphasizes that it is necessary to provide the communications software in this platform with capabilities for taking into account signal reflections on the water. In [77], three different RF modems are analyzed for communicating several UUVs. The communication is established when the UUVs have surfaced, thus the communication medium is the air. The modems work in the 900 MHz ISM (Industrial, Scientific and Medical) frequency band. The tree modems tested are the FGR-115RC of FreeWave Technologies, the XTend-PKG-U of MaxStream and the EH900 of NovaRoam Engineering.

Underwater electromagnetic communication is also possible, although the water medium is not the most appropriate for electromagnetic waves to propagate [71]. The advantage of electromagnetic waves is that these can cross the water–air medium without an intermediate node, e.g. a gateway buoy acting as a relay. For example, electromagnetic waves in the ELF band are used for establishing communications with submerged submarines. ELF radio waves are able to propagate under seawater, thus reaching submarines [78]. The problem of this technology is that the antenna size needed for communicating in the ELF band is very large. Other frequencies up to the Very High Frequency (VHF) band can be used, but they present other limitations, for example the signal attenuation [79] or the risk to reveal the submarine location to enemies [80]. This communication technology has been used mostly in military applications and usually for communicating submarines with a surface or ground base station. Thus, this is not commonly used for communicating submarines with each other. Also, the antenna limitations aforementioned do not allow using them in small UUVs. Therefore, for the UUV–UUV communication underwater links, SONAR technology is normally used. When the UUVs are on the water surface or the communication is established among USVs, electromagnetic waves are used.

Next, Table 3 shows a summary of the wireless technologies used in both AANETs and AQNETs.

3.1.3. Routing in UAAV–UAAV networks

Routing protocols can be organized according to different aspects. A first category can be defined for broadcasting protocols, which are those in which every single node in the network must receive a given packet sent by a source node. Also, when routing protocols aim is to guarantee that a packet sent by a source node reaches a single destination node, one of the most common classifications define two main categories [1] such as proactive protocols and reactive ones. Also, a third category could be added to this classification, including the geographical-based protocols [1], which route packets upon geographical information of neighbor nodes. In order to compare the performance of routing protocols designed for ad hoc networks, some works on this topic include static protocols (from fixed-infrastructure networks) as a reference.

Usually, each research work on UAAV networks uses a different routing protocol. The protocol used is usually selected due to its chances to perform properly in the scenario application designed. Normally, the most common routing protocols used for ad hoc networks are the ones that appear more frequently in the literature [26,81,82]. However, several efforts are being put on the development of new routing protocols specifically suited for UAAV networks [53,55,58,73]. A summary of the most common routing protocols used in UAAV networks is shown in Table 4.

Regarding routing in AANETs, in [55], a mesh network is built among UAVs and also a base station located on the ground. For building the mesh network, the IEEE 802.11s implementation is used. For routing purposes, the IEEE 802.11s standard uses the Hybrid Wireless Mesh Protocol (HWMP) [83]. HWMP is a variant of the well-known Ad hoc On-demand Distance Vector routing protocol (AODV) [84]. The same routing protocol is used in [58]. In both [55] and [58], the authors highlight the need for developing new routing protocols for UAAV networks that take into account throughput, link quality and other metrics for selecting the routing path. The reason for this is that IEEE 802.11s mesh implementation favors fewer hops paths without taking into account the link quality. In [85] two different routing protocols are tested and compared: Optimized Link State Routing (OLSR) and Predictive-OLSR (P-OLSR). P-OLSR takes advantage of the UAVs position information in order to estimate the links quality evolution. In addition, P-OLSR is presented as a routing protocol exclusively designed for AANETs.

In [61], the routing protocol used is Dynamic Source Routing (DSR) [86] among all the network nodes, which are both aerial and ground nodes. In [61], DSR is used together with IEEE 802.11b standard. The work described in [62] does not use any specific routing protocol. Instead of that, this work is intended for becoming a platform for testing different routing protocols in UAV networks. This work uses the IEEE 802.11s standard. In [54], an aerial network consisting of 5 UAVs uses the IEEE 802.15.4 standard. The UAVs, which are equipped with XBee Pro ZigBee class 2.4 GHz radios, have the default routing protocol for ZigBee disabled. A flooding-like protocol is used instead in order to perform several experiments over the wireless links. In [87], different routing protocols are tested in an experiment with two UAVs and a ground base station. The routing protocols studied are AODV, OLSR, and Better Approach To Mobile Ad hoc Networking (BATMAN) [95]. The BATMAN protocol outperforms AODV and OLSR in terms of throughput. However, OLSR is very close to the throughput reached by BATMAN. It is important to highlight that BATMAN produces much more routing overhead than the others. BATMAN is also compared with an implementation of the greedy geographical routing scheme. The results showed that the geo-routing solution implemented in [87] is better than BATMAN most of the times.

In [88], the authors proposed Mobility Prediction based Geographic Routing (MPGR). This is a routing algorithm for UAV-to-UAV communications based on the traditional GPSR (Greedy Perimeter Stateless Routing) routing protocol for multi-hop networks [89]. The basic idea of MPGR is to predict the next movements of UAVs so as to forward incoming data packets to the predicted positions. Therefore, it is a routing protocol based on the locations of nodes (coordinates), and consequently, the UAVs should be equipped with a GPS system. The authors compare the proposed MPGR algorithm with GPSR and ADOV routing protocols, showing better results than the two traditional multi-hop routing protocols.

In [90], the AODV routing protocols is enhanced by including geographical information on the request packets during the route formation. The Reactive-Greedy-Reactive (RGR) algorithm is aimed at speeding up the recovery procedure after a breakage of a pre-established route between two UAVs. The idea is to have a table of neighbor nodes including their coordinates. When a route is detected as not available, the source node selects a node close to the destination position in order to re-establish the broken route as soon as possible. This technique is taken from the Greedy Geographical Forwarding algorithm [91]. The authors compare the proposed RGR algorithm with AODV and GGF approaches, showing better results in terms of delay in communications.

A geographical routing protocol for AANETs is presented in [92], where the authors present A-GR. This routing protocol is based on a novel broadcasting approach, namely ADS-B, which includes topology local information in order to construct neighbor tables. The authors compare this protocol against GPSR routing protocol, showing better results in terms of packet delivery and end-to-end delay metrics.

Regarding routing in AQNETs, in [29], a set of USVs is used to create an aquatic WSN. The standard IEEE 802.15.4 is used, with its commercial implementation XBee. This work uses the DigiMesh protocol, which is based on the AODV protocol. In [53], a swarm consisting of 10 USVs is built and both communication and control strategies are analyzed. The IEEE 802.11g standard is used as short-range communication technology. Although this work mentions the possibility of using dynamic topology routing protocols that are designed for MANETs, it states that one of the aims of this work is to develop new routing protocols. There are not any results provided on these newly developed routing protocols mentioned. Therefore, this is expected to be addressed in future works. The same happens with [73], in which new routing protocols for UUV fleets are mentioned to be under development.

In [11], a similar swarm of USVs to the one described in [53] is provided. This swarm also uses IEEE 802.11g as short-range communication technology. The networking solution selected is a broadcast-like protocol in which each USV broadcasts its information to its neighbors every second. In [77] three different RF modems are tested for a surfaced network of UUVs. Two of these modems allow multi-hop routing. The FreeWave modem works with static multi-hop routing, thus it is not able to respond to topology changes in the network. On the contrary, the NovaRoam modem is able to work with dynamic multi-hop routing schemes. The routing protocol used is AODV. Furthermore, DSR is proposed as the routing mechanism appropriated for UUVs ad-hoc networks in [72]. In [72], SONAR technologies are used for establishing communications between the UUVs of the fleet.

QUELAR routing algorithm is presented in [93]. This routing algorithm is based on the machine learning technique known as Q-learning. The objective is to maximize the lifetime of the network. It is done by distributing the forwarding decision among nodes considering the residual energy of nodes.

In [94], the authors test the opportunistic or delay tolerant approach in a combined scenario that consists of both aerial and aquatic nodes. In such mobile and heterogeneous scenario, the authors demonstrate that the communications among nodes can be notably improved by incorporating the opportunistic networking concept.

When comparing aerial and aquatic networks in terms of routing protocols, it should be taken into account that the routing functionality belongs to the network layer of the communication protocol stack. It was highlighted in Section 1 that except for the physical and MAC layers, aerial and aquatic networks can be considered very similar. Thus, there is not a specific type of routing protocols that performs better for AANETs and worse for AQNETs, and vice versa. Also, the performance of a routing protocol depends on the specific metrics measured, and the ones that the UAAV network must guarantee. For example, some proactive protocols like BATMAN have outperformed reactive ones in terms of throughput, as it has been demonstrated in [87]. However, BATMAN produces much more routing overhead than other proactive and reactive protocols. Thus, if an UAAV network in a specific application needs to offer high throughput and is able to deal with high routing overhead, then BATMAN protocol would be a good routing solution. On the contrary, if the application scenario conditions change over time, then other routing approaches would be better than BATMAN. It is important to remark that geographic-based routing protocols have outperformed other ones such as BATMAN [87]. However, this type of routing has not been widely explored in these networks yet.

3.2. UAAV-ground command base station communications

Researchers have used different technologies for the communications between UAAV networks and command centers or base stations. We would like to highlight that when we refer to a control or command base station the kind of commands that may appear in these applications are high-level, as we focus on networks consisting of unmanned vehicles. Other uses of command base stations are to monitor de network remotely. Table 5 presents a summary of the technologies found in the literature. The first thing to notice is that in several implementations they do not use only one technology but multiple ones.

Table 5
Technologies used in communication links established between an UAAV vehicle and a ground base station.

Technology		Reference
VHF, UHF	915 MHz (UHF)	[98]
IEEE 802.11 (Wi-Fi)	IEEE 802.11a	[97]
	IEEE 802.11b	[99,49]
	Other versions or not specified	[100,96,52,53,45,51,46]
IEEE 802.16 (WiMAX)		[53]
GPRS, 3 G, LTE		[100,40,96]
Satellite		[40,46,22,52]
Airmax		[50,101]

This is for cases when one system is not available due to failures. Then, there is still the possibility to use an alternative one for the connection with the UAAV network. There are implementations using cellular communications, satellite, WiMAX (IEEE 802.16) and even proprietary wireless technologies (Ubiquity Airmax). However, IEEE 802.11 is clearly the first choice when designing this type of networks due to its massive use in commercial wireless devices. IEEE 802.11 offers high bandwidth in the order of Mbps, and a range of tens of meters up to 1 km in some of its versions (e.g. IEEE 802.11ah). Nevertheless, this technology would only support star or multi-star topologies. Other technologies would be required to implement the ideal case of hierarchical or flat mesh networks [1]. Another disadvantage of the IEEE 802.11 is the energy consumption because it has not been thought to be used in energy constrained scenarios as is the case of UAAV networks. An alternative for this is the IEEE 802.15.4 standard. Even though it has a smaller bandwidth of tens of kbps, it has been developed to be used in energy constrained mesh networks like WSNs. In [96], the authors implement a combination of IEEE 802.15.4 and IEEE 802.11, where IEEE 802.11 is the technology between the command center and the USVs, and the IEEE 802.15.4 standard is used for exchanging information among the USVs.

In the case of aquatic environments, the command center also communicates with the UAAV network through the IEEE 802.11 standard combined with satellite communications. However, in the case of rivers the satellite communications might be replaced by cellular communications for reducing costs and because of its availability in the surroundings of the river. Regarding the usage of IEEE 802.11 in aquatic environments, in [97] the authors observe that communications in the band of 5 GHz (IEEE 802.11a) have been demonstrated to be more reliable.

4. Evaluation tools

This section is focused on the main aspects that should be considered to evaluate the designs of UAAV networks, which are: i) mobility models, ii) simulators, and iii) real testbeds. Simulation has been the most used tool to evaluate wireless multi-hop ad hoc networks. This is because developing a simulation tool usually requires lower cost and shorter time than building prototypes for real testing. However, it has been demonstrated that the simulation parameters used in simulation studies strongly affect the performance of wireless networks [102], leading to poor performance in reality if bad simulation parameters were used. Because of this, validating the simulation results in real experimentation scenarios and with real prototypes have also received the attention of the scientific community working in multi-hop ad hoc networks, such as is demonstrated in [103–106].

4.1. Mobility models

Mobility models usually consist of a set of rules that represent the movement behavior of nodes. These rules define how an autonomous vehicle's location, velocity and acceleration change over time. Also, mobility models generate trace logs of the vehicles when these are moving, in order to use them afterwards in simulations. It is desirable for mobility models to emulate the desired movement pattern of targeted real life applications in a reasonable way. The mobility behavior of nodes in an ad hoc network plays an important role in the communication protocols performance [107–110], and from this comes the importance of developing mobility models that properly enable the communication between ad hoc networks nodes. Focusing on the unmanned vehicles case, the movement patterns depend on the type of application.

Mobility models can be classified into two main categories: i) Controlled mobility [111], in which the vehicle mobility is controlled either by a human operator using a remote control or an autonomous control system; and ii) random, in which nodes move randomly throughout the scenario. In this paper we focus on autonomous vehicles and thus we do not consider the case of a human operator controlling the vehicles mobility. There are numerous approaches in order to control the mobility of groups of autonomous vehicles. Most of them have been adapted from ground multi-robot mobility strategies [112]. The controlled mobility category can be subdivided into two subcategories: i) deliberative and ii) reactive. In deliberative strategies, which are also known as motion planning or path planning approaches [113,114], specific motion paths are calculated for each vehicle. Usually there is a central controller that calculates the paths for all robots. The controller needs to know the scenario characteristics in advance. Dynamic environments with changing features present problems for this approach. In order to solve this, adaptive planning is used, which recalculates the robots paths when specific sensors detect changes in the scenario.

Within the deliberative or path-defined category, mobility models can also be organized into different groups [115], among these, the most common are: i) cell decomposition, ii) roadmap based mobility models, and iii) artificial potential methods. Cell decomposition based mobility models [116] divide the free space into simple cells and represent it by the adjacency graph of the cells. Roadmap based mobility models [117] build a network of collision free paths based on the space features (the nodes may move along these paths). Finally, artificial potential methods [118–120] represent each point of the space with a specific value (e.g. an electric charge). In this approach, obstacles are usually represented by points that repel the mobile vehicle, and the target destination is represented by an attracting point (e.g. thinking of an electric example, the mobile vehicle and obstacles would have positive electric charge; the destination would have negative electric charge). The fundamentals aspects of path-defined mobility models categories are presented in Table 6. Also, some heuristic approaches can be used for calculating the mobility of autonomous vehicles as a deliberative approach. For example, recent approaches genetic algorithms for finding free-collision paths based on grid models [121]. The genetic algorithm based method finds the optimum trajectory minimizing the deviation with respect to the initial trajectory.

Reactive strategies, also known as behavior-based algorithms [113], do not calculate the vehicle paths in advance. On the contrary, a set of interactions with the environment define the vehicles' behavior. Normally, there is not a central unit controlling the robots movements so they work on a distributed fashion. For that, local interactions between vehicles and the environment create a global behavior that is able to accomplish complex tasks. Examples of reactive mobility are: i) spring mobility model, and ii) swarm strategies, among others. Spring model mobility [122] is based on the dynamics of a mechanical spring. In this case, each pair of UAVs is connected with a virtual spring and UAVs are able to detect other UAV positions. If two UAVs are very close to each other, a repulsion force will make them to separate from each other. On the contrary, if an UAV is located at a long distance from its closest neighbor, an attraction force will make them to move closer to each other. The spring model is normally used in applications where an AANET is required to cover a specific area such as in [4]. In swarm

Table 6
Path-defined mobility models.

Category	Model description
Cell decomposition	The scenario space is divided into cells c_i forming a grid. Where: c_i: (o, d) $o(c_i)\begin{cases} 1, & \text{if the cell is occupied by an obstacle} \\ 0, & \text{if the cell is empty} \end{cases}$ $d(c_i)$: distance of a cell to the target position The available paths can be represented by a tree, in which each node is a cell with an assigned distance d towards the target position.
Roadmap-based	The scenario space is represented by a graph G = (V, E) Where: V: space locations that the vehicle may occupy while moving E: edges that allow the vehicle to move from one vertex to another The way a vehicle traverse the graph when moving from one vertex to another depends on the edges costs. Different algorithms can be used to evaluate different routes costs. The graph G can be built from robot sensor data.
Artificial potential field	Two fields are defined, one representing the attractive forces and another one for the repulsive forces. Specifically, these fields can be defined as follows [120]: Attractive field: $\phi(p') = \begin{cases} p', & \text{if } p' \neq 0 \\ 0, & \text{if } p' = 0 \end{cases} \forall\ (x, y) \in A$ Where: $p' = p_t - p$ p: vector from the origin to the UAV position p_t:vector from the origin to the target point A: scenario area The gradient of the attractive field is the attractive field force Repulsive field: $\varphi(p_i^*) = \begin{cases} \varepsilon e^{-l p_i^*}, & \text{if } p_i^* \leq d_0 \\ 0, & \text{if } p_i^* > d_0 \end{cases} \forall\ (x, y) \in A$ Where: The subscript i refers to the ith obstacle ε, l: alterable coefficients $p_i^* = \tilde{p}_i - p$ $\tilde{p}_i$: vector from the origin to the ith obstacle point which is nearest to the UAV p: vector from the origin to the UAV position d_o: security distance to objects A: scenario area The gradient of the repulsive field is the repulsive field force.

strategies [123] the autonomous vehicles mimic interaction rules which are common in animal communities e.g. ants, birds, fishes. These strategies have shown efficient performance when applied to groups of autonomous vehicles. Some common techniques used are the Particle Swarm Optimization (PSO) algorithm [124], multi-objective evolutionary algorithms [125], and the Ant Colony Optimization (ACO) [126], among others. Recent approaches try to merge deliberative and reactive approaches into hybrid mobility strategies [113].

Within the random mobility models category, nodes move randomly throughout the scenario area. These mobility models are also referred as uncontrolled mobility models in the literature [111]. These mobility models have been developed and used often in MANETs, but they have been also adapted for UAV networks [127]. For example, in the random walk [128] mobility model, a mobile agent randomly chooses heading and speed values, and travels according to them for a random duration. Then, the procedure is repeated iteratively by choosing a new set of values for heading and speed. Speed and direction values are chosen from predefined ranges, [$V_{\min}$, $V_{\max}$] and [0,2π] respectively. If a node reaches a simulation area boundary, it bounces on the border. The Random Waypoint mobility model (RWP) [128] assumes that a mobile agent travels to a destination, which has been selected randomly from within a region, and moves towards the destination also with a randomly selected speed. The random waypoint mobility model has been reported to be unsuitable for simulating ad hoc networks. The reason is that, in this model, nodes tend to concentrate in middle of simulation area [129]. In the Random Direction model [128], a mobile agent randomly chooses a direction and a speed value, moves to the boundary, pauses for a while and then randomly chooses other values for the direction and speed parameters for its next movement. In [130], a specific model for flying vehicles, called the Semi-Random Circular Movement, is developed. In this mobility model the vehicles are flying around the center of a 2D area, i.e. describing curves, in order to gather information from a specific location. Also, another UAV-specific mobility model is described in [131] in which the vehicle is changing among five predefined simple trajectories according to specific probability values assigned to each trajectory. Although random approaches have been used to model the mobility of UAAV nodes in some applications [130–132], they can only represent very simple behaviors, which are far from emulating any real application scenario. The fundamentals aspects of the random mobility models are presented in Table 7.

Also, from the point of view of a group of nodes, mobility models can be classified depending on the interaction among nodes. There are two main categories according to this aspect: i) group mobility models, in which nodes move following a specific node acting as the team leader; and ii) entity mobility models, where the movements of each node are not directly dependent on other nodes. In order to clarify the entity mobility, in this type of models different nodes can collaborate with each other in order to achieve a common goal, e.g. sweeping an area of interest; however, this collaboration does not implies that all the nodes follows the movements of a leading node. There are many examples of both types of mobility models in [133].

Table 7
Random mobility models.

Category	Model description
Random walk	When, in the ith iteration, the time period is over, each node randomly selects: $\lvert\overrightarrow{v_i}\rvert$: node speed for next period φ_i: direction angle for next period t_i: next period duration This selection procedure is repeated for each iteration
Random waypoint	When, in the ith iteration, a node reaches the destination position, it randomly selects: $\lvert\overrightarrow{v_i}\rvert$: node speed for the next trajectory $(x, y)_i$: 2D coordinates of the new destination position This selection procedure is repeated for each iteration
Random direction	When, in the ith iteration, a node reaches a boundary point, it randomly selects: p_i: pause time before starting the next trajectory $\lvert\overrightarrow{v_i}\rvert$:node speed for the next trajectory φ_i: direction angle for next trajectory This selection procedure is repeated for each iteration
Semi-random circular movement	There are two iteration levels: 1. Radius level (outer loop iteration): When, in the ith iteration, a node finishes one round of a circle, it randomly selects: R_i: next circle radius This selection procedure is repeated for each radius level iteration 2. Destination level (within the radius level, i.e. inner loop iteration): When, in the jth iteration with radius R_i, a node reaches a specific destination position within the circle of radius R_i, it randomly selects: $\lvert\overrightarrow{v_j}\rvert$: node speed for the next trajectory φ_j: traveling angle for next trajectory This selection procedure is repeated for each destination level iteration

Apart from the concept and definition of mobility models, the research community has also developed software tools for generating the mobility traces of nodes. These tools are called mobility generators and can be used for creating scenarios in which the aerial or aquatic nodes, i.e. the nodes of the network, move according to some of the aforementioned mobility models. This is very useful for testing how communications protocols perform in simulation environments when nodes have different mobility behaviors. One of the most known mobility generators is BonnMotion [134], which allows users to integrate mobility models with popular network simulators.

4.2. Simulators

The research and development of simulators for wireless networks and unmanned vehicles is becoming a more mature activity nowadays. This activity has also attracted the attention of the industry, in which some companies has been focused on developing realistic network simulators for evaluating their network designs before putting them into practice, saving both costs and risks. Many works have been done in this area, being the main motivations [135]: i) the role of simulators in the adoption of new technologies, ii) their potential for low cost training, and iii) their utility in research. All the simulators found in the literature can be categorized as either commercial or open source simulators [136].

4.2.1. Aerial vehicle simulators

Regarding aerial vehicle simulators, they can be classified into two main categories: i) simulators that model a single UAV, and ii) simulators that model the behavior of several UAVs. The main difference between them is that in the second one the movements of each UAV depend on the rest of the UAVs, as the UAVs usually work cooperatively.

In [137], an open source simulator called FlightGear is proposed. FlightGear was developed for simulating real-time 3D UAV models. Features such as weather conditions, flight modes and geographic conditions are integrated and emulated in FlightGear. This simulator is very important for understanding the dynamic models of flying vehicles and also for testing the flight control laws. Also, other open source UAV simulators are presented in [138] and [139].

Regarding multi-UAV applications, several simulators have been developed in order to test UAVs physical movements, the communications architecture and also new application areas [140–142]. One of the first simulators for testing multi-UAV communications was Real Time multi-UAV simulator (RMUS) [140], which emulates direct communication links between UAVs according to IEEE 802.11 standards. Another option for simulating multi-UAV networks is the X-plane flight simulator, which can be used together with Matlab [141]. The role of Matlab in the simulator is to implement different multi-UAV control algorithms which are then simulated in the flight simulator. Matlab is also used as a framework for developing a UAV simulator in [143]. In [142], the authors present a simulation environment specially oriented to distributed coordination algorithms testing for UAVs. Finally, in [144] a simulator specifically oriented to quadrotor-like UAVs is described.

4.2.2. Aquatic vehicle simulators

Testing aquatic vehicles, in terms of developing mobility models or movement laws under real conditions, is not an easy task because many resources are required. For instance, a lake would be needed for conducting the experiments and, these spaces can be available for testing only for short time periods and using them usually requires government authorizations in advance. In order to solve these disadvantages, several aquatic vehicle simulators have been developed in the last few years [145,146]. However, most of them have been developed within a research project and are oriented to a specific purpose, which means that it is difficult to easily adapt them for other applications.

With regard to open source simulators, the Subsim framework is proposed in [147]. The Subsim is a simulator that allows testing aquatic vehicle designs, the control algorithms to be implemented in the vehicles and also the sensors integration. Another open source simulator is Neptune [148], which emulates the underwater environment conditions and the aquatic vehicle movements based on three different aspects: i) the UUV model, ii) the world model, and iii) the environment model. The UWSim simulator is presented in [145] and provides features for testing underwater control, vision and manipulation aspects. UWSim simulator also includes an easy configurable user interface that allows the users to include specific underwater vehicles and manipulators.

Other type of open source aquatic simulators model the surface water conditions with more detail, such as [149,150]. Within this type, we can find the WaveSim simulator [150]. WaveSim models aquatic obstacles as basic geometric figures, and therefore surface and underwater vehicles are represented as boxes and cylinders, respectively. Another simulator called Kelpie [149] is based on WaveSim and Gazebo [151], but also including improvements such as wind conditions and the effect of the wind in the waves.

Regarding commercial aquatic vehicle simulators, we can highlight Deepworks [152]. This simulator includes full hydrodynamic models, multiple configurable views, full SONAR simulation and pilot training metrics.

4.2.3. Multi-hop network simulators

Most of the simulators mentioned in the previous section are focused on modeling the movements and control laws of aerial and aquatic vehicles. However, they do not take into account the communication aspects among vehicles. In fact, to the knowledge of the authors, there are not specific simulators combining communication and mobility models aspects for UAAV networks. Because of this, when there is the need of simulating both communication and mobility aspects, communication simulators and mobility simulators are used together, but as two different entities integrated with tailored software developments.

Regarding specific network simulators, there are many of them that allow users to emulate different standard communications, propagation models, energy models, routing protocols, and other aspects. A good example are the network simulator 2 (ns-2) [153] and its evolution ns-3 [154], which are the most popular network simulators in the research community. On the one hand, ns-2 is an open source discrete event simulator widely used for education and research purposes. The main advantage of ns-2 is the amount of models that have been developed for it. For instance, there are many MAC protocols, routing protocols, and propagation models already integrated in the simulator. Basically, ns-2 provides two outputs: i) a graphic simulation that allows the users to visualize the deployed networks, and ii) a trace file which includes the list of events occurred during the simulation time. This trace file contains detailed information on the events, and thus, the analysis of such log file is the basic mechanism to evaluate the performance of a networked communication system. On the other hand, ns-3 is also an open source discrete event simulator, which was started in 2006. Although it may be seen as an extension of ns-2, is considered as a new simulator, and in fact, the ns-2 model cannot be used in ns-3. One of the main differences between these simulators is that ns-3 is entirely written in C++, with optional python bindings. Some advantages of using ns-3 with respect to ns-2 are: its capability for handling multiple interfaces of nodes correctly, the usage of IP addressing, a more detailed alignment with Internet protocols, and more detailed IEEE 802.11 models, among others.

Another widely used network simulator is OMNET++ [155]. There are several interesting frameworks based on OMNET++ for wireless networks and ad hoc networks such as MiXim and Castalia. They are focused on the lower layers of communication systems, i.e. the physical and MAC layers. For higher layers, the INET framework provides implementations for IPv4, IPv6, TCP, SCTP, and UDP protocols and several application models. Also, the Global Mobile Information System Simulator (GloMoSim) is presented in [156]. GloMoSim was developed by UCLA Computing Laboratory in order to support studies of large-scale network models (with millions of nodes), using parallel and/or distributed execution on a diverse set of parallel computers (with both distributed and shared memory).

4.3. Experimental testbeds

Most of the existing research in the area of UAAV networks has been conducted using simulations. However, there are some aspects that are not taken into account when simulating complex systems like AANETs. Generally, the results obtained by simulations present differences with the behavior of the systems tested in real scenarios. Therefore, for obtaining most exhaustive results, it is necessary to build real testbeds using real hardware components.

4.3.1. Testbeds for aerial vehicles

In this subsection, we review the latest UAV testbeds. Testbeds for UAV networks can be classified into two categories such as: i) indoor, and ii) outdoor testbeds. In indoor testbeds it is possible to create more controlled environments for initial tests (e.g. without atmospheric phenomena such as rain or wind) and the space needed to build them is more reduced. Also, an important aspect to consider in indoor testbeds is that it is not possible to receive GPS signals for obtaining the vehicles positions; therefore, other methods must be used, such as infrared localization [35]. In outdoor testbeds the GPS signal is normally available and the flying space is generally an open area.

In [157], a testbed for UAVs is presented. The aim of this testbed is to allow conducting indoor experiments for evaluating different autopilot flight control mechanisms. In [158], a testbed to study the behavior of multiple UAVs in long duration operations is developed. This testbed is able to manage up to ten aerial vehicles simultaneously for different multi-vehicle missions. Another indoor testbed is presented in [103], which is oriented to experimental evaluation of multi-robot aerial control algorithms in large rooms. This testbed also addresses the problem of scalability, presenting a solution for controlling multi-UAV systems that is easily scalable.

Regarding outdoor UAV testbeds, in [106], a physical multi-UAV system to test network features is proposed. Some of the features that can be tested are the data link, the formation flight control system, and movement strategies, among others. Also, swarm strategies are proposed for controlling multi-UAV networks in [159], which describes a testbed that receives the name of Sensing Unmanned Autonomous Vehicles (SUAVE). The main application for which SUAVE was conceived is search and rescue operations, however, this system can be adapted to other types of scenarios. Another outdoor testbed is presented in [85], which consists of two small fixed-wing UAVs and a ground base station. The testbed structure defines two possible roles for the UAVs: one UAV is the source of packets to be transmitted; the second one is a relaying node which is in between of the source UAV and the ground node, being the ground base station the destination node. The main aim of this testbed is to test routing protocols performance for AANETs.

Finally and regarding outdoor testbeds, it is important to highlight that nowadays governments have imposed some restrictions for flying aerial vehicles in the form of regulations, such as in the case of Spain [160]. There restrictions refer to the places where these vehicles can fly, the pilot skills and the corresponding flying licenses, among other aspects. For instance, no aerial vehicles are allowed to fly near to airports or restricted flying areas. Also, those flights carried out in places where there are many people that can be at risk (in case of a vehicle failure) are not permitted without previous permission of the competent authority. Regarding the UAV pilots, it is necessary for them to obtain an appropriate flying license and also civil liability insurance.

4.3.2. Testbeds for aquatic vehicles

In comparison with aerial vehicles, the number of testbeds for aquatic vehicles is much lower. However, it is also very important to evaluate the behavior of the vehicles in terms of communication and collaborative movements before implementing real aquatic missions. In general, aquatic vehicles are tested in artificial spaces, for example in water tanks, or in natural spaces such as lakes or even the sea. Also, the testbeds for aquatic networks can be classified in two main categories: i) surface testbeds, and ii) underwater testbeds.

Regarding underwater environments, in [104], a testbed to mimic acoustic communication is proposed, which also allows verifying coordination and cooperation control strategies between aquatic vehicles. Also in this line, in [105], a testbed for testing the performance of underwater vehicles formation and their steering algorithms is proposed. Some testbeds such as the one described in [161] have been developed to test micro aquatic vehicles, in terms of coordination and control algorithms. Also, in [73] a testbed of UUVs is used with the aim of testing new communication protocols for underwater communications.

In [11], ten USV units are used as a test bed for carrying out experiments with different swarm controllers. The testing scenario is a real aquatic scenario, which presents the characteristics of uncontrolled events. In [53], a swarm of USVs is designed and developed as a platform for studying communications and control strategies.

As a summary of the available evaluation tools, Table 8 summarizes the main simulation tools and testbeds available to evaluate the performance of UAAV networks.

Table 8
Evaluation tools for UAAV networks.

Validation tool	Category			Reference
Mobility models	Entity and group mobility	Path defined	Cell decomposition	[116,121]
			Roadmap based mobility models	[117,124,125]
			Artificial potential methods	[119,120]
		Random		[128,130,131]
Simulators	Mobility models			[134]
	Vehicles		Aerial	[135,137,140,140,140,141,143,143,145]
			Aquatic	[145–149,151,152]
	Network		NS-2	[153]
			NS-3	[154]
			OMNET++	[155]
			GloMoSim	[156]
Testbeds	Aerial		Indoor	[157,158,103]
			Outdoor	[106,159,85]
	Aquatic		Surface	[11,53]
			Underwater	[73,104,105,161]

5. Applications and scenarios

This section classifies the different works found in the literature for UAAV networks according to the target application. We divided the reviewed works into 5 categories, namely disaster scenarios, military, environmental monitoring, logistic and others. In the disaster category, we include the works that use UAAV networks for disaster relief operations such as communication among first responders and mesh networks providing Internet access. In the military field falls all the research works that use UAAV networks for military purposes such as surveillance and monitoring application in battlefields. Environmental monitoring applications include those applications in which the UAAV networks sense environmental variables such as temperature, CO_2, etc. The logistics category contains the applications where UAAV networks, especially UAV based networks, are used to deliver parcels. Finally, the other applications category subsection includes all the works that cannot be included in any of the aforementioned categories. These other applications are nowadays emerging applications of UAAV networks and only have few research works devoted to them.

5.1. Disaster scenarios

Disaster scenarios are one of the main application scenarios of multi-hop ad hoc networks due to their appealing decentralized features [162]. UAVs equipped with wireless transceivers can provide in situ communication services to ground nodes such as victims and/or first responders. Moreover, UAVs can be used for search and tracking tasks. Similarly, USVs can perform these same tasks in aquatic environments.

In [4], an AANET plays the role of a support communication network for victims and first responders in a disaster scenario. The UAVs deployment and movements are self-organized. Several nature inspired optimization algorithms are used in order to maximize the number of ground nodes (victims and first responders) under coverage, i.e. the serviced nodes. UAVs share between each other the identity of the ground nodes serviced by each one, which is considered a set. A metric that measures the dissimilarity between two sets can be used to evaluate the victims shared between different UAVs, i.e. those victims that are under the coverage area of several UAVs. The selected metric is the Jaccard distance, which may take values within the range [0, 1]. The target Jaccard is calculated by different optimization algorithms such as hill climbing and simulated annealing. For each iteration, the algorithms return the value that maximizes the number of serviced ground nodes. By doing this, the AANET adapts the UAV positions according to the ground nodes movements. The algorithms also penalize the solutions that disconnect the UAVs from the network, thus a connected network is guaranteed.

In [163], a set of fixed-wings UAVs aims to connect several first responders working in a disaster scenario. An important constraint considered for these UAVs is that they do not have a GPS sensor. Thus, they have to calculate their relative positions with respect to other UAVs only using their own inertial and heading sensors. The main aim of [163] is to design the controllers of the UAVs forming an AANET which connects the first responders efficiently. A secondary objective is to design these controllers in a way that can be easily adapted and reused for other missions, i.e. to have controllers that perform well in scenarios with different requirements. Thus, the UAVs use neural controllers which are evolved by using genetic algorithms. After that, the resulting controller from the genetic algorithm is reverse-engineered in order to understand and capture its behavior. Later in the process, this behavior is used to define simple swarming rules, which will be the actual control rules implemented in the UAVs. This approach makes possible to extend these controllers to a broader type of applications and scenarios. A similar work is presented in [123], whose aim is also to connect two first responders with UAVs lacking from GPS sensors. The main difference between these two works is that, in [123], the Ant Colony Optimization (ACO) [164] algorithm is used in order to explore the scenario, find the first responder and connect him to the base station.

In [62], a multi-hop UAVs network is used to connect two separated ground nodes. The ground nodes are located far from each other and they cannot communicate directly with each other. Thus, UAVs act as relaying nodes between the ground nodes. In the initial stage of this application, the UAVs only know the location of one of the ground nodes. Because of this, they initially perform a search strategy in order to locate the second ground node. After finding the position of the second ground node, an algorithm is run for calculating the best UAVs locations in order to maximize the RSSI. Although the scenario application is not specifically stated, the behavior of the UAVs in which they search for a ground node and establish a connection bridge with another one resembles to the communication links that need to be established between first responders in disaster scenarios.

In [12], a swarm of micro UAVs is used in order to detect and track a plume of toxic gases. The UAVs mobility is defined by following two aims: i) globally, the swarm needs to reach the greatest coverage in order to detect the plume, and ii) from a local point of view, each pair of UAVs need to maintain a proper distance in order to keep the communication links quality. The UAVs are equipped with specific sensors for detecting toxic gases. The information gathered by the UAVs is transmitted to a ground station, called Mission Control Center (MCC), in which further processing and decisions about the emergency operations are taken. From a communication perspective, the UAVs are equipped with IEEE 802.11a/h devices for the interface UAV-UAV and use a hybrid routing protocol. They carry also UMTS/HSPA, LTE (Long Term Evolution) or WiMAX communication devices for the interface UAV-MCC. A similar approach is used in [165] in which a group of UAVs also detects and track a chemical plume by using simple swarming rules.

The aim of [72] is to build an underwater ad hoc network for developing and testing routing protocols performance. The UUVs considered are equipped with acoustic transceivers, i.e. SONAR communication devices. The achievements of [72] are the development of a simulation and visualization tool. The simulator is used to test the routing solutions under study. After the simulator, the objective is to build a physical UUV testbed and validate the routing protocols studied in the simulations in real aquatic scenarios. The real scenarios tests considered are related to search and survey applications. As an example, in [72] the usage of this UUVs network in a sunken airplane black box search and recovery mission is mentioned as one of the potential applications.

In [166], the authors present the ICARUS EU-FP7 project whose objective is the development of a set of integrated components to assist search and rescue operations in dealing with finding human survivors in disaster situations. These components consist of assistive unmanned air, ground and sea vehicles, equipped with victim detection sensors. Under this project, the authors present in [97] the design of the SWIFT (Small Waterjet and Intelligent Flexible Transporter) USV, a small and low cost vehicle, that besides performing general purpose mission of collecting data and survey, it is intended to operate in supporting rescue missions of humans on water.

A recent survey about the application of UAV-networks as WSNs can be found in [18], where the authors present the main application areas for the application of both WSNs and multi-UAV networks.

5.2. Military

In [61], a network made of ground and aerial nodes is analyzed from the communications point of view. This type of network is called Ad Hoc UAV-Ground network (AUGNet). The vehicles used are UAVs of small size. AUGNets are considered as a very powerful communication tools to be used in military scenarios, due to their flexibility, small size and reduced costs. For this reason, this work presents UAVs and ground nodes prototypes built from off-the-shelf commercial communication devices. Particularly, IEEE 802.11b communication devices and the DSR routing protocol are used. Two scenarios were used in order to test the AUGNet: i) a set of UAVs connecting two disconnected parts of a ground nodes network, and ii) UAVs extending the communication capabilities of a ground base station to longer ranges by building a multi-hop bridge. The results show that it is possible to build a low-cost and working AUGNet from commercially available communication devices. The results also showed that the performance of the AUGNets highly depends on the specific conditions of each scenario.

Surveillance tasks may be required in military scenarios where a specific area has to be monitored. Usually, surveillance using traditional methods, e.g. piloted terrestrial or aerial vehicles is costly if the area to monitor is large. Also, in the case of risks in the area to monitor, traditional vehicles can be put in danger. UAV networks are a good alternative in terms of costs and risks. In [13], a group of UAVs performs surveillance missions, and an algorithm is proposed for the coordination of the UAVs which monitors the area of interest collaboratively. Each UAV has a specific sub-area assigned so each one only scans its own sub-area. In the boundaries shared with other areas, UAVs exchange information with other UAVs monitoring the neighbor sub-area. The results have been obtained through simulation studies in Matlab. The UAV model used for the simulations is a quadcopter with simplified communication capabilities. This means that it is considered that two UAVs can communicate with each other if they are separated by a distance smaller than 2 m. Taking into account the simplicity of the communication model between UAVs, if this strategy is taken to a test bed with real UAVs, several wireless technologies may be used such as IEEE 802.11 or IEEE 802.15.4.

In [74], a group of heterogeneous UUVs is used for multi-UUV operation experiments. The experiments aim to better understand the advantages and limitations of using these vehicles in future operations. The main application considered are military-like missions, specifically, mine-warfare. Also, rapid environmental assessment missions are considered. All these UUVs are equipped with acoustic modems for underwater communications. Also, they have IEEE 802.11g devices and other communication technologies for communicating with surface vehicles, satellites or other nodes. The experiments show that the usage of groups of UUVs from different vendors is a reality nowadays. However, for missions that require the operation of different types of UUVs the inter-operability is of paramount importance. For this purpose, the development of inter-operable standards is required in order to enable the seamless operation of UUV networks.

5.3. Environmental monitoring

Environmental monitoring has been the aim of many applications of UAAV networks, both in aerial and aquatic environments [54,99]. Moreover, we can say that this is one of the first applications considered when developing aquatic networks. Either in aerial or aquatic environments, the environmental monitoring applications require the unmanned vehicles to be equipped with specific sensors which are able to measure environmental variables. From the study of these variables the contamination of the air or the water can be inferred and also its impact on living beings.

In [99], the authors propose the use of a USV together with a group of buoys to study aquatic microorganisms in a lake. This will lead to a better understanding of problems like the algae blooming. While mobile boat provides high resolution spatial sampling with low temporal resolutions, the stationary buoys provide low-resolution sampling with high temporal resolution. The stationary buoys are programmed to form an ad-hoc network for multi-hop communications and deliver the information to a remote control center. Two types of sensors are used, fluorometers and thermistors, which are connected to the controller boards of the buoys and the boat through Analog to Digital Converters (ADC). The fluorimeter estimates the concentration of chlorophyll, which is an indicative of the density of photosynthetic microorganisms in the water and the thermistor measures its temperature. In [98], the authors propose a USV based on a catamaran also for the study of the quality of water in a Lake. The catamaran includes an arm that submerges down to 20 m in the water. The arm holds a multi-parameter probe that measures temperature, chlorophyll, turbidity, dissolved oxygen, and incident radiation. The multi probe is connected to the boat CPU through a serial port (RS-2232). As in the previous work, here the catamaran is also integrated to a 50 static nodes wireless sensor network .The WSN allows non-light-of-sight two way communications with remote operators. In [100], the authors propose the use of a fleet of low cost USV in order to cover a greater application area and reducing the operation time. A fleet of USVs is used to measure the temperature of the Lake Taal (Philippines), the conductivity of a canal in Brooklyn (US), and the conductivity and temperature in Allegheny River in Pittsburgh (USA). In a more recent work [96], the authors present a novel multiple robotic boat system configured to measure the spatio-temporal release of methane to atmosphere across inland waterways. The USV network enables scientists to remotely evaluate the performance of sampling modeling algorithms for real-world process quantification over extended periods of time. Tests are carried out in two inland waters with a pair of USVs, and a static floating sensor node on the water body.

Another interesting approach is the use of robotic teams for environmental monitoring, as presented in [17]. They argue that autonomous robotic marsupial systems are especially adequate for this type of task. They present an overview of technologies used for environmental monitoring of water bodies such as sensor networks, airborne monitoring and water monitoring. Then they suggest the advantages of combining the robustness and energy capacity of aquatic surface vehicles with the versatility of aerial vehicles for far-field inspection. They test this concept in the RIVERWATCH experiment, where they combined the ROAZ USV with a multi-rotor UAV.

In [54], a set of fixed-wing micro aerial vehicles (MAVs) are designed and built for creating an aerial network. Despite this AANET is not designed for a specific application, the idea is to equip the UAVs with different sensors for measuring different substances over the air. The IEEE 802.15.4 standard is used for the communication among UAVs. This standard is designed for low-rate data transference, thus making this network to be considered as an aerial WSN. Examples of possible applications of this network could be to detect and track a plume of toxic gases, to take measurements of gases concentrations, or to measure weather-related parameters in specific areas.

In [11], a swarm of USVs is used in an environment monitoring application. The USVs are equipped with IEEE 802.11g standard communication devices for short-range communications, i.e. for coordination tasks among each other. Several experiments are carried out in order to validate simple swarm behaviors: i) homing, when USVs move towards a point of interest in the environment; ii) dispersion, in which each USV keeps a predefined distance from its closest neighbor; iii) clustering, when USVs aggregate in sub-groups; and iv) area monitoring, in which the USVs explore the entirety of an area of interest. Then, evolutionary algorithms are used to synthetize the controllers that best perform in each of these behaviors. After that, more complex behaviors are tested in a real monitoring mission. Ten USVs were given the task of measuring the water temperature of a given area of interest. The USVs all start in a location out of the area of interest. Initially, they travel in formation towards the center of the area, and then they disperse and start taking water temperature samples. After a specific time, the USVs aggregate again and travel back to their starting point.

5.4. Logistics

Using UAVs for delivering goods in parcels may be very convenient for places with bad transport infrastructure (e.g. no highways or roads) and hardly accessible. Rural areas, surrounded by forests are usual examples of these places. Also, post-disaster scenario areas where transport infrastructure has been destroyed are difficult to access. Moreover, highly populated urban areas might suffer from congested roads and this can delay the delivery of important goods. Certain types of goods are delay-sensitive and it is important to deliver them as soon as possible, e.g. medication or medical resources.

In [14], a network of UAVs is used for delivering goods from depots to customers. Each UAV can carry only one parcel at a time. Customer's request, also called jobs, are not known in advance and are modeled as a spatio-temporal stochastic process. Two main approaches for job selection policies are proposed and analyzed in this work: i) the first job first (FJ) and ii) nearest job first (NJ). In the FJ policy, there is a centralized control that maintains the information about all the jobs that are yet to be served. The first UAV to finish a delivery is assigned to the job that was first requested and has not been assigned to an UAV yet. In NJ policy, the UAVs follow a distributed strategy and select the jobs that are the nearest with respect to their position. Different variations of these approaches are analyzed against the number of UAVs used. For instance, the minimum number of UAVs that make the system unstable (e.g. the delivery time increases uncontrolled). Also, an analysis of these approaches associated to the expenditure required for implementing the system has been studied. There is not information about the wireless communications that could be used in a real test of the system. However, several technologies of those mentioned in previous sections could be valid for this purpose.

Other well-known companies have been working on using UAV networks for delivering parcels to customers. An example is the retailer company Amazon, which has publicly stated that the future of the company is linked to the fact of UAVs delivering the parcels automatically [167]. Other mail and logistic services companies are also considering UAVs as a way to reduce costs and deliver items more efficiently in difficult access areas. This is the case of the Spanish company MRW [168].

5.5. Other applications

This subsection includes other application areas where UAAV networks can be found, for example construction and agriculture. These scenarios are emerging UAAV networks applications because there are not many research works on these topics yet. However, it is expected that the number of applications in which UAAV networks can be used will increase considerably in future years.

A collaborative assembly and construction application carried out by a group of UAVs is presented in [35]. This work focuses on planning trajectories for every UAV in the system in a way that avoids collisions and achieves the assembly objective. The collision detection algorithm is based on axis-aligned minimum bounding box. This method represents the UAVs and also the construction materials carried by virtual boxes. If the boxes touch to each other there is a risk of collision and then the UAVs must calculate new trajectories. New trajectories can mean a change of speed or heading, among other parameters. The Particle Swarm Optimization (PSO) algorithm is used in order to find new sub-optimal trajectories meeting the requirements imposed by the construction mission. This system is validated in an indoor environment with 2–5 Hummingbird UAVs from Ascending Technologies.[1] These UAVs are equipped with XBee links working at 2.4 GHz. They also may be equipped with Wi-Fi technologies (probably IEEE 802.11b/g/n/s, although it is not specified). However, for the validation tests the UAVs connect to each other using a central controller. The onboard computer is based on an Intel Atom Processor Z530. Each UAV carries passive markers in several points of its frame. A system with 20 VICON infrared cameras is able to detect these markers and to infer the position and heading of each UAV with an accuracy of the order of centimeters. Thus, although the UAVs do not connect to each other as an ad hoc network, they form a network through the VICON infrared system and the central controller. In relation with the previous application in which UAVs build structures, in [169], a cooperative team of UAVs is used for the inspection of infrastructures. Specifically, the team is composed by fixed-wing UAVs, multi-rotor UAVs and a ground station for gathering the acquired data. The application has been designed for power line inspection, although the same idea could be extended to maintenance and inspection tasks of other infrastructure.

In [114] and [15], UAV platforms are used in agriculture applications. In [114], the usage of UAVs for precision agriculture applications is studied. Precision agriculture is the application of technology for two main purposes: i) to increase the productivity or quality of agriculture fields, and ii) to monitor the effect of the agriculture techniques on the soil, the water, and the surrounding environment. Precision agriculture has been used previously by using satellite imagery and manned aerial vehicles. However the costs of these techniques are high and usually the precision is not enough. With the development of small-sized UAVs, a new alternative has appeared: the usage of UAVs as a tool for precision agriculture. Although there are many advantages, there are several aspects that must be addressed in order to develop UAVs as useful tools for farmers. Some of these aspects are the UAVs platform standardization as an agriculture tool, image geo-referencing and mosaicking, final user usability (e.g. farmers) and information workflow and visualization. Also, other aspects as agriculture-specific sensors weight, UAV processing capabilities, battery endurance and communications (for UAV-base and UAV–UAV links) are very important for creating a proper design of UAVs as a useful agriculture tool.

In [15], a hyperspectral sensor system is developed. This sensor is designed to be mounted on UAVs. This system has been tested for monitoring rice fields. It has been demonstrated that the system is able to estimate chlorophyll densities even under adverse illumination conditions. Although the system proposed is described for only one UAV, this application can be scaled up to a multi-UAV system for large crop areas. For example, in the case of a large field in which the crops have to be scanned at a limited UAV speed (constrained by the quality of the sensor measurements that have to be taken from air), the usage of a unique UAV may force it to return to the base several times in order to recharge the batteries. By using a group of UAVs this activity can be performed faster and with the quality required.

6. Lessons learned and open challenges

This section presents the main lessons learned and open challenges derived from this survey. In the lessons learned section, a frequency analysis is performed over the references reviewed for this paper according to the different topics they are focusing in. The main aim of the lessons learned section is to show quantitatively in which areas there have been more research works, and thus which one has received more attention from the research community so far. Several qualitative aspects complete the analysis in order to complete the lessons learned section. In the open challenges section, the main issues that UAAV networks will face in the future are described from a qualitative point of view.

6.1. Lessons learned

We divide this subsection into two parts. First, we present a bibliometric study of the references used in this survey. Second, we present the main open challenges related to UAAV networks that deserve more attention.

6.1.1. Bibliometric study

To graphically illustrate the main lessons learned in this survey, more than 100 references to journals and conferences papers have been selected and several bibliometric-based analyses have been performed

---

[1] http://www.asctec.de/en/uav-uas-drones-rpas-roav/asctec-hummingbird

over them. First, each reference has been categorized attending to two different criteria. The first one, called Tag 1, has been used for classifying the papers attending to their focus on different aspects, such as wireless communications, mobility models, and simulators. These aspects haven analyzed in Sections 2 and 3. It is worth mentioning that throughout the literature reviewed for this survey, many works have been found which do not belong to any of the specific categories considered, and thus, the category *other* has been created for classifying those papers. The second criterion, called Tag 2, considers the final application targeted by each paper according to the categories described in Section 4. These categories are specifically: disaster scenarios, military, environmental monitoring and logistics. The category *other applications* includes those research works belonging to less frequent applications of UAAV networks, such as agriculture, construction, infrastructure monitoring, among others. Finally, in Tag 2, there is another category called *no specific application*, this category covers all the research works in which there is not a clear application defined. For example, this is the case when a research work focuses on studying a specific aspect of a UAAV network, e.g. the throughput, but in a generic scenario. The figures below (Figs. 4 and5) illustrate the distribution of the research works according to the two previously defined tags.

In Figs. 4 and5, the y-axis represents the different categories in which the references reviewed were classified. The x-axis represents the frequency with which these categories are treated in the literature, i.e. the number for research works that fall in each category. In Fig. 4, the obtained results show that most of the papers focus on the UAAV–UAAV communication links. This makes sense as the main interest of the UAAV networks research relates to the communication among the nodes forming the network, i.e. the aerial and aquatic vehicles. The second category, in terms of frequency over the literature, is about the links among UAAV and ground devices. These communication links are very important for UAAV networks because in most of the cases they serve for monitoring the network performance and the mission development. The categories *other* and s*oftware simulator* are in the third and fourth position, respectively. Both categories have the same number of research works. It is worth to highlight that the category *Other* has an important number of works and this may be due to the fact that many references could not be clearly classified in the main categories used in this survey. Finally, only few works are focused on topics such as mobility models.

In Fig. 5, the distribution of references according to the target application categories shows that most of the papers are not focused on a specific application, and thus the majority belongs to the category *no specific application*. These works normally deal with several issues regarding wireless communications of UAAV networks, but without having in mind any particular scenario. The category *disaster* is the second one including a bigger number of research works. This result is due to the fact that disaster scenarios are the main target application scenario for multi-UAV systems. Under the harsh conditions presented in disaster scenarios, UAVs are expected to perform relevant tasks for supporting rescue operations such as searching for victims, tracking first responders, and providing communication coverage, among others. In the third position, the category *other applications* includes a myriad of applications, however, very few works has been found for each of these applications. Some examples of these applications of UAAV networks are agriculture and construction, among others. The military and *environmental monitoring* scenarios are also two common applications considered in the literature. Regarding military applications, it is known that they always have some privacy restrictions which limit the public distribution of results, so the number of developments that belong to this category it is very difficult to confirm. Also, it is important to highlight that environmental monitoring applications are one of the main target scenarios for unmanned aquatic vehicles. Monitoring rivers, lakes and seas using USVs and UUVs is a promising application. Also, there are several multi-UAV applications that fall in the category of environmental monitoring. Finally, logistic applications are still in an early stage of development.

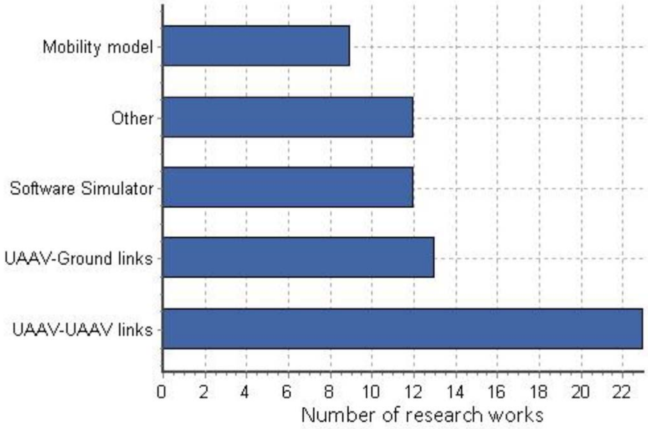

Fig. 4. Distribution of references according to Tag1.

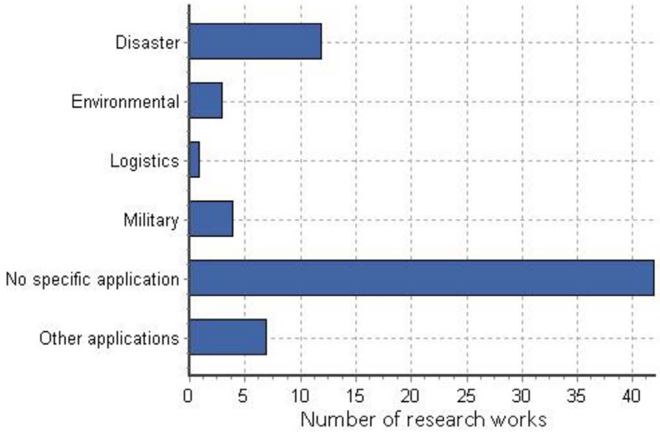

Fig. 5. Distribution of references according to Tag2.

6.1.2. Detected findings

Now on we add some qualitative aspects that are also considered lessons learned. Referring to wireless communication aspects, different wireless communication technologies can be used for UAAV–UAAV communication links. Each of these technologies perform well in certain situations (those for which they were designed) and do not work properly in other situations. One of the most representative examples arises from comparing IEEE 802.11 and IEEE 802.15.4. The former technology is able to transmit at higher data rates but demands more energy, the latter is low-consumption by design but transmits at rates of the order of kbps. Also, some IEEE 802.11 versions like 802.11ah have even longer communication ranges than IEEE 802.15.4, which fit better for applications in which the vehicles are separated from each other by longer distances. This presents one of the main ideas to highlight: there is not a single wireless communication technology that can be marked as “the best one”. The same happens for both types of networks, aerial and aquatic.

Regarding long range communications, other wireless technologies such as satellite and mobile communications (e.g. LTE) have been also used for UAV to ground communications, however, the IEEE 802.11 standards are also the preferred ones for these links with ground nodes. This is due to the fact that mobile communication technologies need of a fixed infrastructure (e.g. antennas, base stations, eNodeBs, etc.) that may be not available in disaster or military scenarios, thus using IEEE 802.11 standards following the ad hoc paradigm is a more feasible solution. Also, satellite communications may be available for disaster and military scenarios; however, there are more restrictions for accessing to satellite communications than accessing for IEEE 802.11. These restrictions come mainly from the fact that there are many requirements needed for working with satellite communications (e.g. permissions, charges for use, among others) in contrast to the easiness of working with IEEE 802.11 communication systems, which have numerous off-the-shelf products available in the market at lower prices.

When referring to IEEE 802.15.4, this technology is mainly for applications in which the UAAVs navigate close to ground nodes with which they need to exchange information. Thus, the short distance between UAAVs and ground nodes allows using this technology which requires less energy consumption. However, if the application needs to transfer high data rates, the IEEE 802.15.4 standard could not be appropriate as its data rates only reach up to the order of hundreds of kbps. In the case of aquatic networks, SONAR technology is the most suitable for underwater communications, and for surface communications, the IEEE 802.11 standards are the most used for short and medium range communications.

With regard to the usage of different unmanned vehicles from different vendors (either aerial or aquatic), we have noticed that the interoperability between them is sometimes a limiting factor. This has been mentioned in the literature, as for example in [74] for aquatic missions and in [114] for aerial missions. It is not strange to find applications that need vehicles with different capabilities, i.e. a heterogeneous set of vehicles in which each one (or each sub-group) has a different role which is equally important for the successful accomplishment of the mission objectives. Often, to work with vehicles with different features implies acquiring some from a vendor and others from a different one. To the knowledge of the authors, there is none or few efforts put in solving interoperability issues.

Referring to routing protocols, there is a set of protocols that can be used for setting up a UAAV network. However, and as it has been stated before, many of these protocols come from other network paradigms such as MANETs. It is obvious that there are important differences between generic MANETs and specific AANETs [3] and AQNETs. Also, it is important to study the already available routing algorithms for UAAV networks in application specific situations. For example, it is not the same to have an AANET in which the UAVs acts as access points (i.e. hovering in specific positions as if they were fixed access points), than another situation in which UAVs are flying all over the scenario area in an exploration mission. For these two situations most of the existing routing protocols will probably perform well in one of the two situations, while doing it badly in the other one. Thus, there is not a single routing protocol that can be pointed as the best one among the others. It is important to highlight that hybrid routing approaches have been developed, for example, mixing the advantages of reactive and proactive routing protocols. Also, developing some intelligent strategies that allows the network to reconfigure its routing protocol and adapting it to the application requirements is a very interesting research direction. This is an approach worth to consider when developing new routing solutions for UAAV networks.

Regarding aquatic networks, there are still few implementations of swarms of vehicles. Most efforts have been put in developing robust surface or underwater vehicles. In general, the scenarios observed in this survey are mainly between one USV and a command center, or among a few UUVs or USVs and a command center. However some works like [51,53] and [96] are working towards even lower cost prototypes in order to deploy a larger swarm of vehicles. This directly relates to the scalability issue, which few works have treated properly [53,103]. The fact that most of the works, both aerial and aquatic, concentrate on developing solutions for a low number of vehicles pose the question whether these solutions will be applicable to more numerous UAAV networks or on the contrary they will not be scalable.

By comparing aerial and aquatic networks, we have detected that there is a higher number and more strict requirements for UAV–UAV wireless communications than for aquatic vehicles. This may be due to the fact that the majority of aquatic applications are devoted to environment monitoring, which have less demanding wireless communication requirements. On the contrary, as we have seen on the literature reviewed, aerial applications are usually oriented to disaster or military scenarios, which implies developing the mission tasks in the minimum amount of time and thus the UAAV network needs to provide accurate communication services in short time slots. Because of the aforementioned aspects, the wireless communication requirements are more challenging in aerial applications.

6.2. Open challenges

Apart from the specific communication technology used, there are several challenges that must be addressed in order to guarantee reliable, robust and application-efficient communications between unmanned vehicles, no matter the technology selected [170].

Control communication links need to be more robust and reliable, which means that more demanding requirements in terms of latency and security must be achieved. This requirement is important for UAAV–UAAV links as well as for UAAV-ground links. The main problem related to this challenge is the vehicles' mobility. If one of the nodes of the network is moving rapidly, serious Doppler frequencies may appear thus deteriorating the communications performance [171]. Also, it is widely known that the air is a widely used communication channel. This clearly makes interferences an aspect that should be taken into account in most of the research devoted to AANETs, however, we have find very few works that have this aspect into consideration. Interference cancellation strategies must be carefully considered in UAAV–UAAV links in order to reduce the interference effects. This is not a trivial aspect as UAAV networks usually use frequency bands which are license free. Interference cancellation among the different wireless technologies implemented in the vehicles should be also considered. This may be even more problematic in critical applications such emergency response.

Regarding the communication between drones in the underwater environment, there is plenty of room for improvement because acoustic communications have not been developed greatly so far. A few ideas for improvement are: the migration from single carrier transmission to multi-carrier modulation in the form of orthogonal frequency division multiplexing (OFDM); and the possibility of using multi-input multi-output (MIMO) techniques for rate and performance improvement [21]. Other aspects to be considered as well are the traffic congestion control, due to the delay; efficient multi-hop acoustic routing, because considering flooding and proactive routing is not possible; distributed localization and time synchronization, because of the lack of GPS signal; and efficient multiple access, because contention-based mechanisms are not suitable [21]. In the aquatic surface environment, there is a need for defining an adequate communication protocol for USV–USV communication, where the IEEE 802.15.4 arises as an interesting candidate to be thoroughly evaluated. DTN is a candidate communication paradigm that should be explored in field when prototype vehicles are available for deployment. There are studies for the use of DTNs in maritime environments that can be adapted to the case of USV networks. With regard to underwater networks, there is a lack of propagation models for these environments.

There is a real need for developing new mobility models for UAAV networks. Clearly, it is not appropriate to evaluate applications where the network nodes tend to move together using simple mobility models like the famous random waypoint mobility model. Multi-vehicle coordination must be addressed effectively in order to guarantee the network connectivity under a dynamic topology. Topology control strategies have been developed mainly for MANETs [172]. Also, several works have addressed this issue for AANETs [12] and AQNETs [32]. Nevertheless, more control strategies can be developed in order to strengthen the solutions available for addressing this challenge. For example, in [11] several basic mobility tasks for multi-vehicle operations are designed and tested, which are: i) homing, ii) dispersion, iii) clustering, and iv) area monitoring. Obviously, real applications need more complex mobility algorithms than basic ones. However, already developed and tested basic mobility models which take care of topology control and the effect on communication protocols, among other aspects, could be used to create a database-like compilation of basic mobility components. This compilation would make easier to build more complex mobility algorithms from basic ones, and also it would require less time of development. Also, this approach could enable to reuse algorithms and software solutions for different types of applications. This approach of basic components reuse [173] is widely used in other research areas such as computer science and also in the software development industry, and it would be interesting to put research efforts in this direction in order to see whether it also favors the development of UAAV networks solutions or not.

In autonomous mobile vehicles, energy-efficient operation must be developed in order to guarantee persistent service delivery and successful task accomplishment. In aerial and aquatic vehicles, the most energy demanding aspect comes from the motor operation. However, the energy demands varies considerably depending on the type of vehicle, for example, a multi copter would drain a battery faster than a fixed-wing aerial vehicle of the same size and weight, due to the nature of the vehicle dynamics (a fixed-wing aerial vehicle takes advantage of aerodynamics for flying, while a multi copter has to push air down in order to maintain its altitude). Also, the environment conditions are very important both in aerial and aquatic scenarios, because atmospheric phenomena (such as rain, tides, water or air currents, among others), could increase importantly the vehicles energy consumption. Also, some applications of UAAV networks are characterized by long operation missions, thus the vehicles forming the network should be on operation for hours. Replenishment strategies have been considered as a solution for dealing with energy consumption aspects in some works [25]. Different mechanisms can be used in order to schedule charging time slots for each vehicle. This is one of the biggest challenges for AANETs and more specifically for those using rotary-wing UAVs as these are the most energy-consuming vehicles. Less energy-demanding than the mobility of the vehicles are the communications, however they should be taken into account as they also requires energy from the same batteries than power the vehicles motors. Low consumption communication links and cross-layer energy efficient wireless technologies are one approach to address this issue. Usually, this is addressed by maximizing the relation between the amounts of information bits successfully delivered per energy unit. Clearly, the wireless technology used and its range also affects to the energy consumption aspects, for example, IEEE 802.15.4 is a low-consumption standard per design which works at lower data rates than IEEE 802.11. Also, some versions of the IEEE 802.11, like 802.11ah, have higher transmission ranges than IEEE 802.15.4. Because of this, the wireless technology, the application requirements and the type of vehicle used should be selected coherently when designing a UAAV network from an energy consumption perspective. The viability of the success of UAAV networks as a tool for many real applications closely depends on the developments on energy related aspects.

Having already addressed and described the technology used for UAAV–UAAV links and also some of the main challenges that are faced by them, it is important to highlight that the wireless technology performance is highly dependent on the application and there is not a preferred one. We envision that, in the future, each node in a UAAV network will be equipped with different communication technologies. As aforementioned, each of these communication technologies will perform better than the others in a specific application scenario. Then, the software that controls the communication tasks of each node will be able to monitor the communication channel and the scenario conditions in order to select the most appropriate technology for each situation. This process should be done in a distributed manner in which each pair of nodes in the network agrees on using the most appropriate communication technology for them. This is similar to the concept of heterogeneous wireless networks (HWN) [174] and self-organizing networks (SON) [175] that have been under study for several years now. These concepts are focusing on common infrastructure networks such as the mobile communication framework. However, this same idea could be used in UAAV networks by thinking of intelligent aerial and aquatic vehicles that are able to select autonomously the specific wireless technology that is more appropriate for communicating with each other in a specific situation. Or also, future UAAV networks will be able to change to a less energy-demanding or less interference-sensible wireless communication technology if it is needed. These situations may seem far goals today, and there is a lot of work to do for reaching them, however if we have today more intelligent networks in other communication fields, we believe that in the future this would be a reality for UAAV networks.

Regarding simulation-related aspects, several works such as [13] and [4] carry out simulations with UAVs considering a very simple communication model between UAVs. This could be improved by using a more complete model. The integration of these UAV-movements simulators with network simulators could be a step forward for providing more reality to the simulated applications. Furthermore, many simulators have been proposed for UAAV networks, especially for UAVs. In these simulators, it is common to emulate movement and control laws [137,140,148,149]. However, they do not consider the communication between vehicles in terms of being able to emulate new routing protocols, energy models and propagation models, which are common parameters in network simulators [153,154]. Therefore, it could be interesting to integrate the proposed simulators for UAAVs and well-known network simulators.

It has already been pointed out in the Section 6.1, that several works found interoperability issues when developing UAAV networks applications with vehicle types from different vendors [114,74]. In the future, UAAV networks would become part of our lives and it is now the time to start working on interoperability and standardization aspects. It is obvious that, from the standardization point of view, the collaboration from the research community, the industry and regulatory organizations (e.g. governments) would be beneficial for an efficient development of the technology. Also, focusing in the regulatory aspects, governments have issued the first regulations concerning UAVs usage for civilian applications recently [160].

7. Conclusions

The use of UAAV networks for a plethora of common applications will make possible a near future, in which our skies and high water areas will be full of unmanned vehicles providing communication services. To accomplish this objective, many technological challenges related to the wireless communication among UAAVs need to be solved. This survey has presented together the main features of AANETs and AQNETs, from an ad hoc wireless communication point of view. The aim of presenting together both types of networks is to raise awareness on solutions and approaches that can be valid for both AANETs and AQNETs. We have reviewed the main types of wireless communications in UAAV networks and the wireless technologies that can be used. We have also reviewed the main evaluation tools available nowadays to assess UAAV networks. In addition, we include the results of several bibliometric-based analyses performed over the literature reviewed as part of the main lessons learned. Finally, the main open challenges about the design and evaluation of UAAV networks have been indicated. We hope that this survey will be useful as a starting point for many researchers, practitioners and professionals interested in working on the UAAV networks design.

References

[1] L. Gupta, R. Jain, G. Vaszkun, Survey of important issues in UAV communication

networks, IEEE Commun. Surv. Tutor. 18 (2) (2015) 1123–1152.

[2] S. Hayat, E. Yanmaz, R. Muzaffar, Survey on unmanned aerial vehicle networks for civil applications: a communications viewpoint, IEEE Commun. Surv. Tutor. 18 (4) (2016) 2624–2661.

[3] I. Bekmezci, O.K. Sahingoz, Ş. Temel, Flying ad-hoc networks (FANETs): a survey, Ad Hoc Netw. 11 (3) (2013) 1254–1270.

[4] J. Sánchez-García, J. García-Campos, S. Toral, D.G. Reina, F. Barrero, An intelligent strategy for tactical movements of UAVs in disaster scenarios, Int. J. Distrib. Sens. Netw. 12 (3) (2016) 1–20.

[5] H. Ferreira, C. Almeida, A. Martins, J. Almeida, N. Dias, A. Dias, E. Silva, Autonomous bathymetry for risk assessment with ROAZ robotic surface vehicle, IEEE OCEANS, Bremen, Germany, 2009, pp. 1–6.

[6] J. Cui, S.J. Kong, M. Gerla, The challenges of building scalable mobile underwater wireless sensor networks for aquatic applications, IEEE Netw. 20 (2006) 12–18.

[7] D.N. Sandeep, V. Kumar. “Review on clustering, coverage and connectivity in underwater wireless sensor networks: a communication techniques perspective”. IEEE Access. doi:10.1109/ACCESS.2017.2713640.

[8] M. Ayaz, I. Baig, A. Abdullah, I. Faye, A survey on routing techniques in underwater wireless sensor networks, J. Netw. Comput. Appl. 34 (2011) 1908–1927.

[9] S. Gomáriz, I. Masmitjà, J. González, G. Masmitjà, J. Prat, GUANAY-II: an autonomous underwater vehicle for vertical/horizontal sampling, J. Mar. Sci. Technol. 20 (1) (2015) 81–93.

[10] M. Conti, S. Giordano, Mobile Ad Hoc networking: milestones, challenges, and new research directions, IEEE Commun. Mag. 52 (1) (2014) 85–96.

[11] M. Duarte, V. Costa, J. Gomes, T. Rodrigues, F. Silva, S.M. Oliveira, A.L. Christensen, Evolution of collective behaviors for a real swarm of aquatic surface robots, PLoS One 11 (2016) 1–25.

[12] K. Daniel, S. Rohde, N. Goddemeier, C. Wietfeld, ”Cognitive agent mobility for aerial sensor networks”, IEEE Sens. J. 11 (11) (2011) 2671–2682.

[13] J.J. Acevedo, B.C. Arrue, J.M. Diaz-Bañez, I. Ventura, I. Maza, A. Ollero, One-to-one coordination algorithm for decentralized area partition in surveillance missions with a team of aerial robots, J. Intell. Robot. Syst. 74 (1) (2014) 269–285.

[14] P. Grippa, D.A. Behrens, C. Bettstetter and F. Wall, “Job Selection in a Network of Autonomous UAVs for Delivery of Goods”, (2016). arXiv:1604.04180.

[15] K. Uto, H. Seki, G. Saito, Y. Kosugi, Characterization of rice paddies by a UAV-mounted miniature hyperspectral sensor system, IEEE J. Select. Top. Appl. Earth Observat. Remote Sens. 6 (2) (2013) 851–860.

[16] P. Tokekar, E. Branson, J.V. Hook, V. Isler, Tracking aquatic invaders: autonomous robots for monitoring invasive fish, IEEE Robot. Autom. Mag. 20 (3) (2013) 33–41.

[17] F. Marques, A. Lourenço, R. Mendonça, E. Pinto, P. Rodrigues, P. Santana, J. Barata, A critical survey on marsupial robotic teams for environmental monitoring of water bodies, IEEE Oceans, Genova, Italy, 2015, pp. 1–6.

[18] M. Erdelj, M. Król, E. Natalizio. “Wireless sensor networks and multi-UAV systems for natural disaster management”. Comput. Netw. doi:https://doi.org/10.1016/j.comnet.2017.05.021.

[19] A. Wichmann, B.D. Okkalioglu, T. Korkmaz, The integration of mobile (tele) robotics and wireless sensor networks: a survey, Comput. Commun. 51 (2014) 21–35.

[20] J. Scherer, S. Yahyanejad, S. Hayat, E. Yanmaz, T. Andre, A. Khan, V. Vukadinovic, C. Bettstetter, H. Hellwagner, B. Rinner, An Autonomous multi-UAV system for search and rescue, First Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use (DroNet'15), Florence, Italy, 2015, pp. 33–38.

[21] J.H. Cui, J. Kong, M. Gerla, S. Zhou, The challenges of building mobile underwater wireless networks for aquatic applications, IEEE Netw. 20 (3) (2006) 12–18.

[22] D.G. Reina, J.M. León-Coca, S.L. Toral, E. Asimakopoulou, F. Barrero, P. Norrington, N. Bessis, Multi-objective performance optimization of a probabilistic similarity/dissimilarity-based broadcasting scheme for mobile ad hoc networks in disaster response scenarios, Soft Comput. 18 (9) (2014) 1745–1756.

[23] R. Ciobanu, D.G. Reina, C. Dobre, S. Toral, P. Johnson, JDER: a history-based forwarding scheme for delay tolerant networks using Jaccard distance and encountered ration, J. Netw. Comput. Appl. 40 (2014) 279–291.

[24] M. Conti, S. Giordano, Multihop ad hoc networking: the reality, IEEE Commun. Mag. 45 (4) (2007) 88–95.

[25] M. Di Felice, A. Trotta, L. Bedogni, K. Chowdhury, L. Bononi, Self-organizing aerial mesh networks for emergency communication, IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication, Washington DC, USA, 2014, pp. 1631–1636.

[26] B.T. Sharef, R.A. Alsaqour, M. Ismail, Vehicular communication ad hoc routing protocols: a survey, J. Netw. Comput. Appl. 40 (2014) 363–396.

[27] J.M. León-Coca, D.G. Reina, S.L. Toral, F. Barrero, N. Bessis, Intelligent transportation systems and wireless access in vehicular environment technology for developing smart cities, Big Data and Internet of Things: A Roadmap For Smart Environments, Springer International Publishing, Switzerland, 2014, pp. 285–313.

[28] J. Sánchez-García, J.M. García-Campos, D.G. Reina, S.L. Toral, F. Barrero, A self-organizing aerial ad hoc network mobility model for disaster scenarios, 8th International Conference on Developments in e-Systems Engineering, Dubai, UAE, 2015, pp. 35–40.

[29] F.J. Velez, A. Nadziejko, A.L. Christensen, S. Oliveira, T. Rodrigues, V. Costa, M. Duarte, F. Silva, J. Gomes, Wireless sensor and networking technologies for swarms of aquatic surface drones, Vehicular Technology Conference (VTC Fall), Boston, MA, USA, 2015, pp. 1–2.

[30] Y.L. Wang, Q.L. Han, Network-based fault detection filter and controller coordinated design for unmanned surface vehicles in network environments, IEEE Trans. Ind. Inf. 12 (5) (2016) 1753–1765.

[31] Z. Peng, D. Wang, Z. Chen, X. Hu, W. Lan, Adaptive dynamic surface control for formations of autonomous surface vehicles with uncertain dynamics, IEEE Trans. Control Syst. Technol. 21 (2) (2012) 513–520.

[32] P. Millán, L. Orihuela, I. Jurado, F.R. Rubio, Formation control of autonomous underwater vehicles subject to communication delays, IEEE Trans. Control Syst. Technol. 22 (2) (2013) 770–777.

[33] E. Thurman, J. Riordan, D. Toal, Real-time adaptive control of multiple colocated acoustic sensors for an unmanned underwater vehicle, IEEE J. Ocean. Eng. 38 (3) (2013) 419–432.

[34] K. Dalamagkidis, Classification of UAVs, Handbook of Unmanned Aerial Vehicles, Springer Netherlands, Netherlands, 2015, pp. 83–92.

[35] D. Alejo, J.A. Cobano, G. Heredia, A. Ollero, Collision-free 4D trajectory planning in unmanned aerial vehicles for assembly and structure construction, J. Intell. Robot. Syst. 73 (1) (2014) 783–795.

[36] I.G. Petrovski, GPS, GLONASS, Galileo, and BeiDou signals, GPS, GLONASS, Galileo, and BeiDou for Mobile Devices, Cambridge University Press, United Kingdom, 2014, pp. 39–87.

[37] H. Skinnemoen, UAV & satellite communications live mission-critical visual data, IEEE International Conference on Aerospace Electronics and Remote Sensing Technology (ICARES), Yogyakarta, Indonesia, 2014, pp. 12–19.

[38] Z. Liu, Y. Zhang, X. Yu, C. Yuan, Unmanned surface vehicles: an overview of developments and challenges, Annu. Rev. Control 41 (2016) 71–93.

[39] M.C. Domingo, An overview of the Internet of underwater things, J. Netw. Comput. Appl. 35 (6) (2012) 1879–1890.

[40] K.H. Low, G. Podnar, S. Stancliff, J.M. Dolan, A. Elfes, Robot boats as a mobile aquatic sensor network, Proceedings of the IPSN-09 Workshop on Sensor Networks for Earth and Space Science Applications, San Francisco, CA, USA, 2009, pp. 1–8.

[41] T. Schmickl, R. Thenius, C. Moslinger, J. Timmis, A. Tyrrell, M. Read, L. Manfredi, CoCoRo–the self-aware underwater swarm, Fifth IEEE Conference on Self-Adaptive and Self-Organizing Systems Workshops (SASOW), Ann Arbor, MI, USA, 2011, pp. 120–126.

[42] J. Kong, J.H. Cui, D. Wu, M. Gerla, Building underwater ad-hoc networks and sensor networks for large scale real-time aquatic applications, IEEE Military Communications Conference (MILCOM), Atlantic City, NJ, USA, 2005, pp. 1535–1541.

[43] D. Sutantyo, P. Levi, Decentralized underwater multi-robot communication using bio-inspired approaches, Artif. Life Robot. 20 (2) (2015) 152–158.

[44] J. Curcio, J. Leonard, J. Vaganay, A. Patrikalakis, A. Bahr, D. Battle, M. Grund, Experiments in moving baseline navigation using autonomous surface craft, Proceedings of MTS/IEEE OCEANS, Washington DC, USA, 2005, pp. 730–735.

[45] C.C. Françolin, A.V. Rao, C. Duarte, G. Martel, Optimal control of a surface vehicle to improve underwater vehicle network connectivity, J. Aerosp. Comput., Inf. Commun. 9 (1) (2012) 1–13.

[46] M. Grund, K. Ball, A mobile communications gateway for AUV telemetry, IEEE Oceans, San Diego, CA, USA, 2013, pp. 1–5.

[47] C. Murphy, J.M. Walls, T. Schneider, R.M. Eustice, M. Stojanovic, H. Singh, CAPTURE: a communication architecture for progressive transmission via underwater relays with eavesdropping, IEEE J. Ocean. Eng. 39 (1) (2014) 120–130.

[48] S. Singh, S.E. Webster, L. Freitag, L.L. Whitcomb K. Ball, J. Bailey, C. Taylor, Acoustic communication performance of the WHOI micro-modem in sea trials of the Nereus vehicle to 11,000 m depth, MTS/IEEE OCEANS, Bremen, Germany, 2009, pp. 1–6.

[49] J. Curcio, J. Leonard, J. Vaganay, A. Patrikalakis, A. Bahr, D. Battle, M. Grund, Experiments in moving baseline navigation using autonomous surface craft, Proceedings of MTS/IEEE OCEANS, Washington DC, USA, 2005, pp. 730–735.

[50] T.A. Johansen, A. Zolich, T. Hansen, A.J. Sorensen, Unmanned aerial vehicle as communication relay for autonomous underwater vehicle-field tests, IEEE Globecom Workshops, Austin, TX, USA, 2014, pp. 1469–1474.

[51] A. Amory, B. Meyer, C. Osterloh, T. Tosik, E. Maehle, Towards fault-tolerant and energy-efficient swarms of underwater robots, IEEE 27th International Parallel and Distributed Processing Symposium Workshops & PhD Forum (IPDPSW), Cambridge, MA, USA, 2013, pp. 1550–1553.

[52] J.A. Curcio, P.A. McGillivary, K. Fall, A. Maffei, K. Schwehr, B. Twiggs, P. Ballou, Self-positioning smart buoys, the Un-Buoy solution: logistic considerations using autonomous surface craft technology and improved communications infrastructure, IEEE Oceans, Singapore, Singapore, 2006, pp. 1–5.

[53] A.L. Christensen, S.M. Oliveira, O. Postolache, M.J. de Oliveira, S. Sargento, P. Santana, L. Nunes, F. Velez, P. Sebastião, V. Costa, M. Duarte, J. Gomes, T. Rodrigues, F. Silva, Design of communication and control for swarms of aquatic surface drones, 7th International Conference on Agents and Artificial Intelligence (ICAART), Lisbon, Portugal, 2015, pp. 548–555.

[54] J. Allred, A.B. Hasan, S. Panichsakul, W. Pisano, P. Gray, J. Huang, R. Han, D. Lawrence, K. Mohseni, SensorFlock: an airborne wireless sensor network of micro-air vehicles, Proceedings of the 5th international conference on Embedded networked sensor systems (SenSys '07), Sydney, Australia, 2007, pp. 117–129.

[55] S. Hayat, E. Yanmaz, C. Bettstetter, Experimental analysis of multipoint-to-point UAV communications with IEEE 802.11n and 802.11ac, IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Hong Kong, China, 2015, pp. 1991–1996.

[56] M. Asadpour, D. Giustiniano, K.A. Hummel, S. Heimlicher, Characterizing 802.11n aerial communication, Proceedings of the second ACM MobiHoc workshop on Airborne networks and communications (ANC), Bangalore, India, 2013, pp. 7–12.

[57] M. Asadpour, B. Van den Bergh, D. Giustiniano, K.A. Hummel, S. Pollin, B. Plattner, Micro aerial vehicle networks: an experimental analysis of challenges and opportunities, IEEE Commun. Mag. 52 (7) (2014) 141–149.

[58] E. Yanmaz, S. Hayat, J. Scherer, C. Bettstetter, Experimental performance analysis of two-hop aerial 802.11 networks, IEEE Wireless Communications and Networking Conference (WCNC), Istambul, Turkey, 2014, pp. 3118–3123.

[59] G.R. Hiertz, D. Denteneer, L. Stibor, Y. Zang, X. Pérez-Costa, B. Walke, The IEEE 802.11 Universe, IEEE Commun. Mag. 48 (1) (2010) 62–70.

[60] E. Yanmaz, R. Kuschnig, C. Bettstetter, Achieving air-ground communications in 802.11 networks with three-dimensional aerial mobility, Proceedings of the IEEE INFOCOM, Turin, Italy, 2013, pp. 120–124.

[61] T. Brown, B. Argrow, C. Dixon, S. Doshi, R.G. Thekkekunnel, D. Henkel, Ad hoc uav ground network (AUGNet), AIAA 3rd "Unmanned Unlimited" Technical Conference, Chicago, IL, USA, 2004, pp. 1–11.

[62] S. Morgenthaler, T. Braun, Z. Zhongliang, T. Staub, M. Anwander, UAVNet: a mobile wireless mesh network using unmanned aerial vehicles, IEEE Globecom Workshops, Anaheim, CA, USA, 2012, pp. 1603–1608.

[63] ZigBee Alliance, ZigBee Alliance, [Online]. AvailableAccessed on: February 6 http://www.zigbee.org/, (2016) Accessed on: February 6.

[64] Digi International Inc., XBee, [Online]. Available:Accessed on: February 6 http://www.digi.com/lp/xbee, (2016) Accessed on: February 6.

[65] J.M. Kahn, J.R. Barry, Wireless infrared communications, Proc. IEEE 85 (2) (1997) 265–298.

[66] IrDA, Infrared Data Association, [Online]. Available:Accessed on: March 21 http://www.irdajp.info/index.html, (2016) Accessed on: March 21.

[67] F. Ducatelle, G.A. Di Caro, C. Pinciroli, F. Mondada, L. Gambard, Communication assisted navigation in robotic swarms: self-organization and cooperation, IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, CA, USA, 2011, pp. 4981–4988.

[68] A.C. Watts, V.G. Ambrosia, E.A. Hinkley, Unmanned aircraft systems in remote sensing and scientific research: classification and considerations of use, Remote Sens. 4 (6) (2012) 1671–1692.

[69] H. Sheng, H. Chao, C. Coopmans, J. Han, M. McKee, Y. Chen, Low-cost UAV-based thermal infrared remote sensing: platform, calibration and applications, IEEE/ASME International Conference on Mechatronics and Embedded Systems and Applications (MESA), Qingdao, China, 2010, pp. 38–43.

[70] M. Saska, T Krajnik, L. Pfeucil, Cooperative μUAV-UGV autonomous indoor surveillance, International Multi-Conference on Systems, Signals and Devices (SSD), Chemnitz, Germany, 2012, pp. 1–6.

[71] M.A. BinYusof, S. Kabir, Underwater communication systems: a review, Progress In Electromagnetics Research Symposium Proceedings (PIERS), Marrakesh, Morocco, 2011, pp. 803–807.

[72] R. Nitzel, C. Benton, S.G. Chappell, D.R. Blidberg, Exploiting dynamic source routing to enable undersea networking over an ad-hoc topology, Proceedings of the 2002 International Symposium on Underwater Technology, Tokyo, Japan, 2002, pp. 273–277.

[73] R.J. Komerska, S.G. Chappell, A Simulation environment for testing and evaluating multiple cooperating solar-powered AUVs, IEEE OCEANS, Boston, MA, USA, 2006, pp. 1–6.

[74] R. Martins, J.B. de Sousa, C. Carvalho Afonso, M.L. Incze, REP10 AUV: shallow water operations with heterogeneous autonomous vehicles, IEEE Oceans, Santander, Spain, 2011, pp. 1–6.

[75] IT - Instituto de Telecomunicações, “PROJECT/HANCAD”. [Online]. Available: https://www.it.pt/Projects/Index/1962. Accessed on: May 9, 2016.

[76] S. Nolfi, D. Floreano, Evolutionary Robotics: The Biology, Intelligence, and Technology of Self-Organizing Machines, MIT Press, Cambridge, MA, USA, 2000.

[77] R. Bartos, V.S. Gorla, L.N. Cyril, R. Sharma, R.J. Komerska, S.G. Chappell, Experimental evaluation of RF modems for use in fleets of multiple cooperating autonomous undersea vehicles, IEEE Oceans, Boston, MA, USA, 2006, pp. 1–6.

[78] S. Wolf, J. Davis, M. Nisenoff, Superconducting extremely low frequency (ELF) magnetic field sensors for submarine communications, IEEE Trans. Commun. 22 (4) (1974) 549–554.

[79] D.F. Rivera, Submarine towed communication antennas: past, present and future, IEEE Antennas and Propagation Society International Symposium, Boston, MA, USA, 2001, pp. 426–429.

[80] M. Callaham, Submarine communications, IEEE Commun. Mag. 19 (6) (1981) 16–25.

[81] D.G. Reina, S.L. Toral, P. Johnson, F. Barrero, A survey on probabilistic broadcast schemes for wireless Ad Hoc networks, Ad Hoc Netw. 25 (Part A) (2015) 263–292.

[82] J.M. García-Campos, J. Sánchez-García, D.G. Reina, S.L. Toral, F. Barrero, An evaluation methodology for reliable simulation based studies of routing protocols in VANETs, Simul. Modell. Pract. Theory 66 (2016) 139–165.

[83] S.M.S. Bari, F. Anwar, M.H. Masud, Performance study of hybrid Wireless Mesh Protocol (HWMP) for IEEE 802.11s WLAN mesh networks, International Conference on Computer and Communication Engineering (ICCCE), Kuala Lumpur, Malaysia, 2012, pp. 712–716.

[84] C. Perkins, E. Belding-Royer, S. Das, Ad hoc on-demand distance vector (AODV) Routing (RFC 3561), Network Working Group, The Internet Engineering Task Force (IETF), 2016 [Online]. Available https://tools.ietf.org/html/rfc3561 Accessed on: February 9.

[85] S. Rosati, K. Krużelecki, G. Heitz, D. Floreano, B. Rimoldi, Dynamic routing for flying ad hoc networks, IEEE Trans. Vehicul. Technol. 65 (3) (2016) 1690–1700.

[86] D. Johnson, D. Maltz, Dynamic source routing in Ad Hoc wireless networks, Mobile Computing, Springer US, USA, 1996, pp. 153–181.

[87] M. Asadpour, S. Egli, K.A. Hummel, D. Giustiniano, Routing in a fleet of micro aerial vehicles: first experimental insights, Proceedings of the Third ACM Workshop on Airborne Networks and Communications, Philadelphia, USA, 2014, pp. 9–10.

[88] L. Lin, Q. Sun, S. Wang, F. Yang, A geographic mobility prediction routing protocol for ad hoc UAV network, Proceedings of the IEEE Globecom Workshop (GC Wkshps), 2012, pp. 1597–1602.

[89] B. Karp, H.T. Kung, GPSR: greedy perimeter stateless routing for wireless networks, Proceedings of the 6th Annual ACM International Conference on Mobile Computing and Networking (MobiCom), 2000, pp. 243–254.

[90] R. Shirani, M. St-Hilaire, T. Kunz, Y. Zhou, J. Li, L. Lamont, On the delay of reactive-greedy-reactive routing in unmanned aeronautical ad-hoc networks, Proc. Comput. Sci. 10 (2012) 535–542.

[91] R. Shirani, M. St-Hilaire, T. Kunz, Y. Zhou, J. Li, L. Lamont, The performance of greedy geographic forwarding in unmanned aeronautical ad-hoc networks, Communication Networks and Services Research Conference (CNSR), 2011, pp. 161–166.

[92] S. Wang, C. Fan, C. Deng, W. Gu, Q. Sun, F. Yang, A-GR: a novel geographical routing protocol for AANETs, J. Syst. Archit. 59 (2013) 931–937.

[93] T. Hu, Y. Fei, QELAR: a machine-learning-based adaptive routing protocol for energy-efficient and lifetime-extended underwater sensor networks, IEEE Trans. Mobile Comput. 9 (2010) 796–809.

[94] L.T. Lilien, L. Othmane, P. Angin, A. DeCarlo, R.M. Salih, B. Bhargava, A simulation study of ad hoc networking of UAVs with opportunistic resource utilization networks, J. Netw. Comput. Appl. 38 (2014) 3–15.

[95] E. Kulla, M. Hiyama, M. Ikeda, L. Barolli, Performance comparison of OLSR and BATMAN routing protocols by a MANET testbed in stairs environment, Comput. Math. Appl. 63 (2) (2012) 339–349.

[96] M. Dunbabin, Autonomous greenhouse gas sampling using multiple robotic boats, Field and Service Robotics, Springer International Publishing, Switzerland, 2016, pp. 17–30.

[97] D. Machado, A. Martins, J.M. Almeida, H.G.B. Ferreira, A. Matos, E. Silva, Water jet based autonomous surface vehicle for coastal waters operations, IEEE Oceans, St. John's, NL, Canada, 2014, pp. 1–8.

[98] M. Dunbabin, A. Grinham, J. Udy, An autonomous surface vehicle for water quality monitoring, Australian Conference on Robotics and Automation (ACRA), Sydney, Australia, 2009, pp. 2–4.

[99] G.S. Sukhatme, A. Dhariwal, B. Zhang, C. Oberg, B. Stauffer, D.A. Caron, Design and development of a wireless robotic networked aquatic microbial observing system, Environ. Eng. Sci. 24 (2) (2007) 205–215.

[100] A. Valada, P. Velagapudi, B. Kannan, C. Tomaszewski, G. Kantor, P. Scerri, Development of a low cost multi-robot autonomous marine surface platform, Field and Service Robotics 92 Springer Berlin Heidelberg, Germany, 2014, pp. 643–658.

[101] E. Pinto, F. Marques, R. Mendonça, A. Lourenço, P. Santana, J. Barata, An autonomous surface-aerial marsupial robotic team for riverine environmental monitoring: benefiting from coordinated aerial, underwater, and surface level perception, IEEE International Conference on Robotics and Biomimetics (ROBIO), Bali, Indonesia, 2014, pp. 443–450.

[102] D. Hiranandani, K. Obraczka, J.J. García-Luna-Aceves, MANET protocol simulations considered harmful: the case for benchmarking, IEEE Wirel. Commun. 20 (4) (2013) 82–90.

[103] N. Michael, D. Mellinger, Q. Lindsey, V. Kumar, The GRASP multiple micro-UAV testbed, IEEE Robot. Autom. Mag. 17 (3) (2010) 56–65.

[104] Z. Feng, G. Shan, L. Lian, A low-cost testbed of underwater mobile sensing network, IEEE Oceans, Sydney, Australia, 2010, pp. 1–5.

[105] B. Chen, D. Pompili, A testbed for performance evaluation of underwater vehicle team formation and steering algorithms, IEEE SECON, Boston, MA, USA, 2010, pp. 1–3.

[106] J. Xiangyu, W. Sentang, L. Xiang, D. Yang, T. Jiqiang, Research and design on physical multi-UAV system for verification of autonomous formation and cooperative guidance, Proceedings of the 2010 International Conference on Electrical and Control Engineering (ICECE '10), Wuhan, China, 2010, pp. 1570–1576.

[107] A. Alshanyour, U. Baroudi, Random and realistic mobility models impact on the performance of bypass-aodv routing protocol, Wireless days, Dubai, UAE, 2008, pp. 1–5.

[108] E.S.A. Ahmed, B.E.S. Ali, E.O. Osman, T. Amin, M. Ahmed, Performance evaluation of personal ad-hoc area network based on different mobility models, Int. Res. J. Eng. Technol. 3 (2) (2016) 585–589.

[109] F. Bai, N. Sadagopan, A. Helmy, IMPORTANT: a framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks, Twenty-second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM), San Francisco, CA, USA, 2003, pp. 825–835.

[110] E. Royer, P.M. Melliar-Smith, L.E. Moser, An analysis of the optimum node density for ad hoc mobile networks, International Conference on Communications (ICC), Helsinki, Finland, 2001, pp. 857–861.

[111] G. Maia, D.L. Guidoni, A.C. Viana, A.L.L. Aquino, R.A.F. Mini, A.A.F. Loureiro, A distributed data storage protocol for heterogeneous wireless sensor networks with mobile sinks, Ad Hoc Netw. 11 (5) (2013) 1588–1602.

[112] Z. Yan, N. Jouandeau, A.A. Cherif, A survey and analysis of multi-robot coordination, Int. J. Adv. Rob. Syst. 10 (12) (2013) 1–18.

[113] S. Joyeux, F. Kirchner, S. Lacroix, Managing plans: integrating deliberation and reactive execution schemes, Rob. Autom. Syst. 58 (9) (2010) 1057–1066.

[114] C. Zhang, J.M. Kovacs, The application of small unmanned aerial systems for precision agriculture: a review, Precis. Agricul. 13 (6) (2012) 693–712.

[115] C. Goerzen, Z. Kong, B. Mettler, A survey of motion planning algorithms from the perspective of autonomous UAV guidance, J. Intell. Rob. Syst. 57 (1) (2010) 65–100.

[116] M. Soucy, P. Payeur, Robot path planning with multiresolution probabilistic representations: a comparative study, Canadian Conference on Electrical and Computer Engineering, Niagara Falls, Ontario, Canada, 2 2004, pp. 1127–1130.

[117] H. Choset, S. Walker, K. Eiamsa-Ard, J. Burdick, Sensor-based exploration: Incremental construction of the hierarchical generalized Voronoi graph, Int. J. Rob. Res. 19 (2000) 126–128.

[118] T.D. Ngo, Distributed co-optimisation of throughput for mobile sensor networks, Distributed Autonomous Robotic Systems, Springer Japan, Japan, 2016, pp. 419–432.

[119] A.A. Masoud, Managing the dynamics of a harmonic potential field-guided robot in a cluttered environment, IEEE Trans. Indust. Electron. 56 (2009) 488–496.

[120] Y.-b. Chen, G.-c. Luo, Y.-s. Mei, J.-q. Yu, X.-l. Su, UAV path planning using artificial potential field method updated by optimal control theory, Int. J. Syst. Sci. 47 (6) (2014) 1407–1420.

[121] J.A. Cobano, R. Conde, D. Alejo, A. Ollero, Path planning based on genetic algorithms and the Monte-Carlo method to avoid aerial vehicle collisions under uncertainties, International conference on Robotics and Automation (ICRA), Shanghai, China, 2011, pp. 4429–4434.

[122] N. Kubota, Y. Toda, S. Suzuki, Cooperative formation of multi-robot based on spring model, International Conference on Robot, Vision and Signal Processing, Kitakyushu, Japan, 2013, pp. 72–77.

[123] S. Hauert, L. Winkler, J.-C. Zufferey, D. Floreano, Ant-based swarming with positionless micro air vehicles, Swarm Intell. 2 (2) (2008) 167–188.

[124] Z. Cheng, E. Wang, Y. Tang, Y. Wang, Real-time path planning strategy for UAV based on improved particle swarm optimization, J. Comput. 9 (1) (2014) 209–214.

[125] A.J. Pohl, G.B. Lamont, Multi-objective UAV mission planning using evolutionary computation, Winter Simulation Conference, Miami, FL, USA, 2008, pp. 1268–1279.

[126] C. Atten, L. Channouf, G. Danoy, P. Bouvry, UAV fleet mobility model with multiple pheromones for tracking moving observation targets, European Conference on the Applications of Evolutionary Computation, Porto, Portugal, 2016, pp. 332–347.

[127] J. Xie, Y. Wan, J.H. Kim, S. Fu, K. Namuduri, A survey and analysis of mobility models for airborne networks, IEEE Commun. Surv. Tutor. 16 (3) (2014) 1221–1237.

[128] T. Camp, J. Boleng, V. Davies, A survey of mobility models for ad hoc network research, Wirel. Commun. Mob. Comput. 2 (5) (2002) 483–502.

[129] J. Yoon, M. Liu, B. Noble, Random waypoint considered harmful, Twenty-Second Annual Joint Conference of the IEEE Computer and Communications (INFOCOM), San Francisco, CA, USA, 2003, pp. 1312–1321.

[130] W. Wang, X. Guan, B. Wang, Y. Wang, A novel mobility model based on semi-random circular movement in mobile ad hoc networks, Inf. Sci. 180 (3) (2010) 399–413.

[131] O. Bouachir, A. Abrassart, F. Garcia, N. Larrieu, A mobility model for UAV ad hoc network, International Conference on Unmanned Aircraft Systems (ICUAS), Orlando, FL, USA, 2014, pp. 383–388.

[132] J.-D. Medjo Me Biomo, T. Kunz, M. St-Hilaire, Y. Zhou, Unmanned aerial ad hoc networks: simulation-based evaluation of entity mobility models' impact on routing performance, Aerospace 2 (3) (2015) 392–422.

[133] R.R. Roy, Handbook of Mobile Ad Hoc Networks for Mobility Models, Springer US, USA, 2011.

[134] N. Aschenbruck, R. Ernst, E. Gerhards-Padilla, M. Schwamborn, BonnMotion-a mobility scenario generation and analysis tool, Proceedings of the 3rd International ICST Conference on Simulation Tools and Techniques (SIMUTools), Torremolinos, Spain, 2010, pp. 1–10.

[135] V. Rodríguez-Fernández, H.D. Menéndez, D. Camacho, Design and development of a lightweight multi-UAV simulator, IEEE 2nd International conference on Cybernetics (CYBCONF), Gdynia, Poland, 2015, pp. 255–260.

[136] J. Craighead, R. Murphy, J. Burke, B. Goldiez, A survey of commercial & open source unmanned vehicle simulators, International conference on Robotics and Automation, Roma, Italy, 2007, pp. 10–14.

[137] J. Zhang, Q. Geng, Q. Fei, UAV flight control system modeling and simulation based on flightGear, International Conference on Automatic Control and Artificial Intelligence (ACAI), Xiamen, China, 2012, pp. 2231–2234.

[138] T. Vogeltanz, A survey of free software for the design, analysis, modelling, and simulation of an unmanned aerial vehicle, Arch. Comput. Methods Eng. 23 (3) (2016) 449–514.

[139] C. Yun, X. Li, Design of UAV flight simulation software based on simulation training method, WSEAS Trans. Inf. Sci. Appl. 10 (2) (2013) 37–46.

[140] A.H. Goktogan, E. Nettleton, M. Ridley, S. Sukkarieh, Real time multi-UAV simulator, International Conference on Robotics and Automation, Taipei, Taiwan, 2003, pp. 2720–2726.

[141] R. Garcia, L. Barnes, Multi-UAV simulator utilizing X-Plane, J. Intell. Rob. Syst. 57 (1-4) (2010) 393–406.

[142] M. Pujol-Gonzalez, J. Cerquides, P. Meseguer, MAS-planes: a multiagent simulation environment to investigate decentralised coordination for teams of UAVs, International conference on Autonomous agents and multi-agent systems, Paris, France, 2014, pp. 1695–1696.

[143] P. Lu, Q. Geng, Real-time simulation system for UAV based on Matlab/Simulink, International Conference on Computing, Control and Industrial Engineering (CCIE), Wuhan, China, 2011, pp. 399–404.

[144] Q. Yin, B. Xian, Y. Zhang, Y. Yu, H. Li, W. Zeng, Visual simulation system for quadrotor unmanned aerial vehicles, Proceedings of the 30th Chinese Control Conference, Yantai, China, 2011, pp. 454–459.

[145] M. Prats, J. Pérez, J.J. Fernández, P.J. Sanz, An open source tool for simulation and supervision of underwater intervention missions, International Conference on Intelligent Robots and Systems, Vilamoura-Algarve, Portugal, 2012, pp. 7–12.

[146] O. Matsebe, C.M. Kumile, A review of virtual simulators for autonomous underwater vehicles (AUVs), IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles (NGCUV), Killaloe, Ireland, 2008, pp. 31–37.

[147] A. Boeing, T. Brunl, SubSim: An autonomous underwater vehicle simulation package, Proceedings of the 3rd International Symposium on Autonomous Minirobots for Research and Edutainment (AMiRE), Awara-Spa, Fukui, Japan, 2006, pp. 33–38.

[148] P. Ridao, E. Battle, D. Ribas, M. Carreras, NEPTUNE: a HIL simulator for multiple UUVs, IEEE OCEANS, Kobe, Japan, 2004, pp. 524–531.

[149] R. Mendonca, P. Santana, F. Marques, A. Lourenco, J. Silva, J. Barata, Kelpie: a ROS-based multi-robot simulator for water surface and aerial vehicles, International Conference on Systems, Man, and Cybernetics, Manchester, United Kingdom, 2013, pp. 3645–3650.

[150] A.M. Nogueira, WaVeSim - Ambiente de Simulação para Veículos Aquáticos, M.S. thesis Dept. Ciência de Computadores, Universidade do Porto, Porto, Portugal, 2007.

[151] N. Koenig, A. Howard, Design and use paradigms for Gazebo, an open-source multi-robot simulator, International Conference on Intelligent Robots and Systems (IROS), Sendai, Japan, 2004, pp. 2149–2154.

[152] Fugro General Robotics Ltd., "Deepworks". [Online]. Available: http://www.fugrogrl.com/software/. Accessed on: May 30, 2016.

[153] The network simulator, "ns-2". [Online]. Available: http://www.isi.edu/nsnam/ns/. Accessed on: May 30, 2016.

[154] H. Arbabi, M.C. Weigle, Highway mobility and vehicular ad-hoc networks in NS-3, Proceedings of the Winter Simulation Conference, Baltimore, MS, USA, 2010, pp. 2991–3003.

[155] A. Varga, R. Horning, An overview of the OMNeT++ simulation environment, International Conference on Simulation Tools and Techniques for Communications, Marseille, France, 2008, pp. 1–10.

[156] GloMoSim. [Online]. Available: http://pcl.cs.ucla.edu/projects/glomosim/. Accessed on: May 30, 2016.

[157] N. Vitzilaios, N. Tsourveloudis, An experimental test bed for small unmanned helicopters, J. Intell. Robot Syst. 54 (2009) 769–794.

[158] J.P. How, B. Bethke, A. Frank, D. Dale, J. Vian, Real-time indoor autonomous vehicle test environment, IEEE Control Syst. Mag. 28 (2008) 51–64.

[159] S. Cameron, S. Hailes, S. Julier, S. McClean, G. Parr, N. Trigoni, M. Ahmed, G. McPhillips, R. de Nardi, J. Nie, A. Symington, L. Teacy, S. Waharte, SUAVE: combining aerial robots and wireless networking, 25th International UAV Systems Conference, Bristol, United Kingdom, 2010, pp. 1–14.

[160] Boletín Oficial del Estado (BOE), Real Decreto-ley 8/2014, de 4 de julio, de aprobación de medidas urgentes para el crecimiento, la competitividad y la eficiencia, sección 6ª, artículos 50 y 51. [Online]. AvailableAccessed on: April 15 https://www.boe.es/diario_boe/txt.php?id=BOE-A-2014-7064, (2016) Accessed on: April 15.

[161] P. Pruitt, G. Dinolov, A. McAuley, W. Frenc, M. Gonzales, A.L. Bertozzi and R. Levy, "An economical micro-submarine testbed for validation of 3D cooperative control strategies for underwater robots", 2010.

[162] D.G. Reina, M. Askalani, S.L. Toral, F. Barrero, E. Asimakopoulou, N. Bessis, A survey on multihop ad hoc networks for disaster response scenarios, Int. J. Distrib. Sens. Netw. 11 (10) (2015) 1–16.

[163] S. Hauert, J.C. Zuffere, D. Floreano, Evolved swarming without positioning information: an application in aerial communication relay, Auton. Robots 26 (1) (2009) 21–32.

[164] M. Dorigo, Optimization, Learning and Natural Algorithms, Dipartimento di Elettronica, Politecnico di Milano, Milan, Italy, 1992.

[165] M. Scheutz, P. Schermerhorn, P. Bauer, The utility of heterogeneous swarms of simple UAVs with limited sensory capacity in detection and tracking tasks, Proceedings of IEEE Swarm Intelligence Symposium (SIS), Pasadena, CA, USA, 2005, pp. 257–264.

[166] G. De Cubber, D. Doroftei, D. Serrano, K. Chintamani, R. Sabino, S. Ourevitch, The EU-ICARUS project: developing assistive robotic tools for search and rescue operations, IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), Linkoping, Sweden, 2013, pp. 1–4.

[167] L. Eadicicco, Amazon Reveals New Details About Drone Deliveries, Time Inc., 2016 [Online]. Available: http://time.com/4185117/amazon-prime-air-drone-delivery/ Accessed on: April 20.

[168] MRW España, Apostamos por envíos con Drones, [Online]. Available:Accessed on: April 20 http://blog.mrw.es/apostamos-por-envios-con-drones/, (2016) Accessed on: April 20.

[169] C. Deng, S. Wang, Z. Huang, Z. Tan, J. Liu, Unmanned aerial vehicles for power line inspection: a cooperative way in platforms and communications, J. Commun. 9 (9) (2014) 687–692.

[170] Y. Zeng, R. Zhang, T.J. Lim, Wireless communications with unmanned aerial vehicles: opportunities and challenges, IEEE Commun. Mag. 54 (5) (2016) 36–42.

[171] Z. Xiao, P. Xia, X. Xia, Enabling UAV cellular with millimeter-wave communication: potentials and approaches, IEEE Commun. Mag. 54 (5) (2016) 66–73.

[172] S. Gundry, J. Zou, E. Urrea, C. Sahin, J. Kusyk, M. UmitUyar, Analysis of emergent behavior for GA-based topology control mechanism for self-spreading nodes in MANETs, Advances in Intelligent Modelling and Simulation, Springer Berlin Heidelberg, Germany, 2012, pp. 155–183.

[173] J. Karimpour, A. Isazadeh, H. Izadkhah, Early performance assessment in component-based software systems, IET Softw. 7 (2) (2013) 118–128.

[174] E. Obayiuwana, O.E. Falowo, Network selection in heterogeneous wireless networks using multi-criteria decision-making algorithms: a review, Wirel. Netw. (2016) 1–33.

[175] L. Jorguseski, A. Pais, F. Gunnarsson, A. Centonza, C. Willcock, Self-organizing networks in 3GPP: standardization and future trends, IEEE Commun. Mag. 52 (12) (2014) 28–34.