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Internet of Flying Things (IoFT): A Survey

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Abstract

Unmanned Aerial Vehicles (UAVs) have recently received significant attention by the civilian and military community, mostly due to the fast growth of UAV technologies supporting wireless communications and networking. UAVs can be used in order to improve the efficiency and performance of the Internet of Things (IoT) in terms of connectivity, coverage, reliability, stability, etc. In particular, to support IoT applications in an efficient manner, UAVs should be organized as a Flying Ad-hoc NETwork (FANET). The latter is subtype of Mobile Ad-hoc Network (MANET) where nodes are Unmanned Artifact Systems (UAS). However, the deployment of UAVs in IoT is limited by several constraints, such as limited resource capacity of UAVs and ground users, signal collision and interference, intermittent availability of the IoT infrastructure, etc. In this paper a comprehensive survey on the Internet of Flying Things (IoFT) is presented, covering the state of the art regarding flying things, with a focus on IoFT. A taxonomy of related literature on IoFT is proposed, including a classification, description and comparative study of different IoFT works. Furthermore, the paper presents IoFT applications, IoFT challenges and future perspectives. This survey aims to provide the base concepts and a complete overview of the recent studies on IoFT for the scientific researchers.

Keywords: Internet of Flying Things, Unmanned Aerial Vehicle, Unmanned Artifact System, Internet of Things, Flying Ad-hoc NETwork.

I. Introduction

The Internet of Flying Things (IoFT) is a new research domain that has received significant attention of both civilian and military researchers in recent times. IoFT suggests to integrate Unmanned Aerial Vehicles (UAVs), typically known as drones, with the Internet of Things (IoT) in order to support various applications in fields such as communications, smart agriculture, environmental pollution monitoring, surveillance, disaster management, smart city, smart industry, and object tracking [1]. For instance, the IoFT can be used for fire detection and management, where several UAVs are employed in order to collect environmental data such as temperature, pressure and humidity from the different sensors, and send them towards the ground station using IoT devices. The ground station can stock and process the received data in order to detect the fire and, therefore, alert the people in danger through their smartphones [2].

Currently, UAVs are being widely used for expanding a variety of IoT services in order to boost performance thanks to their mobility, flexibility, fast deployment, ubiquitous usability and cost-effectiveness [3]. For instance, UAVs can extend the coverage and reduce the cost of IoT networks by collecting and dispatching data in regions missing an infrastructure to support the IoT applications [4, 5]. The Federal Aviation Administration (FAA) Aerospace Forecast for fiscal years 2019 to 2039 predicts that the number of small UAVs in the U.S. commercial fleet will be increased from 7,397 million in 2019 to 8,806 million in 2039 [6].

A Flying Ad-hoc NETwork (FANET) is a particular case of both Mobile Ad-hoc Networks (MANETs) and Unmanned Artifact Systems (UAS) where the nodes are either the UAVs or fixed Ground Control Stations (GCSs). The FANET nodes can coordinate between them in order to accomplish an operation requiring higher scalability, reliability, survivability, and a lower cost compared to a single-UAV or multi-UAV systems. However, FANET deployment introduces several challenges, such as:

- **Connectivity:** Due to the low density and high mobility of the UAVs, link fluctuations between FANET nodes can affect the network connectivity. Therefore, intermittent FANET connectivity issues can decrease the network performance by introducing a penalty in terms of bit error rate, jitter and latency.
- **UAV electrical battery charge:** energy consumption is perhaps the greatest challenge for current UAVs. The UAV battery is used for flight, communications, real-time data processing, etc. Therefore, the limited capacity of UAV batteries reduces the UAV flight time [7]. Due to the UAV energy limitation, the selection of those UAVs having a higher energy power for the data processing or task offloading is a key challenge for FANETs.
- **UAV storage and computing resources capacity:** The restrictions regarding local UAV capacity in terms of data storage and processing is another FANET challenge [8]. The implementation of a protocol that offloads the collected UAV data towards a remote ground station having higher resource capacity is an important FANET issue.
- **Transmission delay:** When a stable communications infrastructure is not available for the FANET, the multi-hop communication mode can ensure end-to-end connectivity, but with an increased transmission delay [9]. Therefore, real-time FANET operations are limited by the availability of an infrastructure.
- **Interference management:** FANET nodes communicate between them mainly using wireless communications support. Therefore, the limited bandwidth capacity of this communications mode and the rapid change of FANET topologies makes interference management more complex [10].
- **UAVs collaboration and cooperation:** The collaboration and cooperation between UAVs in order to accomplish a mission is another FANET challenge. The latter is limited to the used communication modes (UAV to UAV, or UAV to infrastructure).

The Internet of Things (IoT) is an emerging technology which provides connectivity for any thing or object, such as sensors, actuators and mobile devices, at any time, anywhere [11]. The IoT objects can collect the data, interconnect and exchange these data with each other via the Internet through a network infrastructure [12]. These objects will be structurally organized and coordinated with each other in order to drive various IoT applications and services, such as environment monitoring, E-health, smart city, smart industry, etc. [13]. For a faster and more reliable processing and storage of data, IoT provides multiple intelligent computing technologies, such as cloud-computing, edge-computing, or fog-computing, typically combined with cellular networks (3G, 4G/LTE, 5G) [14, 15, 16, 17]. However, the IoT is restricted by various issues and challenges, such as the following:

- **IoT nodes deployment:** The placement of IoT objects in inaccessible positions or in places where there is no permanent electrical power supply is the main IoT challenge [18]. Therefore, in these cases, the replacement of the node battery introduces a high effective cost by requiring a considerable amount of time.
- **IoT services availability:** IoT services are not always accessible anywhere and anytime, due to the intermittent availability the communication technologies used, or due to an inaccessible deployment of the IoT nodes. To overcome this issue, an efficient protocol should be developed which enables the continuity of IoT services [19].
- **Weather conditions:** Under heavy weather conditions, such as natural disasters or terrorist attacks, the damaged communication infrastructure can severely destroy the IoT coverage. Multi-hop transmission can be used in this case in order to extend the IoT coverage [20].
- **High number of client queries:** IoT applications and services operate a high number of sensors in order to collect the client data. However, the large number of sensors which must be handled by the network nodes introduces high IoT resource requirements in terms of storage, processing, and energy, in addition to increasing delays [21].

- **Energy demand of IoT nodes:** IoT devices and sensors are characterized by limited power [22]. Therefore, efficient management and of the IoT nodes' power supply is an interesting issue.

IoFT have emerged as a practical solution to solve FANET and IoT challenges thanks to the advantages offered by UAVs in terms of flexibility, maneuverability, efficient mobile dissemination of data, fast deployment and low cost [23]. In addition, IoT and associated technologies (e.g. cloud-computing, edge-computing, fog-computing and cellular networks) also offer advantages in terms of connectivity, data processing and storage capacity, real-time services, etc. [24]. The integration of FANETs with IoT networks provides many benefits. Table 1 provides a comparison between IoT, FANET and IoFT according to various key points.

- **Connectivity and coverage**: The use of IoT with UAVs can significantly extend the network connectivity and coverage by jointly using the Internet connection and local connections provided by the FANET. For instance, in rural areas, the IoFT can increase the network coverage by two times compared to a standard IoT approach without UAVs, being that the coverage can reach up to 45 km with an UAV altitude of only 50 m [25]. Therefore, the high IoFT connectivity and coverage increases the IoT services availability and accessibility.
- **Reliability:** In the IoFT, the UAV can play the role of an aerial station which boosts the IoT capacity in order to ensure a reliable downlink and uplink of the data for ground users. Furthermore, the mobility and high altitude of the UAVs can mitigate the signal blockage and shadowing which make the connection between the IoT ground devices more reliable [26].
- **Data processing and storage:** IoT cloud-computing infrastructures provide the processing and storage of massive-scale data [27]. This IoT feature can handle the limited resources of UAVs in terms of processing, storage and energy availability. Therefore, the UAVs can offload their tasks and collected data towards the cloud for processing and storage.
- **Real-time services:** The IoT edge-computing infrastructure is expected as a new technology that analyses the IoT data and provides real-time services efficiently [28]. Therefore, IoFT mitigates the increased transmission delay of UAVs multi-hop communications by integrating the IoT infrastructure.
- **Resistance to weather conditions:** The integration of UAVs with IoT networks can recover the missed connectivity of destroyed IoT infrastructures in bad weather conditions. Furthermore, the cooperation and collaboration between UAVs in a multi-hop manner can handle the IoT connectivity interruptions in such weather conditions.
- **Energy supply of IoT nodes:** In IoFT, the UAVs can be used to provide energy to IoT ground devices [29]. Moreover, several technologies can be adopted to perform this task, including Wireless Power Transfer (WPT) solutions.

Table 1: Comparison between IoT, FANET and IoFT

Feature	**IoT**	**FANET**	**IoFT**
Connectivity and coverage	Connected using the Internet	Locally connected using U2U and U2I communication modes	Highly connected using the Internet and local FANET connections
Reliability	Low	High	Very High
Data processing and storage	Available	Limited to UAVs resource capabilities	Highly available
Energy consumption and supply	Limited to energy power capacity of IoT nodes	Limited to UAV energy power capacity	More flexible management of power of both UAVs and IoT nodes

Cooperation and Collaboration	Limited by Internet availability	Limited by FANET connection availability	Includes IoT and FANET infrastructure and communication modes capabilities
Real-time communication	Limited to IoT connectivity and coverage	Limited to local FANET connection	Highly available due to higher IoFT connectivity
Effective cost	High	Low	Medium

There are several survey papers [9, 30, 31, 32, 172, 33], which addressed the IoFT issues. However, they do not present details about the main IoFT concepts and recent IoFT stat-of-art works in different lines of research, such as flying things, IoFT characteristics, flying cloud-computing, flying edge-computing, flying fog-computing, flying cellular-networks, IoFT applications, IoFT challenges, etc. Table 2 presents a brief comparison between related survey papers on IoFT according to several crucial points. The main contributions of our proposed survey compared with the other IoFT survey papers [9, 30, 31, 32, 172, 33] can be summarized as follows:

- Presentation of the different flying things concepts, such as UAS, UAV architecture, FANET characteristics, etc.
- Description of the main characteristics of IoFT with a comparative study between flying things, IoT and IoFT.
- Proposition of a new taxonomy of existing IoFT related works.
- Recapitulation and a comprehensive comparative study of all referenced IoFT related works.
- Classification and description of the most useful IoFT applications.
- Summary of the proposed survey by presenting the main IoFT issues and challenges with the future directions for IoFT research.

Table 2: Comparison study of related survey papers

Survey paper	**Flying things**	**IoFT characteristics**	**Flying cloud-computing**	**Flying fog-computing**	**Flying edge-computing**	**Flying cellular networks**	**IoFT applications**	**IoFT challenges**	**Description**
Ref. [31] (2015)				√				√	Introduced the based concepts and scenarios of flying fog-computing. The paper outlined a range of issues and challenges of fog-computing services delivered via UAVs.
Ref. [9] (2016)	√							√	Provided a comprehensive survey on the UAVs potentials for the IoT services delivery from the sky, and addressed the relevant challenges and requirements.
Ref. [32] (2018)	√					√	√		Reviewed the UAV application domains over IoT and 5G cellular networks. The paper analyzed the IoT sensors required by the UAVs, and summarized the privacy and security issues of UAV-based IoT.
Ref. [33] (2018)						√		√	Presented a survey of UAV communication for 5G cellular networks. The design challenges and future trends of existing related works on integrated UAV communications with 5G technologies are discussed.
Ref. [172] (2018)							√	√	Provided an overview on Internet of Flying Robots (IoFR), including its designing issues for real-applications, such as coverage, connectivity, limited energy capacity, path planning, search of target, collision avoidance and flying robots navigation. Moreover, the survey reviewed and compared the existing IoFR works and provides some IoFR future perspectives.

Ref. [30] (2019)	√					√			Surveyed the state-of-art on the integration of UAVs into cellular networks. The main issues and opportunities were addressed. Furthermore, the paper outlined the testbed prototypes for UAV-based cellular networks.
Proposed survey	√	√	√	√	√	√	√	√	Surveys the most recent works on IoFT in various fields, such as flying things, flying computing, flying cellular networks, IoFT characteristics and applications, IoFT challenges and futures trends. A general comparative study about the discussed IoFT related works is also provided.

The remainder of this survey paper is organized as follows. Section 2 outlines the flying things-based aspects. Section 3 presents a taxonomy of the most cited IoFT works with a comparative study. In section 4, we classify and describe the IoFT applications. Section 5 discuss the IoFT challenges and presents some future research directions. Finally, section 6 concludes this paper.

For the sake of completeness, table 3 presents the list of abbreviations list used in this survey.

Table 3: Abbreviations used in this document.

Acronym	Definition
IoFT	Internet of Flying Things
FT	Flying Things
IoT	Internet of Things
UAS	Unmanned Artifact System
UAV	Unmanned Aerial Vehicle
GCS	Ground Control Station
WSN	Wireless Sensor Network
FANET	Flying Ad-hoc NETwork
MANET	Mobile Ad-hoc Network
VANET	Vehicular Ad-hoc Network
UANET	Underwater Ad-hoc Network
WPT	Wireless Power Transfer
GPS	Global Position System
RFID	Radio Frequency IDentification
SBC	Single-Board Computer
SOA	Service-Oriented Architecture
API	Application Programming Interface
SDN	Software Defined Networks
NFV	Network Functional Virtualization
SOAP	Simple Object Access Protocol
REST	Representational State Transfer
GSC	General Static Cloud
URC	UAV Resource Controller
UAVaaS	UAV as a Service
IMU	Inertial Measurement Unit
UTM	UAVs Traffic Management
AGMEN	Aerial-Ground Integrated Mobile Edge Network
TDMA	Time Division Multiple Access
AP	Access Point
MES	Mobile Edge Server
SMDP	Semi-Markov Decision Process
DRL	Deep Reinforcement Learning
IoD	Internet of Drones
AG-IoT	AGriculture-IoT
CH	Cluster Head
MEC	Multi-access Edge Computing
LPWA	Low Power Wide Area
DA	Data Analytic
NO2	Nitrogen Dioxide
ORP	Oxidation-Reduction Potential
DO	Dissolved Oxygen
LBPH	Local Binary Pattern Histogram method
LTE	Long Term Evolution
ANN	Artificial Neural Network
MIMO	Multiple Input Multiple Output

II. Flying Things

Flying Things (FT) includes both aircraft units and systems, such as UAV, drones, UAS, FANET, etc. FT provides many benefits, like mobility, flexibility and fast deployment. Therefore, the integration of FT with IoT can extend the IoT coverage and connectivity, and can ensure high performance of data transmission for IoT applications. This section outlines the base concepts of FT, including UAS, UAV architecture, FANET communication, FANET characteristics, etc.

II.1. Unmanned Aircraft System

UAS is a control system composed of three main components: Unmanned Aircraft (UA), known as UAV or more popularly as drone [34], Ground Control Station (GCS), and communication links [35]. The GCS of UAS houses the system operators, while the UAV performs specific operation mission in the flight area. Many civilian and military applications are based on the UAS due to their simplicity of deployment, low cost of acquisition and maintenance, as well as high capability of maneuvering and hovering [36]. For instance, UAS can be applied in fields including agriculture, fire detection and forestry, incident control, pipeline security, water boards, atmosphere analysis, face recognition, surveillance of enemy activity, etc. Figure 1 shows an example of different UAS.

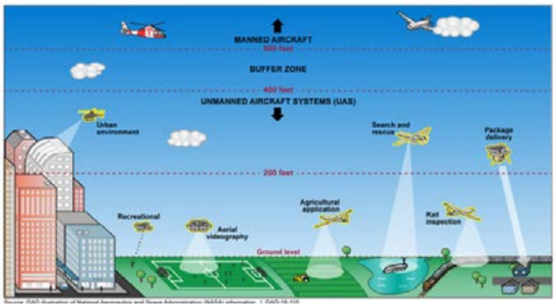

Figure 1: Unmanned Aircraft Systems.

II.1.1. UAS architecture

The main components of UAS are the UAV, GCS and the communication data link. Within a UAV, the most crucial component is the flight controller, which represents the UAV central processing unit. In addition, the UAV is equipped with a communications interface to exchange the commands and data with GCS. Below different UAS components are reviewed.

II.1.1.1 Unmanned Air Vehicles

The UAV is the key component of a UAS, which able to collect, store, process and exchange the sensing data with other UAVs and with GCS. The UAVs can be of different sizes, shapes, components, configurations and missions. As depicted in Figure 2, the UAV is formed mainly by the following components:

- **Airframe:** UAV airframe is the platform which payloads the different UAV components. It is characterized by his lightweight, stability and limited space.
- **Flight controller:** This component is responsible for measuring and monitoring the UAV stability and navigation. In addition, the flight controller generates control signals for the different UAV states in order to provide users a manual control of the UAV.
- **Sensors:** The UAV uses the sensors in order to sense environment data such as temperature, humidity, pressure, gas, etc. The sensing data can be partially processed by the UAV, or transmitted to the GCS for further analysis and processing [37].

- **Global Position System (GPS):** The GPS provides the UAV geographic location, UAV speed and UAV direction at specific time intervals.
- **Radio Frequency IDentification (RFID) reading system:** The RFID reader is used to collect the data from RFID tags using a single antenna. Moreover, the RFID reader carries out the following tasks: tag search in the area, data download from the tags, and tags localization [38].
- **Single-Board Computer (SBC)**: SBC obtains the collected data from the RFID reading system, processes them, and sends these data to the GCS via the UAV communication interface.
- **Communication interface:** The UAV should be equipped with a communication device, such as an omni-directional antenna, which provides wireless communications with other UAVs and the GCS.
- **Battery:** This component is used to supply the power for the different UAV devices. However, the UAV is characterized by limited battery, which requires an efficient energy management algorithm.

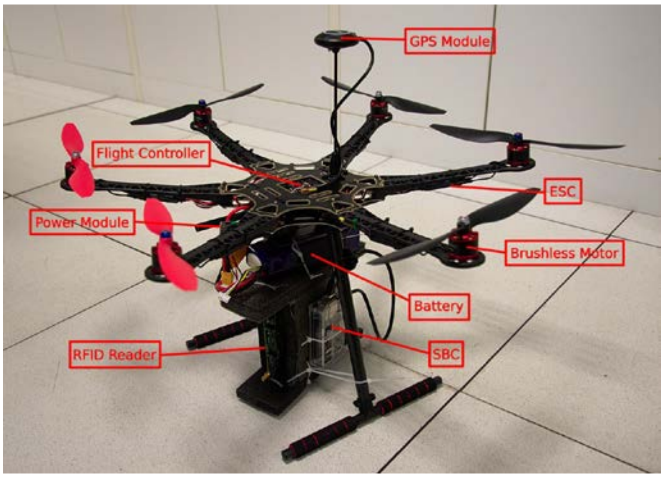

Figure 2: Unmanned Air Vehicle.

II.1.1.2 Ground Control Station

The GCS is an on-land system which provides for the human operator the capability of observation, control and monitoring of the UAVs during their flight [39].

II.1.1.3 Communication links

In a UAS, the communication links ensure the safe exchange of data and control messages between the UAVs and the GCS with highly reliable, low-latency, and two-way communications. These UAS communication links can be classified into two types: control communication links, and data communication links [40]. The first type allows the transmission of control messages in the UAS, such as the commands from GCS to UAV, status reports from UAVs to GCS, and control information between UAVs. On the other hand, the data communication links ensure the transmission of the data captured by the UAVs towards the GCS. These data can be exploited by the user applications.

II.2. Flying Ad-hoc NETwork

A FANET is a special case of a MANET where the communicating nodes are autonomous UAVs connected in wireless ad-hoc manner [41]. These UAVs move with a higher speed compared to MANET nodes, VANET ground vehicles or UANET aquatic vehicles. Each UAV is equipped with some physical devices such as sensors, GPS, camera, etc. FANETs attract the attention of military and civilian applications due to their flexibility, fast deployment, self-configuration, decentralized control, etc. Figure 3 shows an example of a FANET.

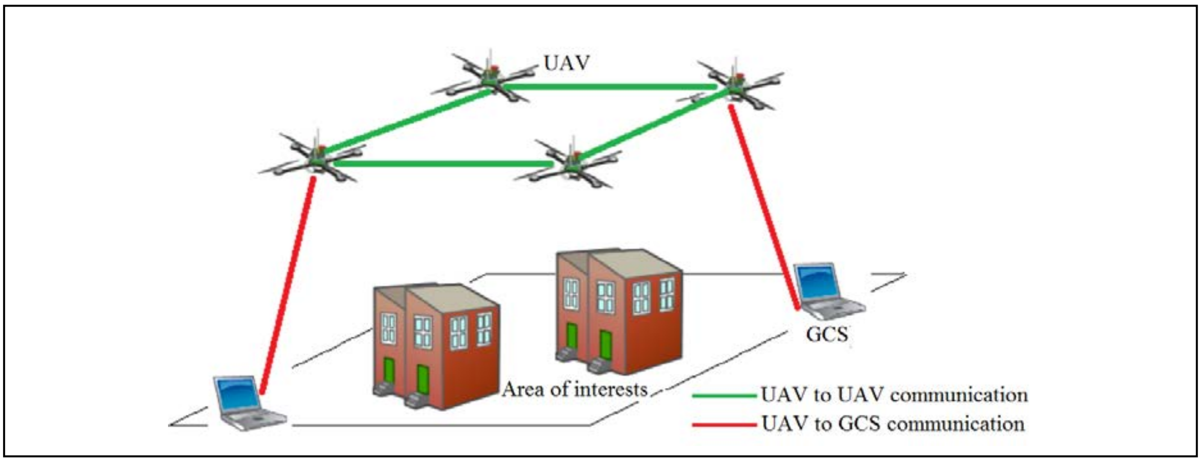

Figure 3: Flying Ad-hoc Network.

II.2.1 FANET communication

In a FANET, the UAVs can exchange real-time data between them or with the ground control station via the wireless medium, and without any infrastructure. The communication between the UAVs handles the problem of a limited communications range and allows the real-time exchange of data. As presented below, there can be three types of communications in a FANET:

- **UAV to UAV communication:** In this type of communication (see Figure 4.a), the UAVs communicate with each other in a multi-hop manner in order to extend the communications range and increase the data rate [42]. The UAV can use this communication type when it wants to send data packets to another UAV or ground station outside of its range.
- **UAV to GCS communication:** In this communication mode (see Figure 4.b), the UAV communicates directly with the GCS which is installed near from the UAV mission area. Using this type of communication, the GCS can provide some services to the UAVs. In addition, the UAV can send some important data to the ground station.
- **Hybrid communication**: This communication type represents a combination between UAV-to-UAV and UAV-to-GCS communications (see Figure 4.c). Therefore, the UAV can send its data directly to the GCS in a one-hop or in a multi-hop fashion via the different UAVs in the mission area.

As mentioned earlier, a FANET is characterized by the frequent topology changes due to the high mobility and low density of UAVs. Therefore, the UAV-to-UAV and/or the UAV-to-GCS communications for data transmission is a challenging issue which requires an efficient routing protocol to be adopted.

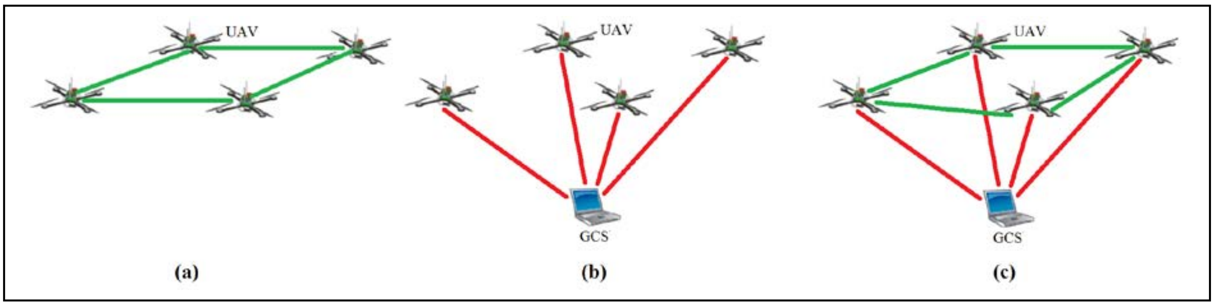

Figure 4: Types of FANET communications.

II.2.2 FANET characteristics

The existing Wireless Ad-hoc Networks (WANETs) are classified into four categories: Mobile Ad-hoc Networks (MANETs) where the nodes are mobile, Vehicular Ad-hoc Networks (VANETs) in which the nodes are ground vehicles, Underwater Ad-hoc Networks (UANETs) where the nodes are aquatic mobile vehicles, and Flying Ad-hoc Networks (FANETs) where the nodes are the mobile UAVs. This classification of WANETs is based on their application, implementation, deployment, communication and objectives [43].

FANETs inherits some properties from MANETs, such as mobility, wireless medium, decentralized control, and multi-hop communication. Otherwise, FANETs have their own characteristics compared with MANETs, VANETs and UANETs, as detailed below. Table 4 summarizes the differences between MANET, VANET, UANET and FANET.

- **UAVs mobility:** The main feature of a FANET is the higher mobility of its nodes compared with MANETs, VANETs and UANETs. According to [44], UAV speed is typically between 30 km/h and 460 km/h. Due to the higher degree of mobility of UAVs, FANET topologies can change frequently, which increases the fluctuation of the link quality between UAVs and affects the network connectivity.
- **Mobility model:** Unlike MANET nodes which move in random directions and with random speed, FANET nodes (UAVs) generally move following a predefined path. Therefore, the FANET mobility model is regular and predictable like the mobility model of VANETs and UANETs.
- **Radio propagation model:** Each WANET is characterized by a specific environment in which its nodes move. For instance, MANET nodes move at ground terrain, while VANET vehicles move in highway or urban roads, UANET aquatic vehicles moves in the water and FANET UAVs fly in the sky. The radio propagation model is affected by the geographic structure of the network environment. Therefore, the FANET radio propagation model is different from the radio propagation models of MANETs and VANETs, because in the FANET environment the number of the obstacles is reduced compared to either of the former ones.
- **UAVs density:** The distance between the UAVs is typically higher than the distance between the mobile nodes in the case of MANETs, VANETs and UANETs [45]. Therefore, the UAVs density, which represents the average number of the nodes within an area, is much lower compared to the other WANETs. This situation increases the link disconnection between the UAVs.
- **Energy and computation power:** Unlike MANET nodes, which are characterized by small battery capacity that reduces the network lifetime, FANETs, like VANETs and UANETs, do not suffer from this problem when the UAVs are ordinary, in which these UAVs are equipped with sufficient energy power resources. However, when the flying nodes are a mini-UAVs, such as drones, the capacity of their batteries is also quite limited [46]. Based on the energy resources, the UAVs can

communicate and react as routers, in addition to their computation capacity for real-time data processing.

Table 4: Comparison between MANET, VANET, UANET and FANET.

Feature	MANET	VANET	UANET	FANET
Nodes Mobility	Medium	High	High	Very High
Network connectivity	High	Low	Low	Low
Mobility model	Random	Regular et predictable	Regular et predictable	Regular et predictable
Environment	Specific ground terrain	Highway/urban road	Water	Sky
Nodes density	High	High	Low	Low
Energy power	Low	High	High	High (Ordinary UAVs) Low (Mini-UAVs)
Computation power	Low	High	High	High (Ordinary UAVs) Low (Mini-UAVs)

In addition to FANET characteristics in the scope of WANETs, FANETs also have specific features when comparing single-UAV with multi-UAV systems. Table 5 summarizes the differences between Single-UAV systems, Multi-UAV systems, and FANETs.

- **Scalability:** Contrarily to single-UAV and multi-UAV systems which are mainly based on UAV-to-infrastructure communication, FANETs are based on UAV-to-UAV multi-hop and UAV-to-infrastructure communications. Therefore, the operation coverage in the mission area can be highly extended, and the coordination between the UAVs can be increased.
- **Mission speedup:** Due to the high number of UAVs in a multi-UAV system and in a FANET, the mission can be completed faster than in the case of a single-UAV system.
- **Reliability:** In single-UAV and multi-UAV systems, the UAV must be connected directly to the infrastructure. Therefore, the UAV may be disconnected from the infrastructure in the presence of adverse weather conditions. However, the UAV-to-UAV communication in a FANET increases the UAV connectivity, which ensures a high network reliability.
- **Survivability:** When a UAV fails, the mission cannot be completed in a single-UAV system. However, in a multi-UAV system and in a FANET, the failure of an UAV does not affect the survivability of the operation mission.
- **Cost:** Generally, multi-UAV systems and FANETs use small UAVs as they introduce lower maintenance and acquisition costs compared to with single-UAV systems based on large UAVs.

Table 5: Comparison between Single-UAV system, Multi-UAV system and FANET.

Feature	Single-UAV system	Multi-UAV system	FANET
Scalability	Low	High	Very High
Communication	UAV-to-infrastructure	UAV-to-infrastructure	UAV-to-UAV UAV-to-infrastructure

Coordination	Not existed	Low	High
Mission speed-up	Low	High	High
Reliability	Low	Low	High
Survivability	Low	High	High
Cost	High	Low	Low

III. Internet of Flying Things

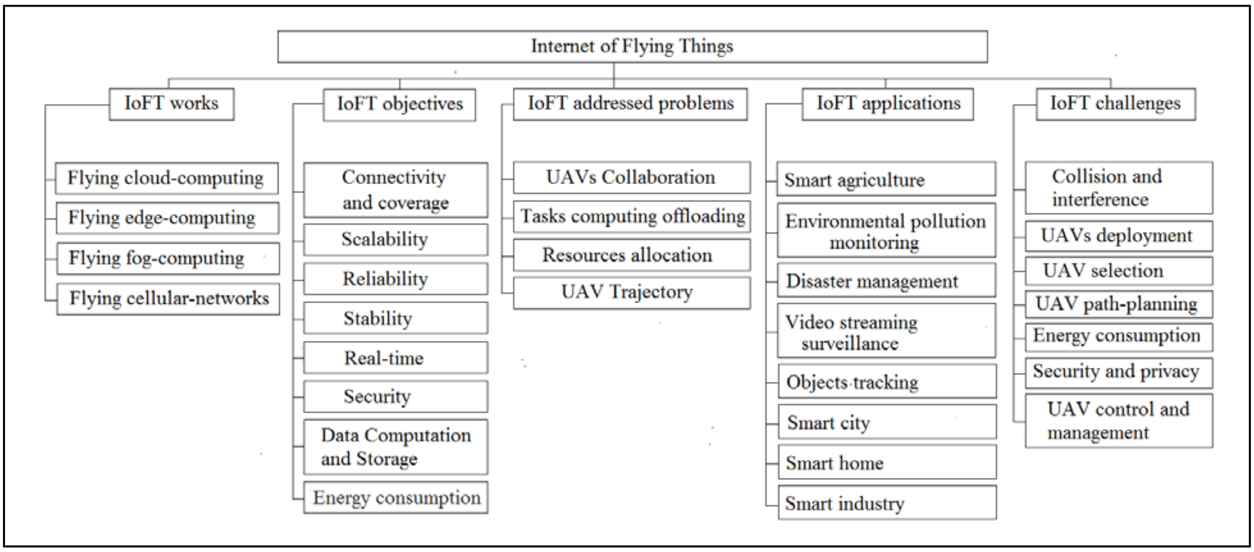

Figure 5: Proposed Internet of Flying Things taxonomy

The fast growth of UAV technology makes it applicable and able to be integrated with the other networks and systems in order to accomplish complex missions, including disaster management, accident prevention, crop management, etc. IoFT is a new research domain that integrates FANETs with IoT in order to efficiently support the different IoT applications with high reliability and flexibility. Furthermore, the IoFT can improve the availability of IoT services in the areas which are badly served by the existing IoT infrastructure, such as the rural area. In this section, a taxonomy of the most important and recent related works in the IoFT literature are reviewed and discussed. We classify IoFT works into four main categories: flying cloud-computing, flying edge-computing, flying fog-computing and flying cellular-networks, as shown in figure 5. All these works aim at improving the IoFT capabilities in terms of scalability, reliability, stability, security, etc. In addition, a recapitulation and a comparative study of all referenced IoFT related works is presented at the end of this section.

III.1. Flying cloud-computing

Flying cloud-computing is presented as an integration of FANETs with cloud-computing, in order to increase the processing, storage, network bandwidth and tenancy capacity of FANETs by sharing the high-power IoT cloud-server resources [47].

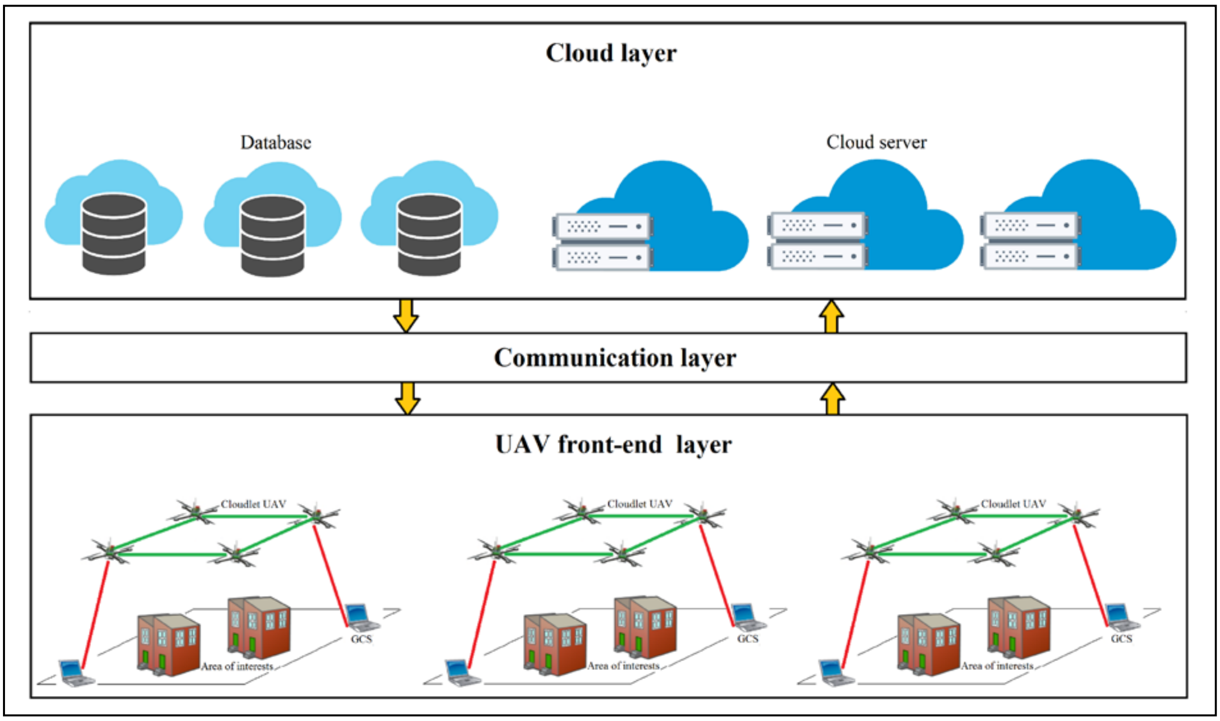

Figure 6: Flying cloud-computing

The flying cloud-computing architecture consists of three layers: UAV front-end, communication, and cloud [48, 49]. As shown in figure 6, the first layer is the UAV front-end layer, which is responsible for collecting the sensor data in the sky, such as temperature, pressure, and gas. Then, the collected data should be transmitted to the cloud for storage and processing. For instance, these data can be used for fire detection, pollution monitoring, environmental recognition, etc. The next layer of flying cloud-computing architecture is named communication, which provides for the UAVs a wireless communications interface to communicate with them and with the GCS. Moreover, in this layer, the UAVs can transfer the collected data to the cloud through an access network using 3G/4G cellular communication devices, or other alternative technologies like WiFi, WiMAx, etc. The last layer includes a cloud server which allows for storage and real-time processing of the streamed data captured by the cloudlet UAVs. The data aggregation is the main objective of cloud storage, in which the civilian and private agencies can easily access the stored data. The cloud servers contain a database or a file system to store the collected data. The latter can be of various types, such as environment variables, geographical location parameters, mission information, sensor data and images, etc. [50]. In addition, to the data storage, the cloud server processes the data received from the cloudlet UAVs in order to detect critical events including forest fires, human activity, etc. Moreover, the cloud layer contains a services interface which enables user applications to control the UAVs missions and parameters.

In the literature of flying cloud computing, several works were proposed. Hong and Shi [51] proposed a multi-UAV cloud-based control system. The proposed system allows multiple users to simultaneously control and monitor different UAVs. Moreover, the system allows users to dispatch missions over the UAVs, in addition to collecting and processing sensor data through the cloud-computing. To demonstrate the effectiveness of the designed system, a simulation based on Software In The Loop (SITL) simulator was performed. However, the proposed system did not take into account the security and collaborative issues of the UAVs.

Mahmoud and Mohamed [52] proposed a Service-Oriented Architecture (SOA) for collaborative cloudlet UAVs. In the proposed SOA architecture, the authors propose a mapping between the UAVs and cloud computing in order to combine the UAVs capability with the cloud-computing resources in terms of data storage and processing. The proposed architecture provides for UAV collaboration in terms of essential services, including mission organization, location monitoring, security, real-time control and data storage, in addition to customized services such as sensing, actuation, data analysis, etc. A generic description of the proposed architecture was provided, including its complements and services without any real implementation. In [53, 54], the same authors enhanced their previous work [52] by proposing a UAV-cloud platform which is based on a Resource-Oriented Architecture (ROA) in order to facilitate the modeling of UAV resources and services. In the proposed platform, the UAVs are considered as servers where their resources can be accessed by Application Programming Interfaces (APIs). Moreover, a broker layer was proposed which dispatches the mission-requests to the UAVs. A real prototype of the proposed UAV-cloud architecture was developed using Arduino devices as UAVs with a WiFi shield for the communication, and using RESTful APIs for access to UAVs resources and services. However, the developed prototype of the proposed UAV-cloud platform is very simple due to a limited validation using a simple Arduino board. In [55], Mahmoud et al. extended their implemented prototype in [53, 54] by integrating Arduino on-board with various sensors to detect and measure some environmental events, such as humidity and temperature. Each of these sensors was manipulated using RESTful web services through a Web interface. The authors provided a testbed evaluation study in order to prove the effectiveness of the implemented prototype in terms of access time to UAV resources. However, the scalability of this prototype is limited since the experimental testbed was applied to a small network.

In [56, 57], the authors presented a cloud-based softwarization architecture for collaborative UAVs and Wireless Sensor Networks (WSNs). The proposed architecture separates the UAV physical resources layer from the control layer. Moreover, this architecture is based on three strategies which include softwarization, Software Defined Networks (SDN) and Network Functional Virtualization (NFV). The first strategy is based on the modularity concept, which permits the higher layer to be changed easily without modifying the network architecture. The second one consisted of separating the physical layer from the control layer. The third strategy allowed the higher layer to visualize the physical devices. The proposed system which consisted of sensors, UAVs and a WSN controller, which were implemented and evaluated in the scope of an agriculture scenario. However, the proposed architecture should be improved by considering the security factor.

Koubâa et al. [58, 50] proposed Dronemap Planner for the cloud-based management of UAVs. The proposed system allows access to the UAVs through web services (SOAP, REST), UAV missions scheduling, and facilitates the coordination between the UAVs. The communication between the proposed system, UAVs and users is performed using MAVLink [59] and ROSLink [60] protocols. Experimental results have shown the effectiveness of Dronemap Planner to visualize and to facilitate the access to the UAVs through the Internet. However, security and QoS factors should be investigated as well in order to improve Dronemap Planner. In [61], Koubâa et al. proposed a cloud-based system called DroneTrack for real-time tracking of moving objects using UAVs. DroneTrack is based on the Dronemap Planner management system to monitor and communicate with the UAV via Internet. DroneTrack is based on the exchange of UAV and object GPS coordinates over the cloud in order to follow them in real time. The experimental study proved that DroneTrack can track moving objects with low connectivity between the UAVs, cloud and users. However, the DroneTrack tracking accuracy must be further improved.

In [48, 49], the authors studied the stability and reliability of a cloud-based multi-UAV system. In the first step, the authors analyzed the ability of the cloud system to control and monitor the UAVs. Second, the authors modeled the proposed cloud-based UAV control system in order to find out the relationship between the maximum sensor data rate generated by the UAVs with the system stability and reliability.

This relationship was summarized by analyzing the on-demand service capability of both the General Static Cloud (GSC) and the UAV Resource Controller (URC). The simulation results showed that the cloud-based UAV system stability decreased with the increase of the generated data rate. However, the proposed system was validated based on theorical analysis and experimental simulations without any real implementation.

Majumder et Prasad [62] proposed a cloud platform to control the UAVs. This platform allows the users and controllers to communicate simultaneously with the UAVs. The users introduce the UAVs parameters, such as altitude, speed and direction, and the cloud platform monitors the UAVs based on the user requirements. The UAVs communicate with the cloud platform through the GCS, where wireless communications are used between the UAV and GCS, being the Internet used to connect the GCS to the cloud platform.

In [63], Yapp et Babiceanu designed a framework which enables the users to access to the UAV as a Service (UAVaaS) through the cloud for commercial applications. Using the proposed framework, a multiple customer can allocate different UAVs to execute commercial operations, such as uploading the updated waypoint to UAVs, watching the live video, etc. In order to optimize the UAV resource utilization and guaranteeing a better security, a cloud coordinator was proposed. The latter handles the communication between the users and UAVs, manages the tasks assignment, and controls the access to UAVs from different categorized users.

Rodrigues et al. proposed the Cloud–SPHERE platform [64, 65] based on cloud-computing that provides a secure communication channel between the UAVs, and between the UAVs and the infrastructure, including identification, authentication and data security. Furthermore, the designed platform allows the service management for the UAVs to be connected to the cloud, including service classification and service provision. A basic and generic conceptual model of the proposed platform is provided. However, more implementation and experimental evaluations should be performed in order to demonstrate the effectiveness of the Cloud–SPHERE platform.

Hadj et al. [66] proposed a three-layer cloud architecture which uses the UAVs as a sink for ground wireless sensor networks (WSNs). The first layer of the proposed architecture consists of the terrestrial wireless sensor nodes, characterized mainly by a short communications range which makes it not always connected. The second layer represents the cloudlet UAVs which provides a sink for service delivery. Each UAV collects the data from the ground sensor nodes, and collaborates with the other UAVs to transmit these data towards the GCS. The third layer is the cloud control center which is responsible of the processing and the analysis of the collected data in order to take a decision. The numerical evaluation showed that the proposed architecture provides optimal values for the number of terrestrial sensors, delivery delay and UAV energy consumption. However, it would be necessary to validate the proposed architecture through simulation or real experiments.

In [67], the authors presented the AnDrone architecture, which allows the users to access a UAV using the cloud. Furthermore, the proposed system enables a physical UAV to execute simultaneously and separately multiple virtual UAVs. In addition, a virtualization of the UAVs is provided using Linux. An AnDrone prototype was implemented based on a Raspberry Pi 3. Experimental results demonstrated that the AnDrone prototype ensures real-time virtualization and control of the UAVs, secure communication, minimal energy overhead of the UAVs, and low latency.

Zhang et Yuan [68] implemented a cloud-based server using Python in order to analyze the UAV flight data, and to allow the users to remotely control and visualize the UAV. The authors proposed to use 4G to transmit the UAV data to end users. A simple testbed evaluation of the proposed system was performed using a single UAV.

Many other flying cloud-computing were proposed in order to support the storage and computing of large amounts of data, such as [69, 70, 71, 72]. However, cloud computing is not a suitable solution for real-time applications due to associated delays between end-user and cloud-servers, which are located far from these users [73]. To overcome this issue, many IoFT works were based on the flying edge-computing and the flying fog-computing paradigms, that aim to provide low-latency communication by offloading the UAV tasks to cloud-servers that are close-by.

III.2. Flying edge-computing

Flying edge-computing is created in order to extend the flying cloud-computing capabilities for real-time sensitive IoT applications. The edge-layer reduces the computing load by handling some UAVs data locally at the edge IoT devices without an intervention of the cloud. Therefore, this switching of the data computing and storage to the edge layer decreases the latency significantly.

Most recent works on IoFT are based on flying edge computing in order to support real-time IoT applications such as smart transportation, video streaming surveillance, augmented reality, emergency intervention, etc. In [74], Bekkouche et al. proposed to use the MEC with the UAVs Traffic Management (UTM) system in order to reduce the latency (e.g. end-to-end delay) and increase the reliability of the communication between UAVs and UTM. In the proposed system, the control of the UAV flight was performed by the nearest edge server to this UAV in order to ensure the latency and reliability. Furthermore, the authors measure the consumption of MEC resources when varying the number of UAVs in order to determine the required resources to ensure MEC scalability. A realistic experimentation has been performed to prove the effectiveness of the proposed system using only one UAV and one edge server. Therefore, multiple UAVs and edge servers should be considered to efficiently evaluate this system.

In [75], Narang et al. proposed an architecture for a UAV-based MEC infrastructure which solves the problems of challenged networks, including the disfunction and services unavailable under natural disaster situations or in rural areas. The main objective of this architecture is to provide the coverage and the MEC services to users in such situations. Therefore, the UAV and MEC were deployed in order to host the GCSs and the edge-computing resources. The analytical results have showed that the proposed architecture can better cover the user services even when an important number of GCSs fail. However, this architecture can be improved by using coverage optimization techniques.

Cheng et al. [76] proposed an architecture for an Aerial-Ground Integrated Mobile Edge Network (AGMEN) that addressed many edge-computing network issues, such as communication, computing and caching. In this architecture, multiple UAVs are deployed in order to cover spatially and temporally the user areas for data delivery. These UAVs play the role of edge network controllers in order to allocate efficiently the computing and storage resources. Any experimental evaluation of AGMEN was provided in order to prove its effectiveness.

In [77], Zhou et al. proposed an integrated air-ground framework for MEC. The proposed framework combines the capabilities of ground vehicles with UAVs in terms of communication, computing and storage in order to allow fast on-demand deployment of edge servers. Four use cases were introduced in order to demonstrate the effectiveness of the proposed framework which supports high mobility, high throughput and low latency. Simulation results showed that the proposed platform greatly reduces the overall delay.

Chen et al. [78] designed a hybrid Edge-Cloud model for UAV swarms in order to guarantee high QoS for resource-intensive and real-time applications, including crowedsensing within smart cities. The proposed model extends the UAV resources capacity by using the closer edge servers, which are able to process the data with a low delay. Furthermore, cooperation between edge and cloud-computing was proposed for the processing and storage of big data at the cloud. The simulation results showed that the proposed model can improve the QoS of the UAV. However, in order to validate the proposed model, a real implementation and testbed evaluation should be performed.

Zhou et al. [79] proposed a MEC with a UAV-based wireless system in order to handle the limited resource capacity of ground users in terms of energy power and computing. In the proposed system, the UAV transmits the energy to the mobile ground users in order to exploit it for computation tasks. Moreover, an algorithm which minimizes the UAV power consumption was proposed by jointly optimizing the computing offloading and the design of the UAV trajectory. The simulation results showed that the proposed system outperforms the other benchmark schemes in terms of convergence. In [80], the same authors addressed the resource allocation problem in order to maximize the computation rate of users using the system proposed in [79] under binary and partial modes of computation offloading. Two algorithms were proposed in order to guarantee a maximized user computation rate by optimizing UAV computation, energy resources and the UAV trajectory. Simulations showed that the proposed resource allocation scheme is able to converge faster than the other disjoint schemes while introducing a low computation complexity.

In [81], Hu et al. proposed to use a MEC server with a UAV in order to provide MEC services for ground users by using Time Division Multiple Access (TDMA). Furthermore, a globally and locally optimal scheme was proposed which minimizes the user energy consumption by optimizing the UAV coordinates, allocation of time slots, and partitioning of computation tasks. Numerical results demonstrated that the proposed scheme is superior compared to other offloading schemes.

In [82], the authors proposed an UAV-based MEC architecture where the UAV acted as a MEC server that helps ground users to accomplish their tasks. In addition, the UAV offloaded these tasks towards the Access Point (AP) for further computing. In order to minimize the energy consumption of both UAV and users, the authors proposed an algorithm which optimizes the scheduling of computation resources, allocation of bandwidth and UAV trajectories. Simulation results showed that the proposed algorithm provides higher and more stable performance than baseline schemes.

In [83], Li et al. proposed to use the UAV as Mobile Edge Server (MES) in order to provide real-time offloading of computation tasks for ground users. Furthermore, a maximization of user tasks' throughput with limited UAV energy was performed using two technics: Semi-Markov Decision Process (SMDP) and Deep Reinforcement Learning (DRL). The first technique was used to formulate the maximization problem as SMDP, while the second technique was applied to solve this problem. Simulation results showed that the proposed scheme provides optimal user task throughput values with acceptable convergence.

In [84, 85, 86], the authors addressed the task computation offloading problem in MEC-based UAV networks in order to simultaneously reduce the UAV energy overhead and the execution delay. This problem was formulated and solved using a theorical game strategy, where three types of players are considered: UAV, GCS and edge server, all cooperating together for the computing task. Therefore, the task can be processed in the UAV, offloaded to the nearest GCS, or offloaded to the edge server. Simulation results demonstrated that the proposed task computation offloading scheme achieves the best tradeoff between computation cost, energy consumption and execution delay compared to the cases of task execution on UAV, edge server and GCS, respectively.

Sedjelmaci et al. [87] proposed in a cyber defense system for a UAV-Edge computing network in order to protect this network against attacks, while taking into account the limited UAV energy and computation resources. The proposed security system was modeled based on a non-cooperative Stachelberg game, in which each UAV had a security agent that protects it and its offloading link against the attacker agents. Simulation results showed that, with low UAV energy and computation resources, the proposed defense system can provide a high level of the security, while a high number of UAVs and attackers was considered.

In [88], Tian et al. addressed the security and the privacy issues in the Internet of Drones (IoD). The authors proposed an MEC-based authentication framework for UAVs which ensures real-time and fast authentication, high privacy protection and non-repudiation. The proposed framework allows the UAVs to control the generation of its signature key without the problem of key escrow. The analysis results demonstrated that this framework can efficiently protect UAVs against threats to authentication, privacy and repudiation. Moreover, in order to respect the UAV resources constraints, experimental results showed that the proposed framework does not introduce high costs in terms of computation, communication or storage.

In the literature related to flying edge computing, several other works have been proposed [89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107]. Although flying edge-computing is good for IoT real-time applications, some of these applications need the storage and computing of voluminous data, like the video streams, which cannot be supported efficiently by the local resources of edge IoT devices. To overcome this challenge, flying fog computing provides edge computing in order to guarantee low-latency, and it can be expanded to the core network as well (e.g. cloud-computing) [108], for the storage and processing of high volumes of UAV data.

III.3. Flying fog-computing

Flying fog-computing integrates cloud servers and edge IoT devices in order to provide high capacity in terms of storage and computing, and a low latency for UAV-assisted IoT applications. As shown in figure 7, flying fog computing provides an intermediate layer between UAVs and the cloud layer, which is located at the edge of the network, and that consists of a large number of fog nodes. The fog layer can communicate with cloud layer via the Internet, or with the UAVs using a wireless connection.

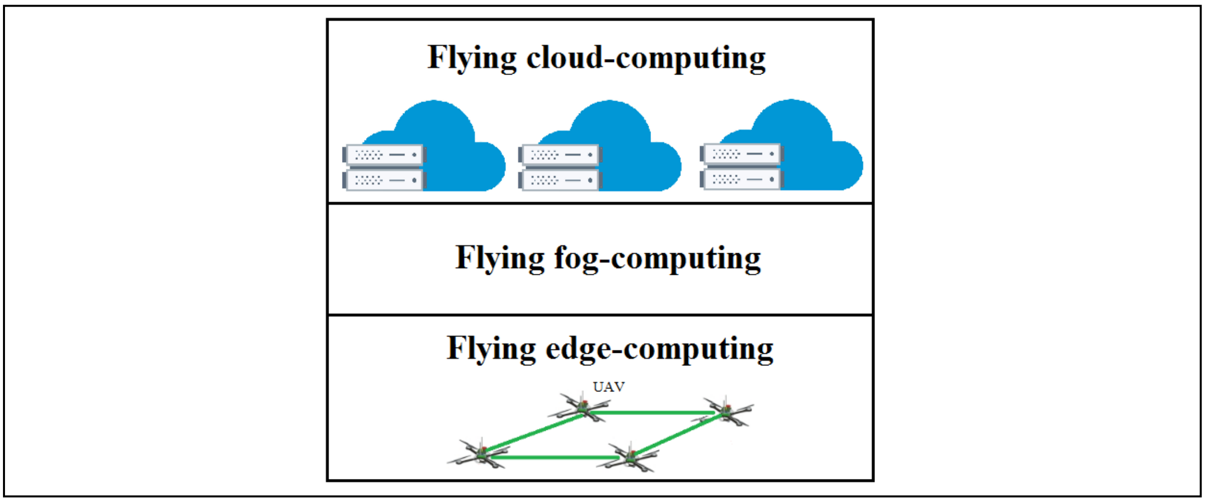

Figure 7: Flying fog computing.

Some flying fog-computing works were proposed in recent years. In [109], Hou et al. proposed the integration of fog-computing with a UAV swarm system in order to handle UAV computation tasks with a low latency and a high level of reliability. Furthermore, the authors proposed a genetic-based heuristic algorithm which optimizes task allocation in order de reduce as much as possible the UAV energy consumption. Simulation results proved that the proposed algorithm can efficiently offload and process UAV tasks, and that it can provide minimal energy consumption while satisfying the latency and reliability requirements. However, the complexity of the proposed algorithm should be reduced in order to further improve its practicability.

Lee et al. studied [110] the problem of UAV-based fog computing for the smart industry 4.0. Furthermore, a framework for task computing offloading was proposed which allows the ground sensors to offload its tasks towards the nearby fog UAVs. In addition, the proposed framework allows the fog UAVs to optimize their task allocation in order to maximize the computed tasks number, while taking into account the communication and latency of computation. A greedy algorithm was proposed in order to perform this optimization. Simulation results showed that the proposed algorithm can effectively optimize task allocation with an optimum gap which is not higher than 7.5 %. However, the proposed platform can be extended by optimizing the UAV trajectory.

Mohamed et al. [111] proposed a UAV-based fog-computing system named UAVFog in order to provide data storage, flexible communication, and low latency for IoT applications. UAVFog exploits the fog-computing capabilities and the UAV mobility in order to support IoT applications at different locations. Furthermore, many IoT services are offered by UAVFog, such as discovery and integration of IoT resources, broker services, and location-based services, as well as invocation and security services. A prototype of UAVFog was implemented, and the experimental results proved the effectiveness of UAVFog in terms of latency.

In [112], He et al. addressed the security, safety and privacy protection issues of fog UAVs in an airborne fog-computing platform. Therefore, the authors proposed a GPS spoofing detection method which is based on a monocular camera and the Inertial Measurement Unit (IMU) of the UAV. Experimental results showed that the proposed method is more effective than solely using the IMU.

Ti and Le [113] studied the computation offloading in a UAV-assisted hierarchical fog-computing system. This proposed system exploits the distribution architecture of UAVs and the centralized architecture of the cloud for task computing. Furthermore, Multiple Input Multiple Output (MIMO) technology was employed to ensure efficient data communications. In order to minimize the system power consumption, the authors proposed to optimize computing offloading, resource allocation, user-cloud/cloudlet association and path planning using a convex optimization method.

The flying fog-computing paradigm extends the storage and processing capacity of flying cloud-computing towards the flying edge-computing in order to reduce service latency and ensure a higher computing capacity to end users. However, the main challenge of flying fog-computing is how to integrate the UAVs at the edge-computing layer to the cloud-computing layer. This integration can be performed through various communication technologies, such as WiFi, WiLAN, cellular-networks, etc.

III.4 Flying cellular-networks

Flying cellular-network is considered as a promising technology for real-time applications, due to its high reliability, high data rate and low latency. Furthermore, flying cellular networks can enhance the IoFT performance in many aspects, such as connectivity, accessibility, monitoring, management, navigation and cost-effectiveness [114].

Many recent works on flying cellular networks have been proposed. For instance, in [115]**,** Challita et al. addressed wireless connectivity and security challenges in cellular-connected UAVs. An Artificial Neural Network (ANN)-based solution was introduced in order to overcome these challenges. In order to prove the effectiveness of the proposed solution, three use-case applications of cellular-connected UAVs have been considered: UAV-based delivery, UAV-based real-time streaming of multimedia, and UAV-based intelligent transportation.

The authors in [116], proposed an interference-aware path-planning algorithm for cellular-connected UAVs. The proposed algorithm is based on deep reinforcement learning in order to maximize the energy efficiency and jointly minimize the interference and latency.

Mei et al. proposed [117] an inter-cell interference coordination solution for the uplink transmission from the UAV to cellular base stations. In order to maximize the network throughput, and to mitigate the uplink interference, the proposed solution jointly optimizes the UAV uplink cell association, transmit power and resource block allocation.

In [118], Moon et al. proposed a preamble design technique for UAV communication in cellular networks using scalable sequences. In order to increase the detection performance, and to reduce the

UAV battery consumption, three scalable sequence techniques were proposed, analyzed and compared depending on the bandwidth capacity, and under different channel conditions.

Chowdhury et al. [119] addressed the UAV trajectory optimization in cellular networks based on dynamic programming. The proposed work aims to the enhance the wireless coverage and to maximize the data rate of cellular-networks. Both interference in cellular networks and UAV mission duration constraints were considered to find the optimum UAV trajectory.

Zhang et al. proposed [120] a cooperative UAV protocol for data uploading in cellular networks. The proposed protocol enables data sensing from the UAV to the base station using both UAV-to-infrastructure and UAV-to-UAV communications. Furthermore, an optimization algorithm of sub-channel allocation and of UAV speeds is proposed in order to maximize the uplink data rate. Simulation results showed that the proposed algorithm outperforms the greedy algorithm.

In [121], Amorosi et al. proposed to enhance the cellular-network coverage using UAVs, and they proposed to recharge the UAVs and ground sites batteries using solar panels. The latter were installed in different ground sites over the cellular network infrastructure. Furthermore, a modified genetic algorithm based on a decomposition-based technique was proposed in order to guarantee a high cellular-network coverage with maximized UAVs and ground site battery level, while taking into account the UAVs mission duration.

In [122], Azari et al. developed a generic framework that improves the UAVs' connectivity in cellular networks. Furthermore, the analytical results of the integrated UAV with a cellular network showed that the optimum choice of the UAV antenna tilt and UAV altitude can highly improve the link coverage and throughput.

III.5 Comparison of IoFT works

The existing IoFT works suggest integrating FANETs with IoT in order to improve the connectivity, reliability, scalability, stability, data storage and processing and security for IoT real-time applications. Table 6 provides a summary of existing IoFT works in the literature, including their objectives and addressed problems, explained as follows:

- **Connectivity and coverage:** The proposed IoFT work guarantees a high network connectivity and large-scale coverage.
- **Scalability:** Capability of the network to grow without any major changes in its overall design.
- **Reliability:**Measured based on error-free operations on the network. Ideal network reliability means that no errors or failures were produced in this network.
- **Stability:** Measured by the fast access and rapid error recovery. The high UAV mobility decreases the network stability.
- **Real-time latency:** The network ability to guarantee a reduced transmission delay for real-time services.
- **Security:** The network safety against external threats and attacks.
- **UAVs controlling:** The ground user ability to control the UAVs via the IoT devices.
- **Cloud processing:** The network capacity to process the UAVs data using sufficient processing resources.
- **Cloud storing:** The network stockage capacity of voluminous data collected by the UAVs.
- **Energy consumption minimization:** Capacity of the network to supply and manage the powered energy of UAVs and IoT ground devices.
- **UAVs collaboration:** The UAVs collaborate with them in order to accomplish a mission.
- **Tasks computing offloading:** The UAVs transmit their tasks towards the IoT cloud for processing and storage.

- **UAVs trajectory:** Take into account the UAVs trajectory optimization in order to minimize the UAVs energy consumption.
- **Resources allocation:** Proposing a resource allocation strategy in order to mitigate the collision and interference problems.
- **Routing optimization:** Proposing a new routing protocol in order to improve the data transmission in IoFT.

As shown in the table 6, we have categorized the IoFT works according to the used IoFT technology for the computing and data transmission into four categories: flying cloud-computing, flying edge-computing, flying fog-computing and flying cellular-networks. We can see in this table that each IoFT work have been proposed in order to ensure a specific objective, such as connectivity and coverage, scalability, reliability, stability, low latency, UAVs controlling, data storage and processing, energy consumption reducing, security. Furthermore, the table 6 depicts that each work addressed some problems in order to ensure his objectives, such as UAVs trajectory optimization, resources allocation, UAVs collaboration, tasks computing offloading, routing optimization, etc.

We can remark from that table that most flying cloud-computing studies aim to guarantee a high computation rate and storage of UAVs' collected data by offloading the tasks towards the cloud servers. The latter are characterized by a high resource capacity in terms of data processing and storage. However, the low latency cannot be ensured by flying cloud-computing works due to the high transmission time of the data between the UAVs and the cloud servers which are located far from these UAVs.

The table 6 illustrates that the flying edge computing and flying fog computing studies to ensure a low data transmission latency. This is achieved thanks to the local processing and storage of the UAVs collected data at the edge and fog nodes of the network. However, most flying edge-computing works cannot provide high computation rates and data storage of massive data, due to the limited resources of edge nodes. In addition, table 6 proved that flying fog-computing works can achieve q minimal latency with high data computation and storage, because this IoFT works category combines local resources of fog nodes with cloud nodes' resources.

As shown in table 6, works on flying cellular networks aim to enhance the network connectivity and coverage while providing a minimal latency. This result is motivated by the effective use of the available cellular network infrastructure in order to reinforce the data transmission from the UAVs towards the internet servers. We remark in table 6 that few of the IoFT works have to deal with the routing optimization problem. However, the latter is a very interesting issue and can highly enhance the IoFT performance.

Table 6: Objectives and addressed problems of open research on Internet of Flying Things

		Objectives	**Addressed problems**

IoFT category	**Reference (s)**	**Connectivity and coverage**	**Scalability**	**Reliability**	**Stability**	**Security**	**Real-time latency**	**UAVs controlling**	**Cloud processing**	**Cloud storing**	**Energy consumption minimization**	**UAVs collaboration**	**Tasks computing offloading**	**UAVs trajectory**	**Resources allocation**	**Routing optimization**
Flying cloud-computing	Mahmoud and Mohamed [53]								√	√		√				
	Mahmoud and Mohamed [54]								√	√		√				
	Mahmoud and Mohamed [52]								√	√		√				
	Mahmoud et al. [55]								√	√		√				
	Koubâa et al. [58]							√	√	√		√				
	Luo et al. [48]			√	√			√	√	√						
	Yu et al. [69]								√	√						
	Majumder and Prasad [62]							√	√	√						
	Koubâa et al. [61]							√	√	√						
	Koubâa et al. [50]							√	√	√		√				
	Wang et al. [49]			√	√			√	√	√						
	Van't hof and Nieh [67]					√	√	√	√	√	√					
	Hong and Shi [51]							√	√	√						
	Mahmoud et al. [56]								√	√		√				
	Yapp and Babiceanu [63]					√		√	√	√						
	Mahmoud et al. [57]								√	√		√				
	Capello et al. [70]								√	√						
	Gao et al. [71]			√					√	√	√		√		√	
	Rodrigues et al. [65]					√			√	√						
	Hadj et al. [66]						√		√	√	√	√				
	Rodrigues et al. [64]					√			√	√						
	Zhang and Yuan [68]							√	√	√						
	Sulaj et al. [72]						√		√	√						
Flying edge-computing	Narang et al. [75]	√					√									
	Dong et al. [90]						√								√	
	Zhou et al. [77]	√		√			√								√	
	Chen et al. [78]						√		√	√		√				
	Zhou et al. [79]						√				√		√	√		
	Zhou et al. [80]						√		√		√		√	√	√	
	Cheng et al. [76]						√									
	Jeong et al. [91]						√				√		√	√	√	
	Hu et al. [81]						√				√		√	√	√	
	Xiong et al. [100]						√				√		√	√	√	
	Bekkouche et al. [107]						√							√	√	
	Liu et al. [92]						√						√			√
	Messous et al. [84]		√				√				√		√			
	Cao et al. [93]						√						√	√		
	Zhang et al. [94]						√				√		√	√	√	
	Bekkouche et al. [74]		√	√			√	√								
	Hu et al. [97]						√						√	√		
	Wang et al. [98]						√				√		√		√	
	Hu et al. [82]				√		√				√		√	√	√	

	Xu et al. [99]						√				√		√			
	Hua et al. [101]						√				√		√		√	
	Callegaro et Levorato [102]						√						√			
	Messous et al. [85]						√				√		√			
	Du et al. [95]						√				√				√	
	Bai et al. [89]					√	√				√		√			
	Qian et al. [103]						√				√		√	√		
	Yu et al. [104]						√							√	√	
	Fan et al. [96]						√				√			√	√	
	Zhang et al. [105]						√				√		√	√	√	
	Li et al. [83]						√						√			
	Sedjelmaci et al. [87]					√	√				√					
	Sharma et al. [106]	√		√			√				√					
	Tian et al. [88]		√			√	√		√	√						
	Messous et al. [86]						√				√		√			
Flying fog-computing	Mohamed et al. [111]		√				√		√	√						
	Hou et al. [109]			√			√		√	√	√		√			
	Ti and Le [113]						√		√	√	√		√	√	√	
	Lee et al. [110]						√		√	√			√		√	
	He et al. [112]					√	√		√	√						
Flying cellular-networks	Challita et al. [115]	√				√	√									
	Challita et al. [116]						√				√					
	Mei et al. [117]										√				√	
	Moon et al. [118]										√					
	Chowdhury et al. [119]	√					√							√		
	Zhang et al. [120]														√	
	Amorosi et al. [121]	√					√				√					
	Azari et al. [122]	√														

IV. IoFT applications

IoFT is currently shaping various human application domains, such as smart agriculture, environmental pollution monitoring, disaster management, video streaming surveillance, objects tracking, smart city, smart industry, etc. This section presents some recent works addressing different IoFT applications.

IV.1. Smart agriculture

Precision smart agriculture is one of the domains which can use the IoFT advantages in order to improve the production efficiency and to optimize crop quality with minimizing the negative impact on the environment.

In the IoFT literature, several smart agriculture works have been proposed in order to increase the food quality and quantity. Uddin et al. proposed [123] a dynamic clustering and data collecting scheme based on UAVs for Agriculture-IoT (AG-IoT). This study proposes to use a set of IoT ground devices to control various parameters related to environment, soil and crops. Moreover, a UAV is used to locate and assist these IoT devices to form a cluster and to select the best Cluster Head (CH). Therefore, the use of a UAV allows the proposed clustering scheme to achieve a reliable uplink for data collection.

In [124], Saha et al. presented different solutions that combine IoT with drones for crop quality improvement in smart agriculture. The work proposed an IoT-based drone model which consisted of a Raspberry Pi integrated with various sensors and modules, such as GAS sensor, RGB-D sensor, and GPS module. The Raspberry Pi module collects the agriculture data from different sensors, including soil temperature, ground images, humidity, etc. Moreover, The Raspberry Pi sends these data to a cloud-based storage area for further analysis.

In [125], Faraci et al. proposed an IoFT platform for smart agriculture monitoring in rural areas. To provide the connectivity, the proposed platform constituted of a set of UAVs which collect the agriculture data from some critical places in the territory, such as trees, plants, rivers, soil, cropland, etc. Therefore, these UAVs transfer the collected data using 5G to a local data center that consisted of a limited number of servers. The data center uses a Multi-access Edge Computing paradigm [126] for the management, processing and storage of the collected agriculture data. To handle the electrical power unavailability in rural areas for UAVs batteries recharge and data center supply, the proposed platform integrated a hybrid power generation system which consisted of diesel and power renewable generators. An analytical model is defined in this work to design and evaluate the performances of the proposed platform. However, the design of the latter did not consider some issues, such as the variation of the number of UAVs that are in the ground to be recharged.

IV.2. Environmental pollution monitoring

Environmental pollution causes changes to the ecosystem and the atmosphere due to various forms of chemical and energy pollutants which can deteriorate the quality of the environmental air, water and soil. Therefore, these pollutants directly affect the life of biological entities in the environment.

Many IoFT studies on environmental pollution monitoring have been proposed in order to keep our nature safe. Elijah et al. [127] proposed a smart Malaysian river monitoring solution that controls the water pollution. The proposed solution was based on UAV, IoT, Low Power Wide Area (LPWA) communication technology and Data Analytics (DA). The UAV is used for monitoring the river water, collecting river water sample data and sending them towards IoT cloud server using LPWA. The latter provides a long range, low-power and low-cost wireless communication system [128]. The DA allows to know the water quality and pollution level discharged into the river based on the collected data. The proposed smart river monitoring solution provides low-cost, high-resolution in time and space, real-time monitoring and pollution identification. However, this work did not resolve the UAV electrical power supply and proposes to use only one UAV.

In [129], Hernandez-Vega et al. presented an air pollution monitoring system based on UAVs and IoT that measures the air quality in a smart city. The proposed system was composed of a UAV which uses a set of MQ sensors to control the criterion pollutants in the air: carbon monoxide, hydrogen, ozone, and carbon dioxide. The UAV also uses a data acquisition system to covert the analog data values of the sensors to numerical data values which can be manipulated by the computer. In addition, the proposed system also included a ground control station that monitors the UAV, receives the air quality data for processing, and uploads these data to the IoT servers. A radiofrequency communication channel is used for the data transmission between the UAV and ground control station. Experimental results showed that the used UAV MQ sensors are ideal due to their size and weight, but fail to provide a reliable measure of the air quality.

Agarwal et al. designed [130] an air and water monitoring system based on a master drone, four slave robots and IoT. On the one hand, and to cope with air pollution monitoring, two flying slave robots are used which are composed of a microcontroller and some sensors for air pollutants detection, such as Nitrogen Dioxide (NO2) gas sensor, Ozone (O3) gas sensor, humidity sensor, and temperature sensor. On the other hand, two land slave robots are mobilized for monitoring the water pollution. Each land slave robot consisted of a microcontroller and a set of water pollutants detection sensors, like Oxidation-Reduction Potential (ORP) sensor, Dissolved Oxygen (DO) sensor, PH sensor and temperature sensor. Moreover, the four slave robots have a power supply and an RF modem to communicate with the master drone. The latter receives the real-time air and water quality data from the slave robots, records and maintains these data, and uploads them towards the IoT servers in order to analyze the different levels of air and water pollution. This proposed designed system should be implemented in order to prove its real efficiency for air and water pollution monitoring.

In [131], Yang et al. proposed an IoT-based flying system for environmental pollution monitoring. The designed system was composed of three parts: quad-rotor UAV, environmental detection module and web servers. The quad-rotor UAV supports the environmental detection module, which serves to detect the different environmental parameters using some sensors, such as temperature, humidity and air quality. Furthermore, the environmental detection module sends the collected environmental data to the web servers using 3G technology and TCP/UDP transmission protocols in order to analyze and process these environmental data. Although the proposed system can efficiently monitor the environmental pollution, the power shortage problems of quad-rotor UAV batteries was not addressed in this work.

Hu et al. presented [132] an air quality monitoring architecture based on IoT and UAVs. This architecture consisted of four layers: sensing layer, transmission layer, processing layer and presentation layer. The first layer is composed of ground devices and UAVs, which collect the real-time air quality data from the environment and transmit it to transmission layer using wireless communications. The second layer consists of base stations which guarantee the bidirectional communication between the sensing layer and processing layer. The third layer is composed of web servers and database servers which receive the air quality data via IoT communication from transmission layer, analyze these data, and predict the air quality values using spatial fitting and short-term prediction techniques. The last layer provides a graphic interface for the users and system managers. This proposed architecture takes into account the deployment strategies of UAVs and ground devices in the environment, and also considers the control power of UAVs and ground devices in order to achieve a balance between the data accuracy and power consumption. However, this system did not consider the transmission and processing delay of sensing real-time air quality data.

IV.3. Disaster management

This type of applications aims to manage natural disasters, such as forest fires, floods, storms and earthquakes, in order to ensure a suitable and immediate assistance to victims, and to provide a rapid and effective recovery in such situations.

Some works were proposed which examine the usefulness of IoFT for disaster management. In [133], Kalatzis et al. proposed an agent-based layered architecture for early forest fire detection based on UAVs and IoT. The proposed architecture is composed of three layers: edge-computing layer, fog-computing layer and cloud-computing layer. This architecture aims to select in real-time the forest fire images, and to reduce the utilization of UAV energy, processing and communication resources. The first layer provides UAVs with a low-latency access to the servers. The second layer accomplishes the most energy-consuming tasks, such as the classification, recognition and selection of UAV-captured images. The third layer receives the fog selected images from fog-computing layer for further processing and analysis. The initial experiments showed that the processing of the captured images at the fog-computing layer provided better results in terms of energy consumption, response time and network load than the processing of these images at the edge-computing or cloud-computing layers. This work can be improved by including different resource allocation techniques in order to optimize the utilization of UAV resources in terms of energy and processing.

Kumar et al. proposed [134] to combine UAVs and IoT in order to collect environmental data from sensors in disaster-prone areas, and send them towards the GCS. The collected data represents the critical environmental parameters, such as temperature, humidity, luminosity, strain, stress, etc. Moreover, the disaster types considered in this study can be of different types: fires in forests and buildings, landslides, heavy floods, etc. For the real-time communication between the UAVs and a ground station, the authors propose to use the Internet. The ground station receives the collected data and protects the UAVs during extreme conditions. The efficiency of the proposed solution is proved based on a series of experimental tests. However, only the temperature parameter is considered in this experiment. Furthermore, the solution did not consider the electrical supply of UAV batteries.

In [20], Liu et al. proposed an emergency extension of IoT coverage using UAVs in disasters when the communication infrastructures are destroyed. Two optimal transceiver schemes were proposed in order to uplink the data from the ground devices to the UAV, and in order to downlink data from the UAV to ground devices. Moreover, the proposed solution relies on multi-hop device-to-device communications to extend the coverage of the UAV. Simulation experiments proved the effectiveness of the proposed solution to extend the IoT coverage using the UAV, and to guarantee a reliable transmission. However, the proposed scheme can be improved by using multiple UAVs, and by handling the UAV electrical supply problem.

Luo et al. proposed and implemented [135] a UAV-cloud platform for disaster sensing applications, considering some constraints such as intermittent network connectivity, network resources' limitation, high volume of data, limited UAV resources, etc. The proposed platform consisted of two parts: client and server. The client component represents the UAVs that collect the data, stores them in its onboard hard disk, performs the pre-processing of these data, and sends them to the cloud network and to the control center. The server component represents the cloud-computing network which stores the received data and performs its post-processing to reduce the utilization of UAVs resources. The results proved that the proposed framework is suitable when the disaster applications require a large amount of real-time data, such as video streaming data.

In [136], Choksi et al. proposed the use of UAVs to collect the real-time data from sensors, and transmit them to the cloud platform in disaster situations. The UAV of the proposed system is equipped with IoT devices to achieve IP-based communication with the ground station and with the cloud-servers. The ground station receives the real-time sensor data, such as temperature, luminosity and humidity a via 802.15.4 radio, and sends it to the UAV. Therefore, when the UAV receives the sensors' data, it transmits them to the cloud-platform. Afterwards, the latter analyses the received data and alerts the authorities about the location of the disaster. This study proposed to use only one UAV, failing to adequately cover all the region associated to a disaster.

IV.4. Video streaming surveillance

Video streaming-oriented flying things enables the dissemination and real-time communication of video among IoT devices using a set of UAVs. The latter can capture the video using their local camera, and forward it towards the IoT network for processing and storage.

In the IoFT-related literature we can find many state-of-art video streaming surveillance works. In [137], Motlagh et al. presented a UAV-based IoT platform for crowd surveillance based on face recognition. The proposed platform consisted of set of UAVs which are equipped with various devices such as camera, IoT devices, WIFI devices, GPS, sensor, etc. These devices allow UAVs to collect and deliver the video data towards the ground station and towards the Mobile Edge Computing (MEC) nodes. This transfer of UAV data is performed by a wireless network, such as a WiFi or a cellular-network (such as 4G-LTE and 5G). Two case studies were considered in this work: when the video processing is performed locally by the UAV, and when the offloaded video is processed by MEC nodes in the network. The work proposed to use the Local Binary Pattern Histogram method (LBPH) in order to perform face recognition. The testbed results have been demonstrated that face recognition at the MEC nodes significantly reduces the UAV energy and the video processing time.

Qazi et al. presented [138] an architecture for real-time video streaming surveillance by using UAVs and 4G LTE communication technology. The proposed architecture included several outdoor cells, each representing a UAV equipped with camera for external video streaming monitoring of the building (OK). In addition, this architecture consisted of several indoor cells which contained UAVs equipped with cameras within the controlled building. Therefore, both outdoor and indoor cells capture and send the real-time video to base stations using 4G-LTE cellular network. Simulation results showed that the UAVs number and mobility are both factors that influence data throughput.

In [139], Grasso et al. proposed a Tactile Internet architecture for video-surveillance based on UAVs, and a set of sensors and actuators installed on the ground. This architecture is composed of three domains: the master, the network and the slave. The first domain represents the users which control the UAV operations for the video-surveillance. The second domain allows the interconnection between the master and slave domains. The last domain consisted of UAVs equipped with a camera to capture the images, and also of sensors and actuators fixed on the ground. Moreover, each UAV is equipped with a micro-controller which combines the received images from the local camera with the received sensors data to generate the jobs. In addition, the UAV consisted of a micro-computer to process the generated jobs and consisted of a job queue. The simulation results proved that the proposed system can provide an end-to-end delay not greater than 1ms, and a loss probability not greater than 10^{-7}. However, the UAV energy power consumption is not considered in this architecture.

Although the most recent IoFT application studies were cited in this section, we can find in IoFT research other application works in various domains, such as object tracking [140, 141, 142], smart cities [143, 144], smart home [145], smart industry [146, 147], etc. These IoFT applications are very diversified, and keep increasing every day.

V. IoFT challenges and future perspectives

Due to the advancement in FANET and IoT technologies, the integration of these two networks provides a flexible support for various IoT services including control and monitoring, surveillance, emergency management, or search and rescue scenarios. However, IoFT faces various challenging issues, such as collision and interference, UAV deployment, UAV selection, energy consumption, security and privacy, UAV control and management, and UAV path planning. In this section, we outline the different IoFT challenges that need a more in-depth study. Furthermore, we propose future IoFT perspectives to overcome the highlighted challenges, and to guide scientists to develop novel solutions which make the IoFT more reliable, efficient and secure. Table 9 summarizes the open research challenges of IoFT, along with the different recommended references and proposed future research directions.

- **Collision and interference:** The offloading of voluminous data, such as a real-time video streams by the multiple UAVs, to GCS under high IoFT connectivity, can produce significant collisions and interference among the UAVs and the GCS. Many IoFT works have addressed the collision and interference management challenges [148, 149, 150, 151, 152]. In order to mitigate the interference problem, several IoFT parameters must be optimized: UAV trajectory, UAV path planning, UAV and IoT resource allocation, control of UAV altitude and mobility, etc.
- **UAV deployment:** The deployment of UAVs in critical places is another issue addressed by some IoFT works [153, 154]. The placement of UAVs in suitable locations can reduce the wireless latency of IoT ground users and mitigate traffic congestion. Furthermore, UAV deployment in areas with a high density of users can provide good channel conditions, but it increases the congestion due to the limited capacity of this channel. In contrast, when the UAVs are placed over areas with a low density of users, the offloading of traffic loads can be limited, which affects the wireless latency of the users. An optimum UAV deployment can also maximize the UAV coverage and throughput. While UAV deployment in a three-dimensional space remains an NP-hard optimization problem, different optimization heuristics, such as ant colony, particle swarm, genetic algorithm, etc., can be used to solve this problem with a low complexity.
- **UAV selection:** The selection of an appropriate UAV to do a specific task is another IoFT challenge which is envisioned by different IoFT works in order to reduce both the total energy consumption and the operation time. This selection should take into account several parameters like the remaining UAV energy, the required task energy, the distance to the task location, the UAV speed, or the required time for the task transmission and processing. Some IoFT algorithms and mechanisms have been proposed in order to select the appropriate UAV in these cases [155, 156].
- **UAV path planning:** The development of an optimum UAV path planning mechanism is a great IoFT challenge discussed in different IoFT works [157, 158, 159, 160, 161]. UAV path planning aims to maximize the data collection rate, and minimize the UAV flying cost in terms of flying time, energy consumption and flying risk level. Therefore, different types of information can be used to address this challenge, including geographical topology, locations of static sensor nodes, flying risk levels, and airspace restrictions.
- **Energy consumption:** Although IoFT seeks to minimize the energy consumption of both UAVs and IoT ground devices by integrating the resource capacities of FANET and IoT networks, the energy consumption remains an interesting IoFT challenge. Energy consumption can be used for multiple IoFT activities, such as data processing and storage, data transmission, routing, querying, etc. In the literature, we find that several IoFT works have addressed this issue [162, 163, 164, 165, 166, 167]. Future research can use the wireless medium in order to recharge UAV and IoT device batteries.
- **Security and privacy:** Due to the broadcast nature of the wireless medium, UAVs are prone to face ecurity and privacy issues. The security of exchanged data between UAVs and CGSs against

malicious eavesdropping can be ensured at the physical layer by including relay selection, multiple-antenna arrays, and friendly jamming. Most IoFT works addressing security and privacy challenges [168, 169] focus on the physical layer. However, future IoFT research in this area can handle the security and privacy at the other layers, such as transportation and application layers.

- **UAV control and management:** When the number of UAVs is high, their control and management from a remote Internet locations can become complex due the frequent data transmissions between the concurrent UAVs and the IoT ground devices. Although some IoFT works have addressed this issue [170, 171], efficient algorithms should be proposed to provide some UAV control and management functionalities, such as subscription and notification, data management, UAV localization, group management, etc.

Table 9: Open research issues for IoFT

IoFT challenge (s)	Recommended IoFT reference (s)	Future IoFT research direction (s)
Collision and interference	[148], [149], [150], [151], [152]	Several IoFT parameters must be optimized, such as: • UAV trajectories. • UAV path planning. • UAV and IoT resource allocation. • Control of UAV altitude and mobility.
UAVs deployment	[153], [154]	UAV deployment using optimization heuristics, such as: • Ant colony. • Particle swarm. • Genetic algorithms.
UAV selection	[155], [156]	Take into account several parameters, such as: • UAV energy levels. • Required task energy. • Distance to the task location. • UAV speed. • Required time for the task transmission and processing.
UAV path-planning	[157], [158], [159], [160], [161]	Various information can be used for UAV path planning, such as: • Geographical topology. • Location of static sensor nodes. • Flight risk levels. • Airspace restrictions.
Energy consumption	[162], [163], [164], [165], [166], [167]	Recharge of UAV and IoT device batteries using the wireless medium.
Security and privacy	[168], [169]	Enhancing IoFT security and privacy at three layers: • Application layer. • Transportation layer. • Physical layer.
UAV control and management	[170], [171]	Proposed efficient algorithms for UAV control and management which provide some functionalities, such as: • Subscription and notification. • Data management. • UAV localization. • Group management.

VI. Conclusion

IoFT is becoming a promising filed to efficiently support real-time IoT applications by combining UAVs with IoT. IoFT aims to extend the IoT coverage and to ensure the connectivity, scalability, reliability, stability, high processing and storage capacity with a minimal energy consumption of UAVs and IoT devices. In this survey, we presented the based concepts of flying things, including UAS, UAV architecture, FANET communications, etc. In addition, a comprehensive taxonomy of IoFT research studies was provided, including the IoFT networking and transmission technologies, IoFT objectives, IoFT problems, IoFT applications, IoFT challenges, etc. Furthermore, a classification, study and comparison of different IoFT works (e.g. flying cloud-computing, flying edge-computing, flying fog-computing and flying cellular-networks) is presented. Based on this proposed survey, we conclude that, in order to further improve IoT applications support, IoFT works should address several IoFT issues, including collision and interference, UAV deployment, UAV selection, UAV path-planning, energy consumption, security and privacy, and UAV control and management. As future work, we envisage to conceive a new IoFT scheme which addresses the different IoFT challenges in order to ensure reliable and efficient computing, as well as storage and transmission of UAV collected data towards Internet servers.

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