

Unmanned Aerial Vehicle enabled Internet of Everything: Opportunities and Challenges

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Abstract—The recent advances in information and communication technology (ICT) have further extended Internet of Things from the sole “things” aspect to the omnipotent role of “intelligent connection of things”. Meanwhile, the IoE realization meets critical challenges including the restricted network coverage and the limited resource of existing network technologies. Recently, Unmanned Aerial Vehicles (UAVs) have attracted significant attentions attributed to their high mobility, low cost, and flexible deployment. Thus, UAVs may potentially overcome the challenges of IoE. This article presents a comprehensive survey on opportunities and challenges of UAV-enabled internet of everything (IoE). We first present three critical expectations of IoE: 1) scalability requiring a scalable network architecture with ubiquitous coverage, 2) intelligence requiring a global computing plane enabling intelligent things, 3) diversity requiring provisions of diverse applications. Thereafter, we review the enabling technologies to achieve these expectations and discuss four intrinsic constraints of IoE (i.e., coverage constraint, battery constraint, computing constraint, and security issues). We then present an overview of UAVs. We next discuss the opportunities brought by UAV to IoE. Additionally, we introduce a UAV-enabled IoE (Ue-IoE) solution by exploiting UAVs’s mobility, in which we show that Ue-IoE can greatly enhance the scalability, intelligence and diversity of IoE. Finally, we outline the future directions in Ue-IoE.

Index Terms—Unmanned Air Vehicles, Internet of Everything, Internet of Things, Edge Intelligence, Multi-UAV Ad Hoc networks, Trajectory Optimization

I. INTRODUCTION

INTERNET of Everything (IoE) represents a fantastic vision in the future, in which *everything* is connected to the Internet, thereby offering intelligent services and facilitating decision-making. IoE’s implementation depends on interdisciplinary technical innovations such as sensor and embedded technologies, low power communications and big data analytics. First, the advances in sensor and embedded technologies have made the IoT nodes being more portable and less energy consumption. Second, the appearance of Low Power Wide Area Network (LPWAN) technologies offers the ubiquitous network connection of low power IoT nodes. Furthermore, the breakthrough in artificial intelligence and the availability of massive IoT data have driven the intelligence of IoE. In this way, IoE can be applied in wide applications such as smart manufacturing, smart agriculture and intelligent transportation

system. In summary, IoE is expected to achieve three expectations: 1) *scalability* means to establish a scalable network architecture with ubiquitous coverage; 2) *intelligence* implies to construct a global computing facility enabling intelligent decisions; 3) *diversity* indicates supporting diverse applications. Therefore, the realization of IoE essentially depends on the achievement of the above three expectations.

We have witnessed the rapid development of ICT technologies. In particular, ICT technologies have further extended existing human-oriented Internet to machine-oriented Internet of Things, which consists of wireless sensor networks (WSN) for connecting multiple sensor nodes via a self-organized topology [1], low power wide area network (LPWAN) for offering large-range coverage of power-constrained nodes [2], and 4G and 5G mobile networks for supporting massive-access services of machine-to-machine (M2M) communications [3]. Meanwhile, massive data are generated from various things in real-time manner. The breakthrough of artificial intelligence (AI) technologies integrating with massive IoT data brings the opportunities in realizing intelligent applications including intelligent recognition, intelligent management and intelligent decision [4]. As a result, conventional IoT has been evolved into IoE that supports intelligent connection of things, thereby enabling smart applications, such as smart meter [5], smart grid, smart manufacturing [6], smart agriculture, intelligent traffic scheduling [7]. In this regard, the existing wireless communication networks (including WSN, LPWAN and 5G cellular networks) can help to realize the scalability of IoE. Meanwhile, the cutting-edge big data analysis technologies and artificial intelligence can be used for enabling intelligence to IoE. Finally, the emerging IoE intelligent services have proliferated a huge market for diverse IoE applications.

However, there are still a number of intrinsic limitations preventing IoE from achieving the above three expectations. In particular, IoE has network coverage/access constraints, battery constraint of IoE nodes, security and privacy vulnerabilities. First, the existing network infrastructures are *coverage-constrained* in some harsh and remote geographical areas due to the restricted deployment of network infrastructures. Hence the ubiquitous connections of IoE cannot be achieved. In addition, IoE nodes also suffer from the limited battery capacity due to cost and portability considerations. As a result, the battery-constrained nodes are easily exhausted and eventually lead to the connection-lost. This case is especially severe for the nodes in the coverage-constrained areas. Furthermore, most of the nodes in IoE have no enough computing capability to process local sensor data. Moreover, the over-simplified access protocols (e.g., NB-IoT and LPWAN) also pose potential

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security vulnerabilities in IoE, such as information being eavesdropped or being forged by malicious relay nodes. To address these challenges, IoE requires a flexible-coverage and elastic-deployment so as to achieve the ubiquitous coverage and offer quick response in a highly-efficient and reliable way.

In recent decades, Unmanned Aerial Vehicles (UAVs) have attracted significant attentions from both industrial and academia communities due to their flexible and elastic services. With high mobility and elastic deployment, UAVs can extend the coverage of IoE [8], [9]. In particular, compared with terrestrial networks and satellite remote communications, low-altitude UAVs-enabled wireless networks can be quickly deployed and be flexibly reconfigured to enhance the network coverage and capacity [9]. Furthermore, the flexible deployment of UAVs also enables myriad IoE applications. Through the dedicated configuration and specified control design, UAVs have a variety of applications such as agriculture management [10], marine mammals monitoring [11], and military medical evacuation [12]. However, using UAV in IoE also poses new challenges in the perspectives of dynamic network connection, flexible network topology, precise control and lightweight intelligent algorithms. In order to address these challenges, we need to design the dedicated communication protocols, the flexible resource allocation mechanism, the optimal trajectory plans of UAVs and the portable intelligent algorithms in IoE.

Although several surveys have already discussed the IoE vision in recent decades [13]–[16], they mainly focused on a single IoE technology. For example, the authors in [13] have considered the Internet Protocol version 6 (IPv6) to realize the ubiquitous communication access to the Internet while they ignored the issues about wide coverage and massive accesses of wireless networks. Furthermore, the authors in [15] have focused on cloud plane to realize the virtualized data services for IoE whereas they ignored the orchestration with physical networks and diverse IoE intelligent algorithms. To the best of our knowledge, the previous literature lacks the comprehensive investigation of IoE in three key expectations: scalability, intelligence and diversity.

The limitations of existing surveys motivate us to conduct a more comprehensive survey exploring IoE’s expectations and enabling technologies, along with the extensive applications of UAV-enabled IoE. In particular, this survey has three major contributions: i) summarizing the key expectations of IoE (i.e., scalability, intelligence, and diversity) and reviewing the corresponding enabling technologies; ii) giving an introduction of UAVs technologies (such as maneuverability, communication and other relevant technologies) and discussing the opportunities that UAVs can bring to IoE; iii) integrating UAVs with the existing IoE’s enabling technologies so as to present a UAV-enabled IoE solution.

The rest of this paper is organized as follows. Section II introduces IoE regarding its three expectations, enabling technologies and challenges. Section III reviews UAV’s related work: unmanned aerial system (UAS) and UAV communication networks. In Section IV, we introduce a UAV-enabled IoE (Ue-IoE) solution by combining UAV’s and the existing ICT technologies, in which we show that Ue-IoE can greatly

enhance scalability, intelligence, and diversity of IoE. Further, we outline crucial issues in Ue-IoE as well as future directions in Section V. Finally, Section VI concludes the paper.

II. INTERNET OF EVERYTHING

This section first presents three key expectations of IoE in Section II-A, then outlines the enabling technologies to fulfill the expectations in Section II-B, and next discusses the challenges in Section II-C.

A. Three expectations of IoE

The vision of IoE is to connect ubiquitous electronic devices (i.e., terminal nodes of IoE) to the Internet, then to analyze massive data generated from connected terminal nodes, and thereby to offer intelligent applications for the advancement of human society. To achieve this vision, IoE is expected to fulfill three key expectations: 1) *scalability* means to establish a scalable network architecture with ubiquitous coverage; 2) *intelligence* implies to construct a global computing facility enabling intelligent decisions; 3) *diversity* indicates to support diverse applications. Fig. 1 shows three expectations as well as their typical enabling technologies. In detail, we describe the three expectations as follows.

- 1) *Scalability*: Scalability means to establish a scalable network for IoE to elastically cover *everywhere* and *everything*. In this sense, IoE can satisfy various communication requirements for different geographical scenarios including urban, rural, underwater, terrestrial, aerial, and space. To achieve this goal, the scalable IoE network requires wide coverage, massive access, and ubiquitous connection. Such IoE networks can be built by integrating multiple communication technologies with various transmission-distance (from a few meters to a thousand meters) and different network topologies (including point-to-point topology, star topology, and hybrid topology). The underlining communication networks consist of mobile cellular networks (MCN), wireless local area networks (WLAN), WSN, satellite networks, and Mobile Ad Hoc networks (MAHN). The scalability of IoE supports the physical data collection and further provides data source for intelligent analytics.
- 2) *Intelligence*: Intelligence implies to construct a global computing facility to enable intelligent decisions for IoE. IoE’s intelligence can be realized by obtaining massive IoT data from underlining IoT, extracting the valuable information (such as smart commands or decisions) from the computing plane, and then using these information to enable intelligent actions or controls for *everything*. The global computing plane consists of distributed database and storage systems, on top of which various big data processing algorithms are deployed. The distributed database and storage systems save the collected IoT data. Diverse big data processing algorithms include descriptive, diagnostic, predictive and prescriptive analytical schemes [6], which are necessary to serve different intelligent applications. According to the deployment locations of computing facilities, IoE’s intelligence can be categorized into local intelligence, edge intelligence, and cloud intelligence. Local intelligence,

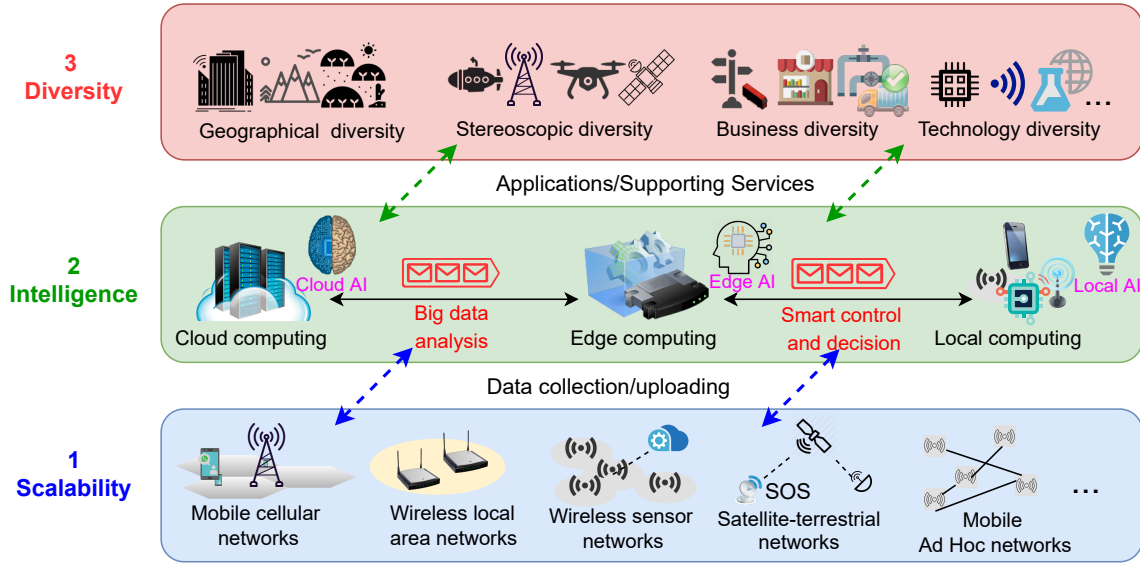


Fig. 1. Three expectations of IoE: scalability, intelligence, and diversity.

edge intelligence and cloud intelligence imply that computing facilities with the corresponding intelligent algorithms are deployed at local side (i.e., at terminal nodes), edge side and remote clouds, respectively. It is necessary to orchestrate local intelligence, edge intelligence, and cloud intelligence so as to realize IoE's intelligence.

- 3) *Diversity*: Diversity indicates to support diverse applications. The realization of diverse IoE applications is essentially based on the scalability and intelligence of IoE since they are the prerequisites for computing capability, security, energy efficiency and network performance. IoE's diversity can be categorized into: i) *geographical diversity* - classified by different geographical regions, ii) *stereoscopic diversity* - classified by different spatial positions, iii) *business diversity* - classified by different social utilities and iv) *technology diversity* - classified by different ICT technologies.

To achieve the above three expectations, it is necessary to deploy a large number of terminal nodes (for local sensing and control), network access nodes (providing ubiquitous connections), and computing facilities (supporting intelligence). Furthermore, the diverse applications will be continuously updated with the increasing demands of various intelligent services. Consequently, it is expected in the future that IoE ceaselessly needs to consume plenty of resources (including battery power, computing, storage space) to support diverse society services. However, we have encountered an imbalance between constrained resources and three expectations due to the limited resources. Hence, during the IoE realization process, the effective solution is to maximize resource utilization efficiency subjected to limited resource supply, thereby satisfying all these expectations in an on-demand manner. The on-demand manner is the fundamental design principle for the IoE enabling technologies, which will be introduced next.

B. Enabling technologies for three expectations of IoE

1) *Enabling scalability*: Scalability for IoE means to build a global network that enables wide coverage, ubiquitous connection, and massive access. Since the network with global and ubiquitous coverage is not present, the IoE's scalability can only rely on the cooperation of various existing networks that can support different kinds of distance communications and fit for a variety of network topologies. These networks that are complementary can coordinate with each other to construct the scalable IoE. In accordance with the previous literature [3], [17], we present an overview of enabling technologies to achieve IoE's scalability. The enabling technologies can be essentially categorized into three types: 1) the technologies enabling the *backbone communication* of IoE (i.e., global networks), 2) the technologies enabling the *limb communication of IoE* (i.e., local networks), and 3) the technologies enabling the *capillary communication* of IoE (i.e., point-to-point connections), as shown in Fig. 2.

The backbone communication of IoE is essentially to offer an overall connection of conducting data collection, transmission, processing and interaction. Hence, to offer a global coverage, the backbone communication of IoE requires the long-distance wireless communication technologies, which can support the communication distance over ten kilo-meters. The suitable candidates include incumbent mobile communication networks (MCN) and low power wide area networks (LPWANs). Particularly, MCN covers most densely crowd areas including business regions, and urban residential regions. Therefore, IoE nodes can access the backbone network via the diverse MCN communication technologies from 2G (GPRS), 3G, 4G (LTE), 5G, and even 5G-Beyond [18]. On the other hand, LPWAN has also attracted significant attentions recent years since it cannot only provide a wide coverage but also a low-power solution for IoE [19]. In this sense, MCNs fit for the IoE nodes with sufficient energy supply (e.g., the nodes in smart meters, smart grids) while LPWANs are suitable for

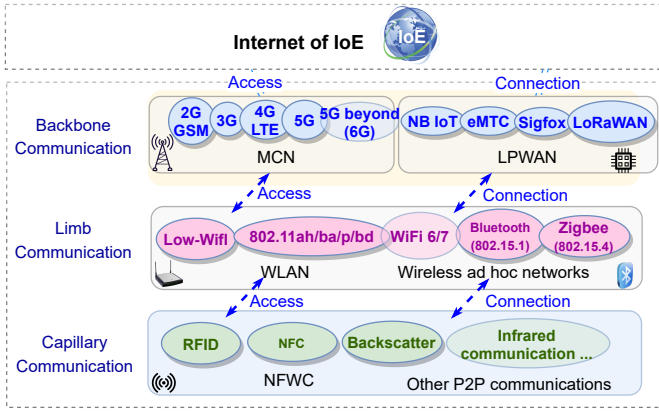


Fig. 2. Enabling communication technologies of IoE's Scalability

massive IoE nodes with power-constraints (e.g., the nodes in forest monitoring, smart agriculture). Therefore, the two technologies may complement with each other to establish the backbone communication of IoE.

Being complementary to the backbone communication, the limb communication of IoE consists of flexible local networks with a communication ranging from a few meters to hundreds of meters. The typical enabling technologies include wireless local area networks (WLAN), low power Bluetooth (BLE), Zigbee, Z-wave, and 802.11ah. In most cases, these limb communication technologies are used to construct Ad Hoc/mesh networks such as wireless sensor networks (WSNs), wireless body area networks (WBANs), wireless personal area networks (WPANs). The aim of Ad Hoc/mesh networks is that all nodes can be connected together to achieve smart controls. Moreover, these networks are suitable for multi-hop communications since they can be easily used in home automation scenarios, industrial process control, body activity monitoring, indoor localization.

The capillary communication offers massive low-cost and point-to-point connections in IoE. The enabling technologies of capillary communications are mainly based on a series of short-range peer-to-peer (P2P) communications, the most of which are near-field wireless communication (NFWC) technologies based on the inductive-coupling principle. Generally, NFWC is a set of communication protocols including back-scattering communication, radio-frequency identification (RFID), and near-field communication (NFC). Practically, the data transferred in NFWC can take place from small tags to readers within a range of a few centimeters, where the tags are attached to circulated products while the reader is generally deployed at a fixed position to transmit the received data to the back-end server (to store the collected data). Hence, it can perform flexible and low-cost peer-to-peer communications. In fact, it has been widely used in myriad applications such as mobile identification systems and logistic monitoring systems [20].

In the above enabling technologies, since the traditional networks of WCN and WLAN have been built to offer human-orientated information services, they are globally allocated with sufficient network resources for reliable information

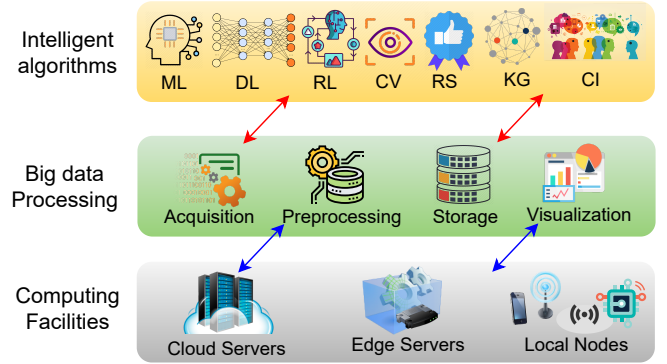


Fig. 3. Enabling technologies of IoE's Intelligence

transmissions. In contrast, other enabling technologies are developed with the goals of low communication power and low hardware cost, to address the imbalance of limited network resources and massive communications between terminal nodes. This phenomenon symbolizes the on-demand principle of IoE. For example, the enabling technology of IoE's limb communication - LPWAN keeps the low power and wide coverage design principle and refers to diverse communication protocols such as LoRaWAN, ZigBee, and NB-IoT [19]. Recently, a series of WLAN protocols have been released to support the specific IoE applications, such as 802.11ah, and 802.11p. Additionally, low hardware cost is also a major concern for communication equipment suppliers. An example is low-cost communication chips and modules with simplified protocols stack and limited storage/battery capacity such as NB-IoT and eMTC [21].

2) *Enabling intelligence*: The intelligence of IoE can be enabled by distributed computing facilities, on top of which distributed big data processing and intelligent algorithms can be executed, as shown in Fig. 3. Distributed computing facilities include cloud servers, edge servers, and local IoT nodes, all of which are interconnected through the backbone, limb and capillary communications. Cloud servers with abundant storage and computing resources can undertake computing-intensive or storage-intensive big data processing tasks as well as intelligent algorithms (e.g., deep learning algorithms) in a centralized manner, thereby enabling the global intelligence of IoE [22]. Edge servers possessing fewer computing resources than cloud servers are deployed at base stations, IoT gateways or access points, in approximation to users. Some less computing-intensive tasks such as data preprocessing, compression and encryption can be conducted at edge servers [23]. Local nodes generally referring to the IoE nodes only have limited storage and computing resources, in which data collections or lightweight data preprocessing tasks can be conducted. Although local nodes and edge servers have less computing capabilities than cloud servers, they can process some context-aware and privacy-sensitive tasks locally. It is a necessity to orchestrate various computing resources and schedule different computing tasks at local side, edge side, and cloud side in order to enable a ubiquitous computing capability across the entire IoE, thereby realizing the global intelligence

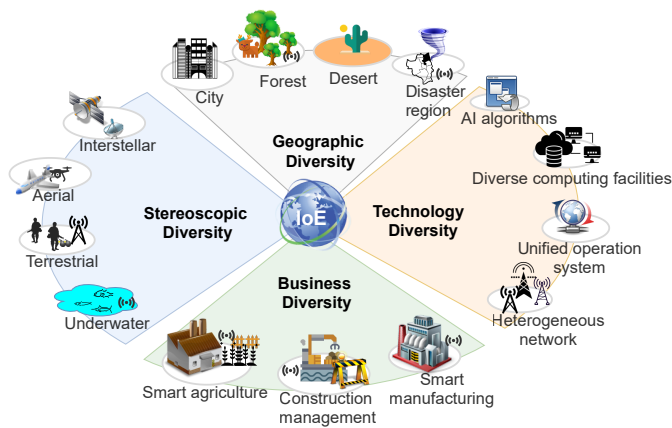


Fig. 4. Enabling applications of IoE's diversity

of IoE.

On top of distributed computing facilities, big data processing schemes and intelligent algorithms can be executed to enable *everything* intelligence. In particular, big data analytics on IoE data can process massive IoE data and conduct descriptive, diagnostic and predictive analysis [6], [24]. Intelligent algorithms can further extract valuable information on big data so as to make predictive and prescriptive decisions [25], [26]. Depending on different computing or storage capabilities of cloud servers, edge servers and local nodes, different big data processing and intelligent algorithms can be executed. Strong computing facilities at the cloud side can support the intensive big data processing tasks and intelligent algorithms, e.g., training deep learning models at GPU clusters, so as to enable *cloud intelligence* of IoE. In contrast, edge servers can only support less computing-intensive tasks or intelligent algorithms with less computational complexity (e.g., lightweight or portable deep learning models) [27], thereby enabling edge intelligence. Similarly, local nodes that can only collect and preprocess IoE data are bestowed on local intelligence.

Regarding intelligent algorithms, there are a wide spectrum of artificial intelligence (AI) algorithms including machine learning (ML), deep learning (DL), reinforcement learning (RL), computer vision (CV), recommendation system (RS), knowledge graph (KG) and collective intelligence (CI). These intelligent algorithms outperform traditional statistical methods in diverse tasks like regression, classification, clustering and decision-making. However, different intelligent algorithms have different computing/storage requirements on underlying computing facilities. For example, deep learning models (multi-layer convolutional neural networks) may require extensive training at cutting-edge computing facilities such as GPU servers, which may not be feasible at edge servers and local nodes. Therefore, lightweight or portable intelligent algorithms which can be executed at edge servers or local nodes are expected to be further explored in the future.

Recent papers reviewed the usage of big data analytics and intelligent algorithms in IoT scenarios. For example, the authors in [25] reviewed big data in IoT field from a historical perspective, covering ubiquitous and pervasive computing, ambient intelligence, and wireless sensor networks. Additionally,

the authors in [24] reviewed the state-of-the-art studies toward big IoT data analytics. Big IoT data analytics, methods, and technologies for big data mining are discussed. All these papers provide a guideline to better use the merits of big data and intelligent algorithms for IoE's intelligence.

3) *Enabling diversity*: Future IoE devices can be used in diverse fields, including digital sensors for data acquisition and mobile intelligent devices for automated services. As discussed in Section I, we have listed four diversity categories of IoE: geographical diversity, stereoscopic diversity, business diversity, and technology diversity, as shown in Fig. 4. Specifically, we summarize related applications in every diversity as follows.

Geographical diversity indicates that IoE applications can be applied in different kinds of geographical regions, including urban, suburban, rural, forests, oceans, and deserts [28], [29]. On the other hand, stereoscopic diversity aims at extending the IoE's application range to diverse stereoscopic levels that include the terrestrial, the aerial, underwater and even space [29], [30]. In addition, business diversity is to focus on IoE-enabled intelligent business sectors, such as intelligent agriculture, smart manufacturing, smart grid and smart city [5], [6], [31]. Moreover, technology diversity relies on a variety of enabling technologies in IoE. These diverse technologies include different technical aspects such as embedded devices, sensing technologies, communication networks, computing technologies, data processing algorithms, and AI algorithms.

It is an inevitable trend that future IoE applications become the fusion of different diversities. This fusion has already been discussed in previous literature. For example, the authors in [17] explored the integration of heterogeneous networks of IoT. The authors in [32] investigated the global virtual computing system combining cloud, edge, fog, and local. The authors in [33] have concentrated on the design of the unified operating system for IoT. Practically, the aforementioned four IoE diversities can benefit from each other. The most obvious fact is that the application in different diversities can coexist with each other for a common suitable reason. For example, urban services are more suitable for terrestrial and business applications. However, forests and deserts scenarios require more aerial and even interstellar networks for flexible and on-demand IoE services. Therefore, different diversities can always fulfill the corresponding application demands with each other. As a result, one open issue in future IoE is to coordinate different applications in the same diversity category or to orchestrate the same application across different diversity categories.

C. Challenges of IoE

Although the aforementioned enabling technologies can potentially realize IoE's scalability, intelligence, and diversity, a number of challenges are rising when implementing those enabling technologies. Attributed to the restricted resources (e.g., network infrastructure, spectrum access, hardware cost), the challenges of IoE are reflected in the following four constraints: coverage constraint, battery (energy) constraint, computing constraint, and security constraint, as shown in Fig. 5. Next, we will discuss the four constraints in detail.

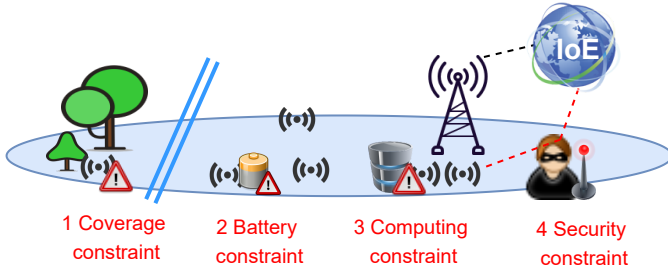


Fig. 5. Challenges of IoE

- 1) *Coverage constraint*: As some harsh and remote geographical areas lack efficient IoE communication infrastructures, the nodes in these areas are hard to be covered. For simplicity, we name these areas as coverage-constrained areas. Deploying the current IoE networks in the coverage-constrained areas is not budget-friendly due to the imbalance between cost and benefit in network construction. A key observation is that the IoE projects in cover-constrained areas do not have such strong communication demands in *everytime* and *everywhere*. Therefore, a flexible and recoverable coverage is the most cost-effective solution to support on-demand IoE communications in the coverage-constrained areas for a particular period.
- 2) *Battery constraint*: There are lots of IoE nodes suffering from the battery constraint. Generally, they are power-limited to save the global hardware cost from the deployment of countless IoE nodes. In this case, IoE tends to use low power or even battery-free communication technologies to support access networks. One inevitable fact is that battery-limited nodes are easily exhausted and eventually lose connections with IoE. The connection-lost problem becomes severe for future ubiquitous nodes distributed in the coverage-constrained areas. Hence, it is necessary to develop sustainable energy supplying and the recovery mechanism for battery-constrained nodes.
- 3) *Computing constraint*: Most of terminal nodes of IoE do not have enough computing capability to process local intelligent algorithms, we call these nodes as computing-constrained nodes. The traditional computing solution for IoE is to transmit all data to the cloud plane where it can offer a centralized intelligence for big data processing. However, the cloud computing brings a huge latency for the latency-sensitive IoE applications. Meanwhile, the increasing number of IoE applications will not only cause the burden to the cloud computing plane but also lead to the unimaginable congestion in IoE. To alleviate the cloud's burden, it is strongly required to utilize edge and local computing plane as supplementary of enabling everything intelligence.
- 4) *Security constraint*: Many potential security constraints are encountered in IoE, attributed to the vulnerability of access protocols. The current IoE mostly adopt the low-cost and simplified access protocols (i.e., NB-IoT, LowPAN) for reducing network cost, but it makes the edge communication vulnerable to be eavesdropped and forged. Hence,

the data emitted from end nodes are hard to keep secrecy, and pseudo-base-stations can easily forge the normal IoE communication links. For these reasons, an effective but easy-deployed security mechanism is required to protect IoE edge communication from intrusion detection.

Discussion: To overcome these constraints, we need to take some efficient measures: i) building a flexible and recoverable network to extend IoE's coverage; ii) developing a sustainable energy-supply mechanism to prolong the life-cycle of IoE's nodes; iii) orchestrating the edge computing with local and cloud computing to optimize the scheduling of multiple computing tasks; iv) designing a reliable security solution to protect the data in these ubiquitous IoE nodes from illegal uses. Particularly, UAVs have enormous potential to provide an attractive solution to address four challenges of IoE, attributed to its flexibility and on-demand deployment. Combining with existing communication networks, wireless power transfer, and edge computing, UAVs can build an extended edge network of IoE with sustainable power, edge intelligence, and physical security protection.

III. OVERVIEW OF UAV

In recent decades, UAVs have attracted a significant attention of scientists and businessmen due to their boundless services. Such a wide variety of UAV applications relies on controllable maneuverability technologies such as flight trajectory optimization, obstacles avoiding. UAV's maneuverability can realized by on-board intelligent algorithms and remote control from ground-based monitoring stations. This section will demonstrate UAVs' controllable maneuverability by introducing the unmanned aircraft system (UAS) and UAV communication networks.

A. Unmanned aircraft system (UAS)

UAS provides the cooperated control services for UAV applications. The control services includes flight control, information processing, tasks scheduling, etc. A typical UAS is composed of three parts: the UAV, the ground-based controller/control station, and the communication link between them [34]–[36]. UAS is quite important to control UAVs' flight and their task scheduling. For large UAVs, the take-off and the landing are controlled by ground control stations for stability. After a large UAV reaches the cruising altitude, the automatic driving mode is switched on, and the corresponding flying task begins. When a large UAVs perform autonomous flight control and on-board task scheduling, the function of the ground controller may be integrated on-board, thus the autonomous UAV itself becomes a UAS. In contrast, the small UAV mainly relies on its small-and-nimble superiority to conduct flying tasks with strong maneuverability. The small size makes it impossible to carry too many mission equipment or too large on-board autonomous system. As a result, small UAVs tend to be dependent on the remote control from ground stations. In this regard, their flight range is limited by the scope of wireless communication with the ground station.

It is necessary to design a dedicated UAS for specific applications such as video monitoring, radar detection, automatic

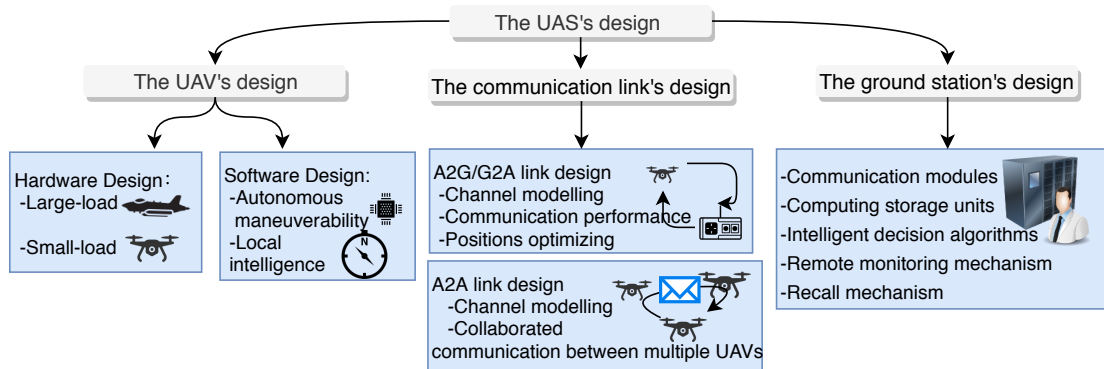


Fig. 6. Design method of the unmanned aircraft system (UAS)

localization and tracking. As shown in Fig. 6, the design of a dedicated UAS includes three aspects, i.e., the UAV's design, the ground control station's design, and the communication link's design. We now discuss these design aspects as follows.

1) *The UAV's design*: UAV - the flexible flying task performer, was early used for military unmanned aircraft that owns a variety of mission equipment [37]–[41]. In order to perform a variety of unmanned military missions (e.g., reconnaissance, tempting enemy and target striking), for a long time, military UAVs are usually adopted the structure with large loads and the fixed-wings. In addition, small UAVs are designed with small loads and short battery life, and they have gradually developed for lots of civilian applications. One example is using small UAVs for aerial photography in a particular region, which is recently getting very popular in aerial enthusiasts. Compared with a large fixed-wing UAV, a small rotary-wing UAV has more flexibility and lower battery consumption. After being special configured, either large UAVs or small UAVs can be applied for various commercial purposes, such as air express, emergency communications, and airbase stations [42], [43]. Next, we will introduce UAVs' design via two aspects: hardware design and software design [44]–[46].

- *Hardware design*: UAVs' hardware design focus on the hardware configuration for suitable flight driven (i.e., flying wings and engine) and mission equipment (i.e., the communication module, computation chip, and other carrying equipment). UAVs' load-size has large impacts on their hardware design in specific flight tasks. For *long-time and long-distance flight tasks* (such as air-to-sea image telemetry or air-to-ground forests fire rescue applications), stability and persistence are main objectives for hardware design of UAVs. In this regard, large-load UAVs are suitable to perform flight tasks with high stability and persistence. Specifically, large-load UAVs can be configured with persistent flight functions (including fixed-winged, long-term battery, and stable engines) and strong mission ability (including on-board cameras, signal processing, carrying capability). For *limited-range and high-maneuverability flight tasks* (such as urban criminal tracking, instant sampling of accident scenes), mobility and efficiency are two main factors impacting the hardware design. Small-load UAVs are suitable

to perform missions requiring high mobility and efficiency. To achieve that, they will be configured with flexible flight structures (e.g., rotor-wing, limit battery capacity) and light mission equipment (containing communication module and on-board cameras).

- *Software design*: UAV's software design aims to develop dedicated on-board algorithms for autonomous flight decision-making. By collecting the surrounding data and inputting the data into the dedicated algorithms, UAVs can make flight decisions of autonomous maneuverability and local intelligence. Autonomous maneuverability requires dedicated designs for stable flight in complex geological/meteorological environments. Basic algorithms are obstacle detection, collision avoidance, gesture adjusting, and trajectory planning. Local intelligence is designed as offline mission algorithms for aerial delivery, emergency communication, geological surveys. For instance, UAVs can be configured with the dedicated communication protocols and trajectory to perform aerial delivery [43], or to conduct the remote data collection [42].

2) *The communication link's design*: There are two kinds of wireless communication links in UAS. One link is the Air-to-Ground (A2G)/Ground-to-Air (G2A) link that connects the UAV with the ground node. Another link is the Air-to-Air (A2A) link that connects multiple UAVs together. A2A links usually appear in collaborative multi-UAV flight tasks. Both two kinds of links require the specified design to work in particular communication scenarios. The design principles include communication connectivity, the fly trajectory of UAVs, and the successful probability of flying tasks. Corresponding studies investigating two kinds of links are summarized as follows.

- The studies investigating A2G/G2A aim at improving the communication performance by optimizing flying positions of UAVs. Generally, the A2G link considers optimizing the communication of feedback information from UAVs to ground stations. The G2A link considers the communication of controlling signals from ground stations to UAVs. To optimize the A2G/G2A communications, flying positions of UAVs are in dedicated selection for satisfying the good link quality. This investigation process is usually accomplished

by firstly building a reasonable channel gain model of A2G/G2A, then setting the condition of communication performance (related to channel gain), and finally optimizing flying positions of UAVs subjected to the condition. The above investigation steps are contained in the related work on UAV-aided communication networks. The corresponding studies are summarized as shown in Section III-B.

- Different from the investigation of A2G/G2A, the studies investigating A2A aim at accomplishing the collaborative flying tasks by multiple UAVs. The A2A link provides communications between multiple UAVs. In this regard, the design objective of A2A is ensuring collaborative communication performance in a multi-UAV network. Additionally, A2A can be easily modeled as line-of-sight propagation, and the link quality of A2A is susceptible with the mobility of multiple UAVs. Hence the investigation direction is transformed from improving the A2A link quality to the collaborated position scheduling of multiple UAVs. Due to UAVs' mobility from time to time, the collaborated positions are variable, which further leads to the investigation of routing protocols. The particular design in A2A links is contained in the related work on multi-UAV Ad Hoc networks. The corresponding studies are summarized as shown in Section III-B.

3) *The ground control station's design:* The ground control station is the decision center of the whole UAS, with its responsibility for UAV's tasks scheduling and remote communications. To accomplish the responsibility, a ground control station is designed with the following functions: wireless communication modules collaborated with UAVs, computing storage units with large enough capacity, intelligent decision algorithms for centralized mission processing, remote monitoring mechanism, and recall mechanism. The communication modules are for achieving remote control to UAVs, hence its design should match with the communication modules of UAVs. The computing storage units are designed for satisfying the required data processing. Intelligent decision algorithms are mainly for making UAV tasks' scheduling scheme, with its objective of arranging all UAVs' flight tasks along with their performing period, overall trajectory, and available resource [47]. The remote monitoring mechanism is used for globally monitoring UAVs' flying states, which can be achieved by periodical receiving the information feedback from UAVs. The recall mechanism is designed for a controllable recall for abnormal cases (e.g., the cases when flying tasks require interruption, or the cases that UAVs are detected as energy shortage).

B. UAV communication networks

Compared to UAS that offers a control system for a specified UAV mission, UAV communication networks mainly offer stable communications between UAVs or between the UAV and the ground station. The state-of-the-art literature provides two classes of UAV communication networks: multi-UAV Ad Hoc networks and UAV-aided communication networks. Tab. I gives a brief summary of these two UAV communication networks. More details are introduced as follows.

1) *Multi-UAV Ad Hoc networks:* Multi-UAV Ad Hoc networks are self-organized topology with high autonomy, and usually independent with current networks. Multi-UAV Ad Hoc networks can support mobile connections and coverage in some specified occasions such as emergency communication networks, aerial surveillance fleet, aerial sensor networks. For instance, the authors in [48] presents such a typical instance, in which a multiple-UAV network assists the vehicular-to-vehicular (V2V) communications in the regions with poor connectivity to infrastructure-based networks. Besides, multi-UAV networks can perform the data acquisition tasks in large-scale sensor deployed areas [49], [50], [54].

The study on multi-UAV networks places emphasis on performance improving of A2A links between multiple UAVs. Particularly, the A2A performance includes wireless connectivity and information collaboration. With the mobility of multiple UAVs, the channel quality of A2A links is variable and then leads the dynamic connectivity and network topology. Consequently, the related work includes two directions: multi-UAV's trajectory optimization and dynamic routing protocol. The two study directions have gained significant attention for multi-UAV networks, as shown in several surveys [8], [37], [59]. For instance, [37] gives a comprehensive summary of routing protocols design principles of multi-UAV communication networks, including self-organization, disruption tolerance, SDN control, seamless handover, and energy efficiency. Besides, [59] compares the performance of existing routing protocols that are classified into two categories: single-hop routing and multi-hop routing, where the comparison metrics contains load balancing, loop-free ability, route update method, dynamic robustness, energy efficiency, and so on.

In addition, previous studies investigated the trajectory optimization of multi-UAV networks when selecting a specified routing scheme, i.e., single-hop or multiple-hop scheme. For instance, the authors in [63], [64] investigated the trajectory optimization joint with power control. Ref. [63], [64] considered a single-hop routing scheme in which every ground node accesses to only one UAV and multiple UAVs cooperatively serve communications to a groups of ground nodes. Additionally, the authors in [60], [61], [74] investigated the trajectory optimization for the case of a multi-hop routing scheme in which multiple UAVs provided collaborative communications to a range of ground nodes, with the objective of end-to-end throughput maximization.

2) *UAV-aided communication networks:* The UAV-aided communication network is the extended edge network of existing networks. Different from independent self-organized architecture of multi-UAV ad hoc networks, UAV-aided communication networks are infrastructure-based topology, with dependent on the existing network access points. Therefore, UAV-aided communication networks adopt the wireless access protocols of the aided networks (e.g., MCNs, and WLANs).

In a UAV-aided communication network, UAVs can be deployed as edge nodes with network functions such as flying base-stations (e.g., [51], [52]) or relay nodes [53], [55], and as just terminal nodes such as the aerial surveillance camera [56], [57]. Whether UAVs utilized as base stations or relay nodes, the objective is to provide flexible communication services

TABLE I
UAV COMMUNICATION NETWORKS

Introduction	Multi-UAV Ad Hoc networks	UAV-aided communication networks
<i>Architecture</i>	Self-organized networks	Edge side of current networks
<i>Characteristics</i>	Flexible topology	Flexible access
<i>Applications</i>	Collaborative communications [48]–[50] Emergency communications [54]	Relay communications [51]–[53] Flying base stations [55]–[57]
<i>Wireless links</i>	A2A links	A2G/G2A links
<i>Research issues</i>	Routing design [8], [37], [58]–[60]	Trajectory optimization [61], [61]
<i>Research methods</i>	Global throughput maximization [62]–[64] Maximizing energy efficiency [67] Dynamic topology/swarm [70], [71] Multi-UAV’s resource allocation [74]–[76] Dense UAV networks [78]	G2A/A2G throughput maximization [53], [65], [66] Maximizing energy efficiency [68], [69] A2G/G2A localization [72], [73] Edge computing [77] Ground node access [79], [80]

in disconnected areas near to current networks. Therefore, UAVs requires to keep the communication links with the aided network and as well as with the disconnected nodes. Under different scenarios, the disconnected nodes are in different distribution and the edge access protocols are very different. All these factors pose the various studies on optimizing the flying trajectory of UAVs. Taking an example into account, for UAV-enabled patrolling, the flying trajectory of UAVs required to satisfy the mobile connectivity, i.e., the mobile A2G/G2A link at UAV-aided communication networks. For this example, the objective of UAVs’ trajectory optimization is ensuring the coverage to the task region and meanwhile keeping the connection with the edge network.

For UAV-aided communication networks, the study directions are mostly related to trajectory optimization of UAVs. In previous studies, trajectory optimization was done by optimizing various performance metrics including QoS of communication links, sufficient coverage [61], time-efficiency, energy efficiency [68], outage probability, etc. For instance, the authors in [81] presented UAVs’ trajectory optimization through an iterative algorithm that reduces the disconnected nodes for covering multiple isolated WSN nodes. Similarly, [51] proposed an optimal placement algorithm for UAV-base stations by maximizing the number of covered users. In addition, [55] designed the trajectory of a single relay UAV by maximizing energy-efficiency. Moreover, [53] optimized UAVs’ trajectory by minimizing the outage probability, where UAVs worked as an amplify-and-forward relay.

Summary: The academic study on UAVs highlighted two critical directions: one is to investigate the UAS for controllable maneuverability of UAVs, and the other is to study the UAV communication networks for ensuring link connectivity (including the connectivity of A2A links and A2G/G2A links). The two study directions share a common research point - UAV’s mobility design (i.e., trajectory optimization). Based a lot of studies investigating the mobility of UAVs [63], [68], [74], [82], we find the opportunities of UAVs enabling IoE.

In next section, we will discuss the convergence of UAVs and IoE.

IV. CONVERGENCE OF UAV AND IOE

As discussed in Section III, UAVs can be employed as various IoE edge nodes, such as aerial base stations, data collectors, jammers, monitors, edge computing nodes, power suppliers, reclaimers. Accordingly, UAVs can provide an enhanced IoE solution for extended coverage, flexible intelligence, and more diverse applications. In this section, we first investigate the opportunities for applying UAVs in IoE. The presented opportunities confirm the capabilities of UAVs to address the four constraints of IoE. Further, we propose a Ue-IoE solution to integrate UAV technologies in IoE. In Ue-IoE, UAV-enabled scalability, intelligence, and diversity are introduced, respectively.

A. Opportunities of UAVs in IoE

With high mobility and reconfigurability, UAVs can potentially address the four constraints of IoE. This potential brings four opportunities to IoE, i.e., ubiquitous connections, aerial intelligence, self-maintenance of communications, sensor powering and deployment, as shown in Fig. 7.

1) *Ubiquitous connections:* Ubiquitous connections are the necessary requirement of IoE to cover *everywhere* and connect *everything*. Flexible UAV communication networks can help IoE to extend its coverage and thereby achieve ubiquitous connection. As in section IV-B1, UAVs can extend the edge access network to the areas with weak-connection via UAV-aided communications networks; UAVs can increase coverage to the areas without network deployment through multi-UAV Ad Hoc networks. Accordingly, ubiquitous connections can be achieved.

2) *Aerial intelligence:* UAVs can enable aerial intelligence by collecting the surround data and then performing on-board intelligent algorithms. The surround data are collected from the UAV itself and from a cluster of outside sensors.

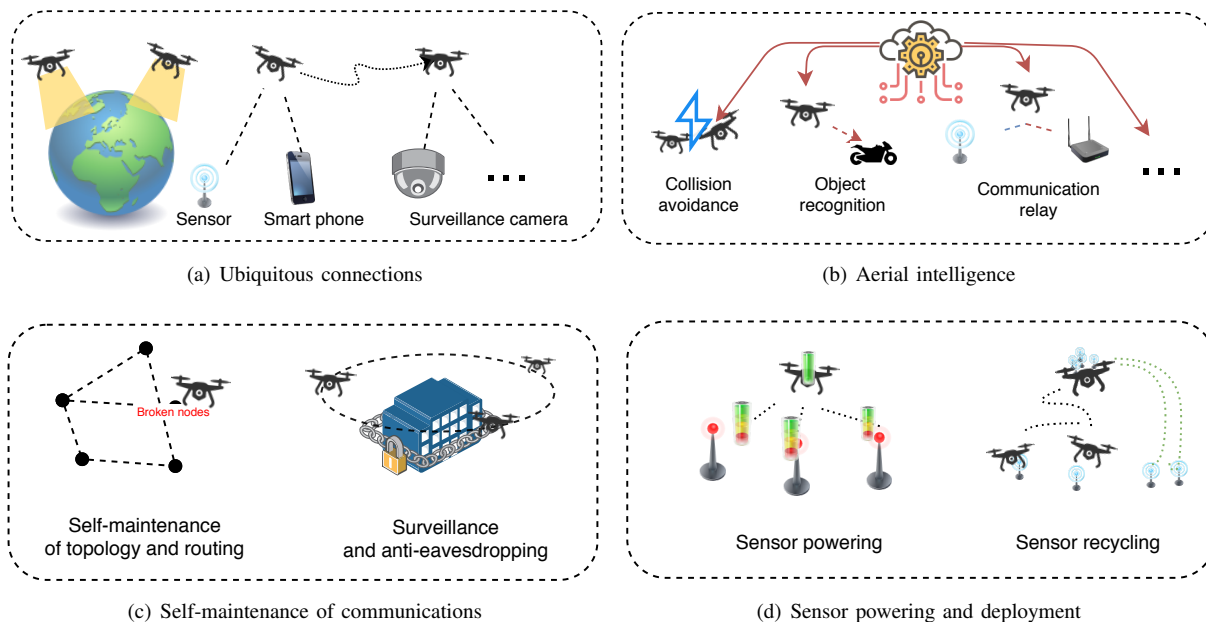


Fig. 7. Opportunities of UAV in IoE

The intelligent algorithms are dedicated designed for different requirements, such as autonomous collision avoidance, adaptive flight gesture adjustment, trajectory optimization for data collection. Thus, UAVs can conduct many aerial intelligent applications. A typical application is the tracking of a moving target by UAVs [83]. Besides, UAVs can play as an aerial command-maker to produce intelligent perception and decision for computing-constrained IoE nodes.

3) *Self-maintenance of communications*: UAVs can support self-maintenance to the IoE's communication. Attributed to various unstable factors from the human or natural environment, some IoE nodes are easily destroyed and even lost. Thus, IoE faces the risk of unpredictable connection lost. To address this risk, UAVs can be dispatched to throw terminal nodes. In addition, some IoE communications with high privacy and confidentiality face security risks of eavesdropping and forging. These risks may cause huge economic losses when they occur in high-confidential communications such as the malfunction sensing of smart manufacturing, the commander transmission in intelligent transport system. In this regard, UAVs can be employed as jammers and form a protective barrier for IoE's physical communication of IoE. The authors in [84] present a UAV-based friendly jamming scheme to interfere with eavesdropper's communications. Besides, the authors in [85], [86] offer enhanced encryption security by configuring the dedicated protocols in UAVs.

4) *Sensor powering and recycling*: UAVs can be re-configured to perform sensor powering and recycling tasks, thus can improve sustainability of IoE. There are some resource-constrained IoE nodes in weak-connection/no-connection areas. These nodes are usually easily running out of their battery and then getting discarded. This phenomenon not only results in a big waste but also causes high pollution. UAVs can potentially avoid this waste or pollution by supplying and updating constrained resource of sensors/the IoE nodes. In particular, UAVs can supply energy to these

nodes by wireless power transfer (WPT) [82] and even can achieve simultaneous wireless information and power transfer (SWIPT) [87]. Besides, UAVs can recycle the damaged nodes or sensors with disabled function and release new nodes as the replacement.

B. A solution: Ue-IoE

Motivated the opportunities brought by UAVs to IoE, we can comprehensively apply UAVs to enhance IoE's capabilities. We develop a UAV-enabled IoE solution (we call it Ue-IoE for simplicity in the rest of this paper) that can enhance three expected abilities of IoE, i.e., scalability, intelligence, and diversity. In particular, we will introduce Ue-IoE based on the three sub-solutions, i.e., UAV-enabled scalability to IoE, UAV-enabled intelligence to IoE, and UAV-enabled diversity to IoE.

1) *UAV-enabled scalability to IoE*: Cooperating with existing networks (i.e., WLAN, MCN, LPWAN, satellite network), UAVs can enable a scalable IoE for covering *everywhere*. UAVs can maximize the coverage of IoE by extending the current IoE network to two main kinds of areas: areas within weak-connection, areas without network deployment.

- (i) *Areas within weak-connection*. These areas are usually covered by the existing networks such as WLAN, MCN, and LPWAN; but these areas are always in the weak-connection state due to the complex geographical environment and serious communication requirements. Four typical regions are *Construction sites in urban*, *Disaster regions in urban*, *Blind coverage spot in city* and the *Transportation road*. These regions are scattered with various obstructions, resulting in the unstable wireless links between above areas with the existing APs. To address this problem, UAV-aided communication networks are required to provide a flexible edge access network. Obviously, UAVs can play as the on-demand relay nodes or base stations or gateways to connect the IoE nodes.

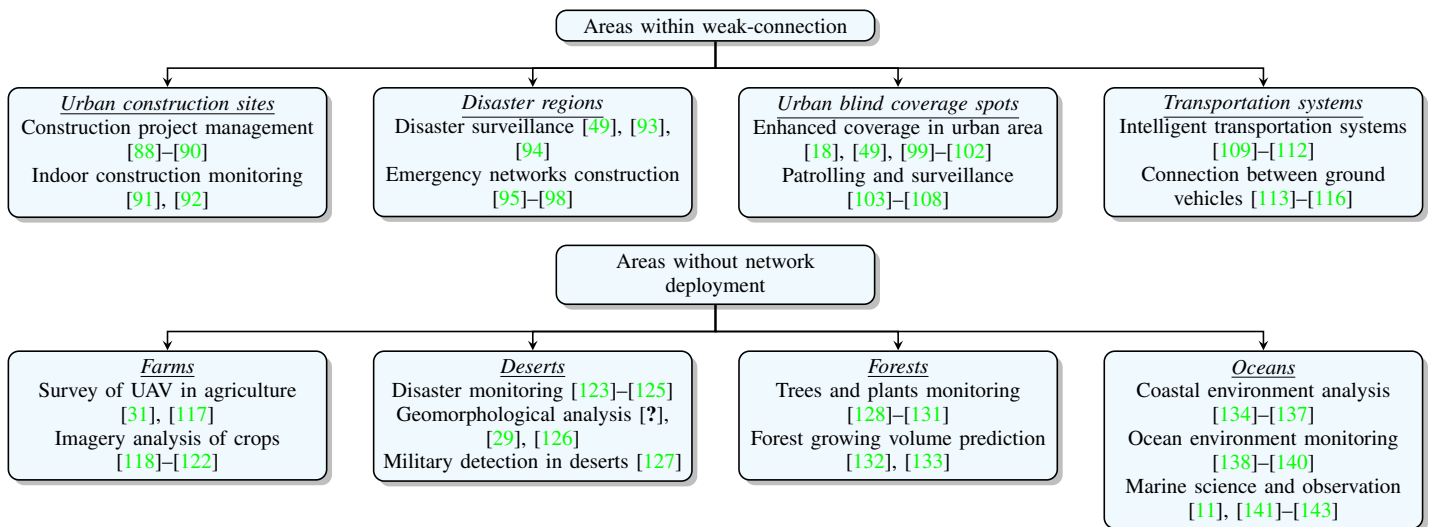


Fig. 8. UAV-enabled scalability to IoE

- (ii) *Areas without network deployment.* These areas are generally remote and lack of inhabitants; hence no network infrastructures are deployed in such areas. Four typical regions are *farms*, *deserts*, *forests*, and *oceans*. To cover these regions, two communication schemes are required: 1) building an independent network for every specific area; 2) designing the access scheme from this independent network to the existing IoE network. Multi-UAV Ad Hoc networks can be applied to achieve above two goals. The multi-UAV network can not only independently cover the remote areas but also execute many specific tasks (including relay communications, remote sensing, data acquisition, etc [144]). From a global perspective, multi-UAV Ad Hoc networks are required to enable the specified coverage when UAVs fly to remote areas. In addition, UAV-aided communication networks are required for IoE's access when UAVs fly back to the ground control center.

Fig. 8 shows a tree diagram about the corresponding studies that use UAVs to cover the two above discussed areas. For the areas within weak-connection, we list four typical regions that are construction sites in urban, disaster regions in urban, blind coverage spots in the city, and the transportation road. In these areas, some recent studies use UAVs to offer an extended network coverage and perform some specified applications such as construction project management, emergency networks, patrolling, and intelligent transportation. Moreover, for the areas without network deployment, UAVs are strongly in demand for achieving a series of unmanned and remote applications in four typical regions (i.e., farms, deserts, forest, and ocean). Some particular applications in these four regions are smart farms, disaster monitoring in deserts, plants monitoring in forests, etc.

2) *UAV-enabled intelligence to IoE:* UAVs can enable IoE's intelligence by embedding some lightweight AI algorithms. In particular, UAVs can make smart decisions or control commands and further enable intelligence to themselves or to the ground IoE nodes. Next, we introduce the UAV-enabled

intelligence of IoE via two respects: UAV-enabled intelligent network and UAV-enabled intelligent aerial service.

- (i) *UAV-enabled intelligent network:* UAVs can enable intelligent network functions to improve network performance. In terms of the bottom-up sight, we introduce three layers of intelligent network functions: the intelligent communication layer, the intelligent network layer, and the intelligent application layer.

The intelligent communication layer lies in the stable wireless connectivity between UAVs and their surround nodes. An intelligent communication requires a good channel state; this can be achieved by deploying UAVs in optimal aerial positions. The related optimization schemes are summarized in section III-B. These studies design the optimal trajectory and the topology for self-organized networks or relay-based edge networks. The intelligent network layer is the smart selection of packet routing for improving the efficiency of packet transition. The routing function relies on recognizing the source address and the destination address of every packet. In multi-UAV Ad Hoc networks, both the source address and the destination address are dynamically changed with flying multi-UAVs, thus the smart routing selection is adjusted with dynamic network topology(e.g., [59]). Besides, in UAV-aided communication networks, since there are unstable packet transitions from multiple nodes to one node (i.e., from massive ground nodes to the UAV and from multiple UAVs to the ground access point), the smart routing selection is transformed into smart access to ensure access efficiency. The intelligent application layer can be achieved by the high-level interface to send intelligent commands for the specified applications. The high-level commands further guide UAVs to perform data operations, such as data compression, and data aggregation.

Discussion. Generally, due to the limited hardware resources, UAVs cannot support the network functions that require much global storage and computation. Fortu-

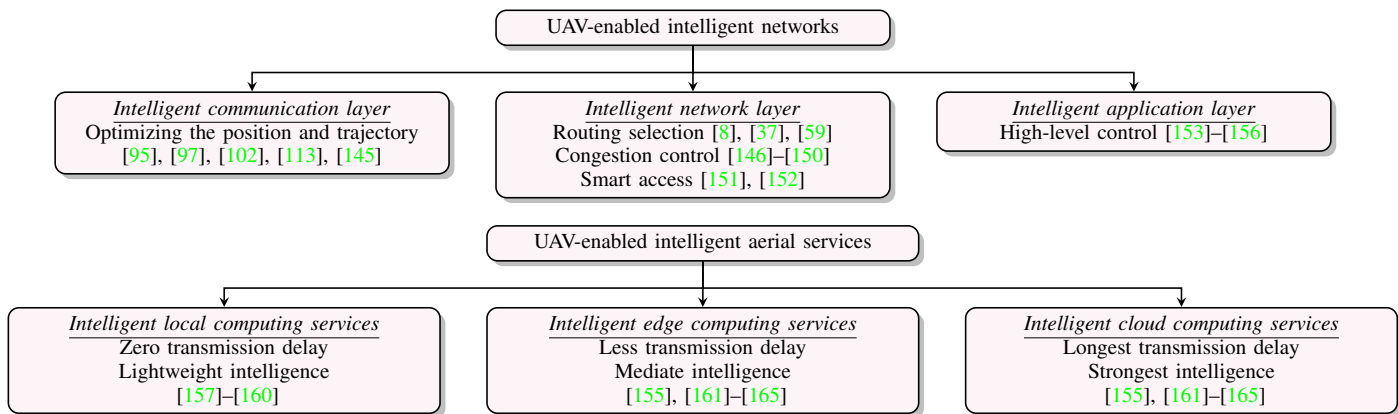


Fig. 9. UAV-enabled intelligence to IoE

nately, the concepts of network functional virtualization (NFV) and mobile edge computing (MEC) give us a solution to enable the above three intelligent network functions at UAVs. The solution is NFV/MEC-driven UAV-enabled intelligent network, in which NFV can virtualize UAV's network functions to programs; MEC can dispersing the virtual function into the specific hardware at every mobile UAV. This solution can enable programmatically efficient network configurations consisting of access, routing, switching, and firewall supports. Practically, this NFV/MEC-driven solution is similar to a mobile software-defined network (SDN). By combining UAVs with SDN, the UAV network functions can be managed by SDN technologies (e.g., [146]).

- (ii) *UAV-enabled intelligent aerial service*: UAVs can provide the intelligent services by performing intelligent algorithms. These intelligent algorithms guide the smart decision making at UAVs. Depending on the specific UAV tasks (e.g., real-time monitoring, flexible tracking, and remote sensing), the decision making is various and the requiring intelligent degree is different. To enable various intelligent services, UAVs connecting with IoE can use local/edge/cloud computing technologies, and enable local intelligent services, edge intelligent services, and cloud intelligent services.

To enable local intelligent services, UAVs require a lightweight AI algorithm that entirely makes smart decisions by UAVs own computing resources. Obviously, the local intelligent services can support quick response without delay but restricted by limited computing resources. In contrast, the edge intelligent services are provided at the near ground access stations of UAVs. The access stations generally have more computing resources than UAVs. Hence, the edge intelligent services face the transmission delay of smart decisions from access stations to UAVs. Furthermore, based on the huge computing resources in cloud side, the cloud intelligent services support the strongest intelligence, but also face the longest transmission delay. To sum up, UAVs can use the local computing for immediate and simple intelligence such as auto-control of flight gesture, obstacles avoiding,

Otherwise, UAVs can use the edge/cloud computing for time-tolerance and complicated intelligence such as a remote photography, the long-distance good-delivery.

The corresponding studies on UAV-enabled intelligence of IoE are summarized as a tree graph in Fig. 9.

3) *UAV-enabled diversity to IoE*: We can utilize UAV technologies (as discussed in Section III) to enable more diverse applications of IoE. For instance, flexible UAV communication networks can be used to serve coverage in different geographic regions as mentioned in Section IV-B1, thus to enable diverse geographical and stereoscopic applications. Additionally, combining with multiple intelligence methods (as mentioned in IV-B2), UAVs are able to develop diverse intelligent algorithms for multiple business scenarios (e.g., intelligent transportation systems, automatic package delivery, and aerial surveillance intelligence). Furthermore, with the prosperous development of IoE, multiple different technologies (including the technologies of both UAV-enabled communications and UAV-enabled intelligence) will cooperate together to provide comprehensive services. We next introduce four typical Ue-IoE applications to show the interaction of different technologies.

- (i) *Intelligent transportation system (ITS)*: ITS as one of the major components of smart city, is expected to automate transportation decisions with security through interconnected vehicles. ITS aims to achieve more efficient decision and lower execution time via automating ITS components including field support team, traffic police, road surveys, and rescue teams. In Ue-IoE, we can employ UAVs as the transportation information collector, the information transmitter, and even the executor for traffic schedule [109]. Consequently, a set of UAVs can act as a field support team with high-efficiency, because they can promptly fly to the incident fields to conduct real-time reports and emergency command. Moreover, UAVs can be aerial traffic officers, when they fly over vehicles on a highway and detecting possible traffic violations. In ITS, internet connection of the real-time transportation information can be offered by UAV communication networks; a fast decision and execution in traffic can be provided by running a dedicated AI

algorithm in UAVs; intelligent information services can be supported by UAVs conveying internet information to road users.

- (ii) *Automatic packet delivery*: We can use Ue-IoE to achieve on-line controls to UAVs for automatic delivery missions. There is always a shortage of living materials in remote-and-underdeveloped areas, and the shortage is especially urgent for the places suffering plague. Due to the disconnected road, an effective method is applying UAVs for automatic package delivery to transport some important materials such as medicines, foods, and clothes [166]–[170]. Besides, dispatching UAVs for ordinary express delivery in urban areas has attracted lots of attention, attributed to flexible deployment and low cost. Detailed studies for delivery UAVs can be found in previous literature. Referring to [43], a long-range and energy-efficient communication system for UAV delivery applications is developed, where LoRaWAN is used for semi-real-time telemetry. Besides, [171] proposes two multi-trip vehicle routing schemes for the cost-efficient drone delivery, in which the effect of battery and payload weight is considered for cost optimization. In addition, further studies for UAV delivery encompass hardware structure design [172] and supplier cooperation [173].
- (iii) *Aerial surveillance intelligence*: Over the last decades, there are growing studies on using UAVs for aerial surveillance system (ASS) [56], [57], [101], in which UAVs embedded with the surveillance camera can employ controllable aerial photograph in a specified area. Different from fixed surveillance cameras that only offer fixed views in a limited region, UAV-enabled aerial surveillance can provide flexible and multi-view detection. Some studies investigate the autonomous capabilities of UAV-enabled surveillance, including regions detection [174], [175], objects positioning [118], and path planning [176]–[178]. In addition, there is a strong demand to design an interface for connecting UAVs with the internet; this connection enables the internet to monitor the UAV states and hence utilize the intelligent algorithm from the internet to analyze the surveillance photographs and videos. Some studies investigate the dedicated AI algorithms for rangeland inventory monitoring [122], emergent trees detections in tropical rainforests [128], soil erosion monitoring [179], forest phenology monitoring [129].
- (iv) *Unmanned military missions*: At the outset, UAVs are frequently used to perform military missions such as remote detection and attack [12]. UAVs can be employed as the aerial detective in chaos battlefield, to detect the movements of enemy's troops and monitor the global battle situation [180]. Besides, UAVs can periodically spy the suspicious region such as border surveillance [127]. The UAV-aided relay communications in military are widely investigated in existing literature (e.g., [181], [182]). Obviously, UAV-enabled military missions (we name it unmanned military missions) save a lot of operating costs in manpower and fixed infrastructures. The unmanned missions must be conducted with re-

liable control to avoid exposure and crash. Especially for some missions in inaccessible areas (mountains, ice roads, deserts, etc.), the reliability of remote control is significant. Due to scalable coverage and intelligent computing resources, Ue-IoE is qualified to support wireless connectivity and enables intelligent anti-detection ability.

Integrating UAVs with IoE, the UAV applications become more diverse due to the wide network coverage, big sharing database, and ubiquitous intelligence; thus, we will achieve very high efficiency in every aspect of our daily life.

V. OPEN RESEARCH ISSUES

There are many technical issues that require dedicated investigations for IoE's realization. To the best of our knowledge, we list five open technical issues: i) restricted resources of UAVs such as battery capacity to support long-distance flying and long-duration communications and computations; ii) no security protocols to limit the illegal actions and communications of UAVs; iii) lack of light-weight AI algorithm for autonomous mobility of UAVs; iv) no general framework of Ue-IoE to make heterogeneous applications compatible; v) lack of enough coordination scheme between UAVs and the cloud. Therefore, in this section, we present some specific study directions to address the four issues by observing some potential methods in previous literature.

A. Resource allocation

Rational resource allocation (allocated resources contain energy supply, data storage, and computation capacity) for every node (including terminal nodes, UAVs, ground access nodes) can enhance the serving efficiency and reduce the cost. The particular study directions of the resource allocation are divided into two categories: the global resource allocation (i.e., the number and the distribution of deployment of every node in Ue-IoE); the local resource allocation (i.e., the dedicated hardware configuration of every node in Ue-IoE). The global resource allocation focuses on the global high-efficiency of costs in time, energy, and the equipment; that decides the distribution of IoE nodes and the trajectory of UAVs. The local resource allocation places emphasis on the dedicated efficiency in every task such as communication, computing, and data storage; that decides the specified resource allocation in power, data rate, duration of communication, data storage, computational complexity, computing time for communication tasks and computing tasks (e.g. [183]). Irrespective of the variation of resource allocation, it always keeps the unique study approach i.e., the on-demand principle to coordinate expected requirement and resource consumption.

B. Security mechanism

UAVs' flexible communications and actions pose security threats such as information eavesdropping and nodes forgery. Specifically, the information transmitted in UAV-based communications may suffer eavesdropping, and the illegal UAVs probably forge the identification to access IoE. In spite of some surveys giving analysis for UAVs' security [184],

[185], the studies on solving the threats in Ue-IoE are not enough. With increasing Ue-IoE applications, it is inevitable to study some security mechanisms that can address the above-mentioned threats. A study direction is to enhance the security level of UAV-based communications (including A2A links and A2G/G2A links). Particularly, the authentication mechanism requires suitable improving to avoid the case that the eavesdropper illegally accesses to UAVs, or eavesdrops the legal communications. Another study direction is the anti-access of pseudo UAVs to IoE nodes and the ground nodes. In this case, the identification recognition mechanism is required to refuse the access requirement from illegal UAVs.

C. Light-weight AI algorithms

To enhance the intelligence of Ue-IoE, the light-weight AI algorithms are required to perform the quick and precise response in UAVs under serious computation constraints. The existing studies using AI algorithms in UAV-based applications are mostly run on the cloud side instead of the local side. For example, some papers present the AI algorithms to detect and count cars by using images and combining with different AI technologies such as a deep convolutional neural network (CNN) [186], and Faster R-CNN [187]. Besides, other similar UAV-based AI algorithms are proposed with various applications such as human detection (i.e., finding pedestrians) [188], weed mapping [189]. Even though these AI algorithms use the imagery recording by UAVs to conduct the mobile object recognition, the computation is either too complex or needing too many databases, not fitting for local processing at UAVs. For local running, there are few studies that investigate low-complex algorithms for UAVs' navigation [190], path-finding [191], and moving-targets' tracking [157]. The future applications on local processing at UAVs need more light-weight AI algorithms to support a really autonomous intelligence with a quick and precise response.

D. Universal standard design

It is necessary to design a universal standard for IoE to orchestrate multiple heterogeneous ICT technologies and as well as diverse IoE applications. The universalized Ue-IoE can not only reduce the usage cost but also increase the serving efficiency. Referring to the network layer model in open system interconnection (OSI), the IoE universal standard should contain the specified rules for every IoE layer (i.e., a physical layer, network layer, and application layer). For three layer, the practical generality designs of IoE should include three aspects: the universal communication chips for end nodes, the universal network control protocols, and the universal computing plane, respectively. Reviewing the related work, the communication chip for end nodes are only designed for particular communication protocols such as NB-IoT, MTC, LoRa-WAN [192]. Besides, the universal network protocols can be achieved by integrating SDN for UAVs, but no global scheme was presented. The universal computing plane can be achieved by integrating local, edge, and cloud computing planes together; this integration is feasible by designing a high-level interface for connecting the computing services between three computing planes.

E. Coordination between UAVs and the cloud side

In the future, the coordination between edge and cloud is an inevitable trend to perform lots of computation-intensive IoE applications. These IoE applications require sufficient centralized AI decisions and distributive big data analytics to work seamlessly for real-time responses, such as smart transportation and intelligent manufacturing. The coordination is usually enabled by scheduling the computation tasks. Regarding to computation-task scheduling, the edge nodes (includes UAVs and APs) first analyze the received computing requirements and then determine whether the task is required to upload to the cloud side [193]. In practice, some data preprocessed at the edge are needed to upload to the cloud for further storage and analytics whereas other data can be computed at edge and do not require to upload. For different data the computing requirements and the coordination mechanism may be specifically designed for the maximized global efficiency; this is dynamically adjustable issues that worthy to be solved as a new study direction.

VI. CONCLUSION

This paper aims at applying UAV to enhance IoE's capabilities with extended coverage, flexible intelligence, and more diverse applications. The envision of IoE in terms of three expectations (scalability, intelligence, and diversity) poses some realization challenges from coverage constraint, battery constraint, computing constraint, and security issues. With high mobility and easy deployment, the studies on UAV can help IoE to overcome these challenges. Therefore, we presented a comprehensive discussion on opportunities and solutions of UAVs in IoE.

In particular, we first analysed the three expectations of IoE (scalability, intelligence, and diversity) and presented an extensive survey of their enabling technologies. Moreover, we highlighted and discussed the critical constraints/issues that hindered IoE's realization such as coverage constraint, battery constraint, computing constraint, and security issues. Further, we made an extensive review of UAV-related work. The review mainly contains two aspects: the UAS design and the study on UAV communication networks. Accordingly, we have explored many opportunities of UAVs in IoE, i.e., the extension to ubiquitous connection, on-demand aerial intelligence, self-maintenance, power supply and sensor recycling, etc. Moreover, we presented a UAV-enabled IoE (Ue-IoE) solution by combining the advantage of UAV's mobility and the current ICT technologies, where it is demonstrated that Ue-IoE can greatly enhance the three expected abilities of IoE (i.e., scalability, intelligence, and diversity). To further enhance the three expected abilities of IoE, three sub-solutions are investigated which are UAV-enabled scalability, intelligence, and diversity to IoE. Each solution and their corresponding studies have been discussed in detail with the potential study direction. Finally, we presented important issues in Ue-IoE as future study directions regarding to resource allocation, security protocols, lightweight AI algorithms, universal standard, and coordination between UAVs and the cloud side. To sum up, we have presented a comprehensive survey on the

opportunities and challenges of UAV in IoE and we assure our readers, that this review will serve as a research guideline for future study on Ue-IoE.

REFERENCES

- [1] I. Khan, F. Belqasmi, R. Glitho, N. Crespi, M. Morrow, and P. Polakos, "Wireless sensor network virtualization: A survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 553–576, 2015.
- [2] A. Froytlog, T. Foss, O. Bakker, G. Jevne, M. Haglund, F. Li, J. Oller, and G. Li, "Ultra Low Power Wake-up Radio for 5G IoT," *IEEE Communications Magazine*, vol. 57, no. 3, pp. 111–117, 2019.
- [3] M. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel, and L. Ladid, "Internet of Things in the 5G Era: Enablers, Architecture, and Business Models," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 510–527, 2016.
- [4] H.-N. Dai, R. C.-W. Wong, H. Wang, Z. Zheng, and A. V. Vasilakos, "Big data analytics for large-scale wireless networks: Challenges and opportunities," *ACM Computing Surveys (CSUR)*, vol. 52, no. 5, p. 99, 2019.
- [5] T.-h. Kim, C. Ramos, and S. Mohammed, "Smart city and iot," 2017.
- [6] H.-N. Dai, H. Wang, G. Xu, J. Wan, and M. Imran, "Big data analytics for manufacturing internet of things: opportunities, challenges and enabling technologies," *Enterprise Information Systems*, pp. 1–25, 2019.
- [7] L. Xu, W. He, and S. Li, "Internet of things in industries: A survey," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2233–2243, 2014.
- [8] M. Arafat and S. Moh, "A survey on cluster-based routing protocols for unmanned aerial vehicle networks," *IEEE Access*, vol. 7, pp. 498–516, 2019.
- [9] Y. Zeng, R. Zhang, and T. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 36–42, 2016.
- [10] X. Wu, X. Wu, L. Qiu, and L. Zhou, "Agricultural unmanned aerial vehicle," Jan. 10 2019, uS Patent App. 16/120,590.
- [11] A. S. Aniceto, M. Biuw, U. Lindström, S. A. Solbø, F. Broms, and J. Carroll, "Monitoring marine mammals using unmanned aerial vehicles: quantifying detection certainty," *Ecosphere*, vol. 9, no. 3, 2018.
- [12] C. Handford, F. Reeves, and P. Parker, "Prospective use of unmanned aerial vehicles for military medical evacuation in future conflicts," *Journal of the Royal Army Medical Corps*, vol. 164, no. 4, pp. jramc-2017-000890, 2018.
- [13] A. J. Jara, L. Ladid, and A. F. Gómez-Skarmeta, "The internet of everything through ipv6: An analysis of challenges, solutions and opportunities," *JoWua*, vol. 4, no. 3, pp. 97–118, 2013.
- [14] A. M. Hussain and M. M. Hussain, "Cmos-technology-enabled flexible and stretchable electronics for internet of everything applications," *Advanced Materials*, vol. 28, no. 22, pp. 4219–4249, 2016.
- [15] S. Abdelwahab, B. Hamdaoui, M. Guizani, and A. Rayes, "Enabling smart cloud services through remote sensing: An internet of everything enabler," *IEEE Internet of Things Journal*, vol. 1, no. 3, pp. 276–288, 2014.
- [16] Y. Miao, X. Liu, K. R. Choo, R. H. Deng, H. Wu, and H. Li, "Fair and dynamic data sharing framework in cloud-assisted internet of everything," *IEEE Internet of Things Journal*, vol. 6, no. 4, pp. 7201–7212, Aug 2019.
- [17] T. Qiu, N. Chen, K. Li, M. Atiquzzaman, and W. Zhao, "How can heterogeneous internet of things build our future: A survey," *IEEE Communications Surveys and Tutorials*, vol. 20, no. 3, pp. 2011–2027, 2018.
- [18] S. Andreev, V. Petrov, M. Dohler, and H. Yanikomeroglu, "Future of ultra-dense networks beyond 5G: harnessing heterogeneous moving cells," *IEEE Communications Magazine*, 2019.
- [19] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low power wide area networks: An overview," *IEEE Communications Surveys and Tutorials*, vol. 19, no. 2, pp. 855–873, 2017.
- [20] T. Fernández-Caramés, P. Fraga-Lamas, M. Suárez-Albela, and L. Castedo, "Reverse engineering and security evaluation of commercial tags for rfid-based iot applications," *Sensors*, vol. 17, no. 1, p. 28, 2017.
- [21] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of lpwan technologies for large-scale iot deployment," *ICT express*, vol. 5, no. 1, pp. 1–7, 2019.
- [22] K. Hwang and M. Chen, *Big-data analytics for cloud, IoT and cognitive computing*. John Wiley & Sons, 2017.
- [23] J. Ren, H. Guo, C. Xu, and Y. Zhang, "Serving at the edge: A scalable IoT architecture based on transparent computing," *IEEE Network*, vol. 31, no. 5, pp. 96–105, 2017.
- [24] M. Marjani, F. Nasaruddin, A. Gani, A. Karim, I. Hashem, A. Siddiqua, and I. Yaqoob, "Big iot data analytics: Architecture, opportunities, and open research challenges," *IEEE Access*, vol. 5, pp. 5247–5261, 2017.
- [25] O. Sezer, E. Dogdu, and A. Ozbayoglu, "Context-aware computing, learning, and big data in internet of things: A survey," *IEEE Internet of Things Journal*, vol. 5, no. 1, pp. 1–27, 2018.
- [26] F. Fang, M. Tambe, B. Dilkina, and A. J. Plumptre, *Artificial Intelligence and Conservation*. Cambridge University Press, 2019.
- [27] J. Zhou, H.-N. Dai, and H. Wang, "Lightweight convolution neural networks for mobile edge computing in transportation cyber physical systems," *ACM Transactions on Intelligent Systems and Technology*, vol. 10, no. 6, pp. 67:1–20, 2019. [Online]. Available: <https://doi.org/10.1145/3339308>
- [28] I. A. T. Hashem, V. Chang, N. B. Anuar, K. Adewole, I. Yaqoob, A. Gani, E. Ahmed, and H. Chiroma, "The role of big data in smart city," *International Journal of Information Management*, vol. 36, no. 5, pp. 748–758, 2016.
- [29] C.-W. Lin, J. Kim, S.-Y. Lin, and Y. Choi, "A new paradigm for aeolain process monitoring employing uav and satellite sensors: Application case in kubuqi desert, china," in *EGU General Assembly Conference Abstracts*, vol. 20, 2018, p. 12235.
- [30] Z. Qu, G. Zhang, H. Cao, and J. Xie, "Leo satellite constellation for internet of things," *IEEE Access*, vol. 5, pp. 18391–18401, 2017.
- [31] T. Perera, A. Priyankara, and G. Jayasinghe, "Unmanned arial vehicles (uav) in smart agriculture: Trends, benefits and future perspectives," 2019.
- [32] A. M. Zarca, J. B. Bernabe, R. Trapero, D. Rivera, J. Villalobos, A. Skarmeta, S. Bianchi, A. Zafeiropoulos, and P. Gouvas, "Security management architecture for nfv/sdn-aware iot systems," *IEEE Internet of Things Journal*, 2019.
- [33] F. Javed, M. Afzal, M. Sharif, and B. Kim, "Internet of things (iot) operating systems support, networking technologies, applications, and challenges: A comparative review," *IEEE Communications Surveys and Tutorials*, vol. 20, no. 3, pp. 2062–2100, 2018.
- [34] S. G. Gupta, M. M. Ghonge, and P. Jawandhiya, "Review of unmanned aircraft system (uas)," *International journal of advanced research in computer engineering & technology (IJARCET)*, vol. 2, no. 4, pp. 1646–1658, 2013.
- [35] S. Manitta, "Unmanned aircraft systems ground support platform," Mar. 10 2016, uS Patent App. 14/793,708.
- [36] A. K. Chan, J. R. Cheatham III, H. W. Chin, W. D. Duncan, R. A. Hyde, M. Y. Ishikawa, J. T. Kare, T. S. Pan, R. C. Petroski, C. T. Tegreene *et al.*, "Reconfigurable unmanned aircraft system," Feb. 27 2018, uS Patent 9,902,491.
- [37] L. Gupta, R. Jain, and G. Vaszkun, "Survey of Important Issues in UAV Communication Networks," *IEEE Communications Surveys and Tutorials*, vol. 18, no. 2, pp. 1123–1152, 2016.
- [38] A. Jamalipour, Z. Kaleem, P. Lorenz, and W. Choi, "Special Issue on Amateur Drone and UAV Communications and Networks," *Journal of Communications and Networks*, vol. 20, no. 5, pp. 429–433, 2018.
- [39] P. Liu, A. Chen, Y. Huang, J. Han, J. Lai, S. Kang, T. Wu, M. Wen, and M. Tsai, "A review of rotorcraft Unmanned Aerial Vehicle (UAV) developments and applications in civil engineering," *Smart Structures and Systems*, vol. 13, no. 6, pp. 1065–1094, 2014.
- [40] C. Zhang and W. Zhang, "Spectrum sharing for drone networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 1, pp. 136–144, 2017.
- [41] S. Granshaw, "RPV, UAV, UAS, RPAS ... or just drone?" *Photogrammetric Record*, vol. 33, no. 162, pp. 160–170, 2018.
- [42] D. Ho, E. Grotli, P. Sujit, T. Johansen, and J. Sousa, "Optimization of Wireless Sensor Network and UAV Data Acquisition," *Journal of Intelligent & Robotic Systems*, vol. 78, no. 1, pp. 159–179, 2015.
- [43] A. Rahmadhani, Richard, R. Isswandhana, A. Giovani, and R. A. Syah, "Lorawan as secondary telemetry communication system for drone delivery," in *2018 IEEE International Conference on Internet of Things and Intelligence System (IOTAIS)*, Nov 2018, pp. 116–122.
- [44] "Dji introduces a smart remote controller with built-in display at ces 2019," <https://www.dji.com/au/newsroom/news/dji-introduces-a-smart-remote-controller-with-built-in-display>, accessed Jan. 8, 2019.
- [45] "Dji introduces mavic 2 pro and mavic 2 zoom: A new era for camera drones," <https://www.dji.com/au/newsroom/news/dji-introduces-a-smart-remote-controller-with-built-in-display>, accessed . 23, 2018.

- [46] M. Orsag, C. Korpela, and P. Oh, "Modeling and Control of MM-UAV: Mobile Manipulating Unmanned Aerial Vehicle," *Journal of Intelligent & Robotic Systems*, vol. 69, no. 1-4, pp. 227-240, 2013.
- [47] A. Crane, "From startup to empire: The evolution of dji drones," <https://dronelife.com/2018/05/14/from-startup-to-empire-the-evolution-of-dji-drones/>, accessed May 14, 2018.
- [48] Y. Zhou, N. Cheng, N. Lu, and X. Shen, "Multi-UAV-Aided Networks Aerial-Ground Cooperative Vehicular Networking Architecture," *IEEE Vehicular Technology Magazine*, vol. 10, no. 4, pp. 36-44, 2015.
- [49] M. Erdelj, M. Krol, and E. Natalizio, "Wireless Sensor Networks and Multi-UAV systems for natural disaster management," *Computer Networks*, vol. 124, pp. 72-86, 2017.
- [50] C. M. de A. Lima, E. A. da Silva, and P. B. Velloso, "Performance evaluation of 802.11 iot devices for data collection in the forest with drones," in *2018 IEEE Global Communications Conference (GLOBECOM)*, Dec 2018, pp. 1-7.
- [51] M. Alzenad, A. El-Keyi, F. Lagum, and H. Yanikomeroglu, "3-d placement of an unmanned aerial vehicle base station (uav-bs) for energy-efficient maximal coverage," *IEEE Wireless Communications Letters*, vol. 6, no. 4, pp. 434-437, 2017.
- [52] J. Lyu, Y. Zeng, R. Zhang, and T. J. Lim, "Placement optimization of uav-mounted mobile base stations," *IEEE Communications Letters*, vol. 21, no. 3, pp. 604-607, 2016.
- [53] S. Zhang, H. Zhang, Q. He, K. Bian, and L. Song, "Joint trajectory and power optimization for uav relay networks," *IEEE Communications Letters*, vol. 22, no. 1, pp. 161-164, 2017.
- [54] P. Sujit, D. Lucani, and J. Sousa, "Bridging cooperative sensing and route planning of autonomous vehicles," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 5, pp. 912-922, 2012.
- [55] D. H. Choi, S. H. Kim, and D. K. Sung, "Energy-efficient maneuvering and communication of a single uav-based relay," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 50, no. 3, pp. 2320-2327, July 2014.
- [56] E. Semsch, M. Jakob, D. Pavlicek, and M. Pechoucek, "Autonomous UAV surveillance in complex urban environments," in *Proceedings of the 2009 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology-Volume 02*. IEEE Computer Society, 2009, pp. 82-85.
- [57] N. H. Motlagh, M. Bagaa, and T. Taleb, "Uav-based iot platform: A crowd surveillance use case," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 128-134, 2017.
- [58] Q. Wu, L. Liu, and R. Zhang, "Fundamental trade-offs in communication and trajectory design for UAV-enabled wireless network," *IEEE Wireless Communications*, vol. 26, no. 1, pp. 36-44, 2019.
- [59] J. Jiang and G. Han, "Routing protocols for unmanned aerial vehicles," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 58-63, 2018.
- [60] B. M. Satharaj, L. C. Jain, A. Finn, and S. Drake, "Multiple uavs path planning algorithms: a comparative study," *Fuzzy Optimization and Decision Making*, vol. 7, no. 3, p. 257, 2008.
- [61] Z. M. Fadlullah, D. Takaishi, H. Nishiyama, N. Kato, and R. Miura, "A dynamic trajectory control algorithm for improving the communication throughput and delay in uav-aided networks," *IEEE Network*, vol. 30, no. 1, pp. 100-105, January 2016.
- [62] F. Wu, D. Yang, L. Xiao, and L. Cuthbert, "Minimum-Throughput Maximization for Multi-UAV-Enabled Wireless-Powered Communication Networks," *Sensors*, vol. 19, no. 7, p. 1491, 2019.
- [63] Q. Wu, Y. Zeng, and R. Zhang, "Joint Trajectory and Communication Design for Multi-UAV Enabled Wireless Networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 2109-2121, 2018.
- [64] X. Xu, L. Duan, and M. Li, "UAV placement games for optimal wireless service provision," in *WiOpt*, 2018, pp. 1-8.
- [65] Z. Wang, L. Duan, and R. Zhang, "Adaptive Deployment for UAV-Aided Communication Networks," *IEEE Transactions on Wireless Communications*, vol. 18, no. 9, pp. 4531-4543, Sep. 2019.
- [66] S. Yin, S. Zhao, Y. Zhao, and F. R. Yu, "Intelligent Trajectory Design in UAV-Aided Communications With Reinforcement Learning," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 8227-8231, Aug 2019.
- [67] M. Hua, Y. Wang, Q. Wu, H. Dai, Y. Huang, and L. Yang, "Energy-Efficient Cooperative Secure Transmission in Multi-UAV-Enabled Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 7761-7775, 2019.
- [68] Y. Zeng and R. Zhang, "Energy-Efficient UAV Communication With Trajectory Optimization," *IEEE Transactions on Wireless Communications*, vol. 16, no. 6, pp. 3747-3760, 2017.
- [69] X. Li, H. Yao, J. Wang, X. Xu, C. Jiang, and L. Hanzo, "A Near-Optimal UAV-Aided Radio Coverage Strategy for Dense Urban Areas," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 9, pp. 9098-9109, Sep. 2019.
- [70] K. S. Koushik A M, Hu F, "Deep q-learning based node positioning for throughput-optimal communications in dynamic uav swarm network," *Transactions on Cognitive Communications and Networking*, 2019.
- [71] M. Y. Arafat and S. Moh, "Localization and Clustering Based on Swarm Intelligence in UAV Networks for Emergency Communications," *IEEE Internet of Things Journal*, pp. 1-1, 2019.
- [72] X. Xi, X. Cao, P. Yang, J. Chen, T. Quek, and D. Wu, "Joint User Association and UAV Location Optimization for UAV-Aided Communications," *IEEE Wireless Communications Letters*, pp. 1-1, 2019.
- [73] Y. Liu and Y. Shen, "UAV-Aided High-Accuracy Relative Localization of Ground Vehicles," in *2018 IEEE International Conference on Communications (ICC)*, May 2018, pp. 1-6.
- [74] G. Zhang, H. Yan, Y. Zeng, M. Cui, and Y. Liu, "Trajectory Optimization and Power Allocation for Multi-Hop UAV Relaying Communications," *IEEE Access*, vol. 6, pp. 48 566-48 576, 2018.
- [75] A. Liu and V. K. N. Lau, "Optimization of Multi-UAV-Aided Wireless Networking Over a Ray-Tracing Channel Model," *IEEE Transactions on Wireless Communications*, vol. 18, no. 9, pp. 4518-4530, Sep. 2019.
- [76] X. Liu, Y. Liu, Y. Chen, and L. Hanzo, "Trajectory Design and Power Control for Multi-UAV Assisted Wireless Networks: A Machine Learning Approach," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 7957-7969, Aug 2019.
- [77] J. Xiong, H. Guo, and J. Liu, "Task Offloading in UAV-Aided Edge Computing: Bit Allocation and Trajectory Optimization," *IEEE Communications Letters*, vol. 23, no. 3, pp. 538-541, March 2019.
- [78] L. Wang, H. Yang, J. Long, K. Wu, and J. Chen, "Enabling Ultra-Dense UAV-Aided Network with Overlapped Spectrum Sharing: Potential and Approaches," *IEEE Network*, vol. 32, no. 5, pp. 85-91, Sep. 2018.
- [79] L. Wang, Y. L. Che, J. Long, L. Duan, and K. Wu, "Multiple Access MmWave Design for UAV-Aided 5G Communications," *IEEE Wireless Communications*, vol. 26, no. 1, pp. 64-71, February 2019.
- [80] W. Feng, J. Wang, Y. Chen, X. Wang, N. Ge, and J. Lu, "UAV-Aided MIMO Communications for 5G Internet of Things," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 1731-1740, April 2019.
- [81] E. P. De Freitas, T. Heimfarth, I. F. Netto, C. E. Lino, C. E. Pereira, A. M. Ferreira, F. R. Wagner, and T. Larsson, "Uav relay network to support wsn connectivity," in *International Congress on Ultra Modern Telecommunications and Control Systems*. IEEE, 2010, pp. 309-314.
- [82] J. Xu, Y. Zeng, and R. Zhang, "UAV-Enabled Wireless Power Transfer: Trajectory Design and Energy Optimization," *IEEE Transactions on Wireless Communications*, vol. 17, no. 8, pp. 5092-5106, 2018.
- [83] J. Zhang, J. Yan, P. Zhang, and X. Kong, "Design and information architectures for an unmanned aerial vehicle cooperative formation tracking controller," *IEEE Access*, vol. 6, pp. 45 821-45 833, 2018.
- [84] Q. Wang, "A novel anti-eavesdropping scheme in wireless networks: Fri-uj," in *Proceedings of the 2019 International Conference on Embedded Wireless Systems and Networks*. Junction Publishing, 2019, pp. 316-317.
- [85] V. Kharchenko and V. Torianyk, "Cybersecurity of the internet of drones: Vulnerabilities analysis and imeca based assessment," in *2018 IEEE 9th International Conference on Dependable Systems, Services and Technologies (DESSERT)*. IEEE, 2018, pp. 364-369.
- [86] D. He, Y. Qiao, S. Chan, and N. Guizani, "Flight security and safety of drones in airborne fog computing systems," *IEEE Communications Magazine*, vol. 56, no. 5, pp. 66-71, 2018.
- [87] J. Xu and R. Zhang, "A general design framework for mimo wireless energy transfer with limited feedback," *IEEE Transactions on Signal Processing*, vol. 64, no. 10, pp. 2475-2488, 2016.
- [88] Z. Zhou, J. Irizarry, and Y. Lu, "A multidimensional framework for unmanned aerial system applications in construction project management," *Journal of Management in Engineering*, vol. 34, no. 3, p. 04018004, 2018.
- [89] Y. Li and C. Liu, "Applications of multirotor drone technologies in construction management," *International Journal of Construction Management*, pp. 1-12, 2018.
- [90] B. Hubbard, H. Wang, M. Leasure, T. Ropp, T. Lofton, S. Hubbard, and S. Lin, "Feasibility study of uav use for rfid material tracking on construction sites," in *Proc., ASCE Annual International Conference*, 2015, pp. 669-676.
- [91] H. Hamledari, "Inpro: Automated indoor construction progress monitoring using unmanned aerial vehicles," *Master of Applied Science University of Toronto, Toronto, Canada*, 2016.

- [92] H. I. Moud, A. Shojaei, and I. Flood, "Current and future applications of unmanned surface, underwater, and ground vehicles in construction," in *Proceedings of the Construction Research Congress*, 2018, pp. 106–115.
- [93] A. Abdallah, M. Z. Ali, J. Mišić, and V. B. Mišić, "Efficient security scheme for disaster surveillance uav communication networks," *Information*, vol. 10, no. 2, p. 43, 2019.
- [94] I. Maza, F. Caballero, J. Capitán, J. R. Martínez-de Dios, and A. Ollero, "Experimental results in multi-uav coordination for disaster management and civil security applications," *Journal of intelligent & robotic systems*, vol. 61, no. 1-4, pp. 563–585, 2011.
- [95] N. Zhao, W. Lu, M. Sheng, Y. Chen, J. Tang, F. R. Yu, and K.-K. Wong, "Uav-assisted emergency networks in disasters," *IEEE Wireless Communications*, vol. 26, no. 1, pp. 45–51, 2019.
- [96] G. Tuna, B. Nefzi, and G. Conte, "Unmanned aerial vehicle-aided communications system for disaster recovery," *Journal of Network and Computer Applications*, vol. 41, pp. 27–36, 2014.
- [97] M. Deruyck, J. Wyckmans, W. Joseph, and L. Martens, "Designing uav-aided emergency networks for large-scale disaster scenarios," *EURASIP Journal on Wireless Communications and Networking*, vol. 2018, no. 1, p. 79, 2018.
- [98] A. D. Ibrah, L. Chuang, L. Na, and Z. Meng-yuan, "Optimization method of relay network deployment using multi-uav for emergency communication," in *Journal of Physics: Conference Series*, vol. 1060, no. 1. IOP Publishing, 2018, p. 012042.
- [99] P. Sujit, J. Manathara, D. Ghose, and J. de Sousa, "Decentralized multi-uav coalition formation with limited communication ranges," *Handbook of unmanned aerial vehicles*, pp. 2021–2048, 2015.
- [100] A. Orsino, A. Ometov, G. Fodor, D. Moltchanov, L. Militano, S. Andreev, O. N. Yilmaz, T. Tirronen, J. Torsner, G. Araniti *et al.*, "Effects of Heterogeneous Mobility on D2D-and Drone-Assisted Mission-Critical MTC in 5G," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 79–87, 2017.
- [101] H. Kim, L. Mokdad, and J. Ben-Othman, "Designing uav surveillance frameworks for smart city and extensive ocean with differential perspectives," *IEEE Communications Magazine*, vol. 56, no. 4, pp. 98–104, 2018.
- [102] S. A. R. Naqvi, S. A. Hassan, H. Pervaiz, and Q. Ni, "Drone-aided communication as a key enabler for 5G and resilient public safety networks," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 36–42, 2018.
- [103] G. Ding, Q. Wu, L. Zhang, Y. Lin, T. Tsiftsis, and Y. Yao, "An amateur drone surveillance system based on the cognitive internet of things," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 29–35, 2018.
- [104] Y. Wu, Y. Luo, G. Zhao, J. Hu, F. Gao, and S. Wang, "A novel line position recognition method in transmission line patrolling with UAV using machine learning algorithms," in *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*. IEEE, 2018, pp. 491–495.
- [105] H. Wang, B. Yan, X. Li, X. Luo, Q. Yang, and W. Yan, "On optimal path planning for uav based patrolling in complex 3d topographies," in *2016 IEEE International Conference on Information and Automation (ICIA)*. IEEE, 2016, pp. 986–990.
- [106] J. Seok, M. Faied, and A. Girard, "Unpredictably dynamic environment patrolling," *Unmanned Systems*, vol. 5, no. 04, pp. 223–236, 2017.
- [107] X. Zhou, W. Wang, T. Wang, X. Li, and T. Jing, "Continuous patrolling in uncertain environment with the uav swarm," *PLoS one*, vol. 13, no. 8, p. e0202328, 2018.
- [108] S. Chen, F. Wu, L. Shen, J. Chen, and S. D. Ramchurn, "Decentralized patrolling under constraints in dynamic environments," *IEEE transactions on cybernetics*, vol. 46, no. 12, pp. 3364–3376, 2015.
- [109] H. Menouar, I. Guvenc, K. Akkaya, A. S. Uluagac, A. Kadri, and A. Tuncer, "UAV-enabled intelligent transportation systems for the smart city: Applications and challenges," *IEEE Communications Magazine*, vol. 55, no. 3, pp. 22–28, 2017.
- [110] R. Ke, Z. Li, J. Tang, Z. Pan, and Y. Wang, "Real-time traffic flow parameter estimation from uav video based on ensemble classifier and optical flow," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 1, pp. 54–64, Jan 2019.
- [111] S. Bertrand, N. Raballand, and F. Viguier, "Evaluating ground risk for road networks induced by uav operations," in *2018 International Conference on Unmanned Aircraft Systems (ICUAS)*. IEEE, 2018, pp. 168–176.
- [112] R. Reshma, T. Ramesh, and P. Sathishkumar, "Security situational aware intelligent road traffic monitoring using uavs," in *2016 international conference on VLSI systems, architectures, technology and applications (VLSI-SATA)*. IEEE, 2016, pp. 1–6.
- [113] O. S. Oubbati, N. Chaib, A. Lakas, P. Lorenz, and A. Rachedi, "Uav-assisted supporting services connectivity in urban vanets," *IEEE Transactions on Vehicular Technology*, 2019.
- [114] Y. Zhou, N. Cheng, N. Lu, and X. S. Shen, "Multi-uav-aided networks: Aerial-ground cooperative vehicular networking architecture," *IEEE vehicular technology magazine*, vol. 10, no. 4, pp. 36–44, 2015.
- [115] S. A. Hadiwardoyo, E. Hernández-Orallo, C. T. Calafate, J.-C. Cano, and P. Manzoni, "Evaluating uav-to-car communications performance: Testbed experiments," in *2018 IEEE 32nd International Conference on Advanced Information Networking and Applications (AINA)*. IEEE, 2018, pp. 86–92.
- [116] S. A. Hadiwardoyo, E. Hernández-Orallo, C. T. Calafate, J. C. Cano, and P. Manzoni, "Experimental characterization of uav-to-car communications," *Computer Networks*, vol. 136, pp. 105–118, 2018.
- [117] G. Milics, "Application of uavs in precision agriculture," in *International Climate Protection*. Springer, 2019, pp. 93–97.
- [118] C. de Souza, R. Lamparelli, J. Rocha, and P. Magalhaes, "Mapping skips in sugarcane fields using object-based analysis of unmanned aerial vehicle (UAV) images," *Computers and Electronics in Agriculture*, vol. 143, pp. 49–56, 2017.
- [119] J. Albetis, S. Duthoit, F. Guttler, A. Jacquin, M. Goulard, H. Poilve, J. Feret, and G. Dedieu, "Detection of flavescence dorée grapevine disease using unmanned aerial vehicle (uav) multispectral imagery," *Remote Sensing*, vol. 9, no. 4, 2017.
- [120] D. Cramp, "The use of an unmanned aerial vehicle (UAV) to investigate aspects of honey bee drone congregation areas (DCAs)," *Journal of Apicultural Research*, vol. 56, no. 2, 2017.
- [121] B. Duan, S. Fang, R. Zhu, X. Wu, S. Wang, Y. Gong, and Y. Peng, "Remote Estimation of Rice Yield With Unmanned Aerial Vehicle (UAV) Data and Spectral Mixture Analysis," *Frontiers in Plant Science*, vol. 10, 2019.
- [122] A. Laliberte, J. Herrick, A. Rango, and C. Winters, "Acquisition, Orthorectification, and Object-based Classification of Unmanned Aerial Vehicle (UAV) Imagery for Rangeland Monitoring," *Photogrammetric Engineering and Remote Sensing*, vol. 76, no. 6, pp. 661–672, 2010.
- [123] M. Abdelkader, M. Shaqura, C. G. Claudel, and W. Gueaieb, "A uav based system for real time flash flood monitoring in desert environments using lagrangian microsensors," in *2013 International Conference on Unmanned Aircraft Systems (ICUAS)*. IEEE, 2013, pp. 25–34.
- [124] I. Sparelli, L. Albertini, T. Izquierdo, M. Abad, P. Mozzi, and A. Fontana, "Geomorphological analysis of recent flash-flood events in the atacama desert using high-resolution uav images," in *EGU General Assembly Conference Abstracts*, vol. 20, 2018, p. 9225.
- [125] D. Sun, J. Zheng, T. Ma, J. Chen, and X. Li, "The analysis of burrows recognition accuracy in xinjiang's pasture area based on uav visible images with different spatial resolution," *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 42, p. 3, 2018.
- [126] T. T. Sankey, J. McVay, T. L. Swetnam, M. P. McClaran, P. Heilman, and M. Nichols, "Uav hyperspectral and lidar data and their fusion for arid and semi-arid land vegetation monitoring," *Remote Sensing in Ecology and Conservation*, vol. 4, no. 1, pp. 20–33, 2018.
- [127] R. I. H. Abushahma, M. A. Ali, N. A. A. Rahman, and O. I. Al-Sanjary, "Comparative features of unmanned aerial vehicle (uav) for border protection of libya: A review," in *2019 IEEE 15th International Colloquium on Signal Processing & Its Applications (CSPA)*. IEEE, 2019, pp. 114–119.
- [128] C. Alexander, A. Korstjens, E. Hankinson, G. Usher, N. Harrison, M. Nowak, A. Abdullah, S. Wich, and R. Hill, "Locating emergent trees in a tropical rainforest using data from an Unmanned Aerial Vehicle (UAV)," *International Journal of Applied Earth Observation and Geoinformation*, vol. 72, pp. 86–90, 2018.
- [129] S. Klosterman, E. Melaas, J. Wang, A. Martinez, S. Frederick, J. O'Keefe, D. Orwig, Z. Wang, Q. Sun, C. Schaaf, M. Friedl, and A. Richardson, "Fine-scale perspectives on landscape phenology from unmanned aerial vehicle (UAV) photography," *Agricultural and Forest Meteorology*, vol. 248, pp. 397–407, 2018.
- [130] C. Carl, D. Landgraf, M. van der Maaten-Theunissen, P. Biber, and H. Pretzsch, "Robinia pseudoacacia L. Flowers Analyzed by Using An Unmanned Aerial Vehicle (UAV)," *Remote Sensing*, vol. 9, no. 11, 2017.
- [131] V. Otero, R. Van De Kerchove, B. Satyanarayana, C. Martínez-Espinosa, M. A. B. Fisol, M. R. B. Ibrahim, I. Sulong, H. Mohd-Lokman, R. Lucas, and F. Dahdouh-Guebas, "Managing mangrove forests from the sky: Forest inventory using field data and unmanned

- aerial vehicle (uav) imagery in the matang mangrove forest reserve, peninsular malaysia,” *Forest ecology and management*, vol. 411, pp. 35–45, 2018.
- [132] S. Puliti, S. Saarela, T. Gobakken, G. Ståhl, and E. Næsset, “Combining uav and sentinel-2 auxiliary data for forest growing stock volume estimation through hierarchical model-based inference,” *Remote Sensing of Environment*, vol. 204, pp. 485–497, 2018.
- [133] F. Giannetti, G. Chirici, T. Gobakken, E. Næsset, D. Travaglini, and S. Puliti, “A new approach with dtm-independent metrics for forest growing stock prediction using uav photogrammetric data,” *Remote Sensing of Environment*, vol. 213, pp. 195–205, 2018.
- [134] K. Jun, B. Jun, H. Lee, S. Kim, and W. Tak, “The study of utilization and precision based on the comparison and analysis of drone-based coastal hazard data and its application in the ocean environment,” *Journal of Coastal Research*, pp. 811–815, 2018.
- [135] M. A. e. a. Trasvina-Moreno C, Blasco R, “Unmanned aerial vehicle based wireless sensor network for marine-coastal environment monitoring,” *Sensors*, vol. 17(3): 460.
- [136] Y. Matsuba and S. Sato, “Nearshore bathymetry estimation using uav,” *Coastal Engineering Journal*, vol. 60, no. 1, pp. 51–59, 2018.
- [137] O. J. Gooday, N. Key, S. Goldstien, and P. Zawar-Reza, “An assessment of thermal-image acquisition with an unmanned aerial vehicle (uav) for direct counts of coastal marine mammals ashore,” *Journal of Unmanned Vehicle Systems*, vol. 6, no. 2, pp. 100–108, 2018.
- [138] S. Wang, L. Liu, L. Qu, C. Yu, Y. Sun, F. Gao, and J. Dong, “Accurate ulva prolifera regions extraction of uav images with superpixel and cnns for ocean environment monitoring,” *Neurocomputing*, vol. 348, pp. 158–168, 2019.
- [139] G. D. Bousquet, M. S. Triantafyllou, and J.-J. E. Slotine, “The unav, a wind-powered uav for ocean monitoring: Performance, control and validation,” in *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2018, pp. 1259–1266.
- [140] G. Fontanesi, H. Ahmadi, and A. Zhu, “Over the sea uav based communication,” *arXiv preprint arXiv:1905.04954*, 2019.
- [141] S. Wu, Q. Wang, B. Liu, J. Liu, K. Zhang, and X. Song, “Uav-borne coherent doppler lidar for marine atmospheric boundary layer observations,” in *EPJ Web of Conferences*, vol. 176. EDP Sciences, 2018, p. 02012.
- [142] D. W. Johnston, “Unoccupied aircraft systems in marine science and conservation,” *Annual review of marine science*, vol. 11, pp. 439–463, 2019.
- [143] G. Rieucou, J. J. Kiszka, J. C. Castillo, J. Mourier, K. M. Boswell, and M. R. Heithaus, “Using unmanned aerial vehicle (uav) surveys and image analysis in the study of large surface-associated marine species: a case study on reef sharks *carcharhinus melanopterus* shoaling behaviour,” *Journal of fish biology*, vol. 93, no. 1, pp. 119–127, 2018.
- [144] M. Gharibi, R. Boutaba, and S. Waslander, “Internet of drones,” *IEEE Access*, vol. 4, pp. 1148–1162, 2016.
- [145] X. Cao, J. Xu, and R. Zhangt, “Mobile edge computing for cellular-connected uav: Computation offloading and trajectory optimization,” in *2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*. IEEE, 2018, pp. 1–5.
- [146] B. Barritt, T. Kichkaylo, K. Mandke, A. Zalman, and V. Lin, “Operating a uav mesh & internet backhaul network using temporospatial sdn,” in *2017 IEEE Aerospace Conference*. IEEE, 2017, pp. 1–7.
- [147] S. ur Rahman, G.-H. Kim, Y.-Z. Cho, and A. Khan, “Deployment of an sdn-based uav network: Controller placement and tradeoff between control overhead and delay,” in *2017 International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE, 2017, pp. 1290–1292.
- [148] Z. Yuan, X. Huang, L. Sun, and J. Jin, “Software defined mobile sensor network for micro uav swarm,” in *2016 IEEE International Conference on Control and Robotics Engineering (ICCRE)*. IEEE, 2016, pp. 1–4.
- [149] R. Kumar, M. A. Sayeed, V. Sharma, and I. You, “An sdn-based secure mobility model for uav-ground communications,” in *International Symposium on Mobile Internet Security*. Springer, 2017, pp. 169–179.
- [150] X. Zhang, H. Wang, and H. Zhao, “An sdn framework for uav backbone network towards knowledge centric networking,” in *IEEE INFOCOM 2018-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE, 2018, pp. 456–461.
- [151] T. Bai, J. Wang, Y. Ren, and L. Hanzo, “Energy-efficient computation offloading for secure uav-edge-computing systems,” *IEEE Transactions on Vehicular Technology*, 2019.
- [152] S. Garg, A. Singh, S. Batra, N. Kumar, and L. Yang, “Uav-empowered edge computing environment for cyber-threat detection in smart vehicles,” *IEEE Network*, vol. 32, no. 3, pp. 42–51, 2018.
- [153] Y. Khosiawan and I. Nielsen, “A system of uav application in indoor environment,” *Production & Manufacturing Research*, vol. 4, no. 1, pp. 2–22, 2016.
- [154] A. M. Madni, M. W. Sievers, J. Humann, E. Ordoukhanian, B. Boehm, and S. Lucero, “Formal methods in resilient systems design: application to multi-uav system-of-systems control,” in *Disciplinary Convergence in Systems Engineering Research*. Springer, 2018, pp. 407–418.
- [155] C. Luo, J. Nightingale, E. Asemota, and C. Grecos, “A uav-cloud system for disaster sensing applications,” in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*. IEEE, 2015, pp. 1–5.
- [156] M. Saigh and X. Zhang, “Uav policing, enforcement and deployment system,” Sep. 7 2017, uS Patent App. 15/061,256.
- [157] M. Khan, K. Heurtefeux, A. Mohamed, K. Harras, and M. Hassan, “Mobile Target Coverage and Tracking on Drone-Be-Gone UAV Cyber-Physical Testbed,” *IEEE Systems Journal*, vol. 12, no. 4, pp. 3485–3496, 2018.
- [158] H. Aasen, A. Burkart, A. Bolten, and G. Bareth, “Generating 3d hyperspectral information with lightweight uav snapshot cameras for vegetation monitoring: From camera calibration to quality assurance,” *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 108, pp. 245–259, 2015.
- [159] K. Van Beeck, T. Tuytelaars, D. Scaramuzza, and T. Goedemé, “Real-time embedded computer vision on uavs,” in *European Conference on Computer Vision*. Springer, 2018, pp. 3–10.
- [160] C. Eling, L. Klingbeil, and H. Kuhlmann, “Real-time single-frequency gps/mems-imu attitude determination of lightweight uavs,” *Sensors*, vol. 15, no. 10, pp. 26212–26235, 2015.
- [161] H. Cao, Y. Liu, X. Yue, and W. Zhu, “Cloud-assisted uav data collection for multiple emerging events in distributed wsns,” *Sensors*, vol. 17, no. 8, 2017.
- [162] M. Itkin, M. Kim, and Y. Park, “Development of cloud-based uav monitoring and management system,” *Sensors*, vol. 16, no. 11, 2016.
- [163] A. Koubaa, B. Qureshi, M. Sriti, A. Allouch, Y. Javed, M. Alajlan, O. Cheikhrouhou, M. Khalgui, and E. Tovar, “Dronemap planner: A service-oriented cloud-based management system for the internet-of-drones,” *Ad Hoc Networks*, vol. 86, pp. 46–62, 2019.
- [164] B. Liu, Y. Chen, A. Hadiks, E. Blasch, A. Aved, D. Shen, and G. Chen, “Information fusion in a cloud computing era: A systems-level perspective,” *IEEE Aerospace and Electronic Systems Magazine*, vol. 29, no. 10, pp. 16–24, 2014.
- [165] D. Turner, A. Lucieer, and L. Wallace, “Direct georeferencing of ultrahigh-resolution uav imagery,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 52, no. 5, pp. 2738–2745, 2014.
- [166] R. D’Andrea, “Can drones deliver?” *IEEE Transactions on Automation Science and Engineering*, vol. 11, no. 3, pp. 647–648, 2014.
- [167] L. J. Myslinski, “Drone device security system for protecting a package,” Feb. 21 2019, uS Patent App. 16/169,328.
- [168] M. S. Evans, “Drone transport system,” Feb. 19 2019, uS Patent App. 10/207,805.
- [169] I. H. B. Pizetta, A. S. Brandão, and M. Sarcinelli-Filho, “Avoiding obstacles in cooperative load transportation,” *ISA transactions*, 2019.
- [170] B. Shirani, M. Najafi, and I. Izadi, “Cooperative load transportation using multiple uavs,” *Aerospace Science and Technology*, vol. 84, pp. 158–169, 2019.
- [171] K. Dorling, J. Heinrichs, G. G. Messier, and S. Magierowski, “Vehicle routing problems for drone delivery,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 1, pp. 70–85, Jan 2017.
- [172] V. Gatteschi, F. Lamberti, G. Paravati, A. Sanna, C. Demartini, A. Lisanti, and G. Venezia, “New frontiers of delivery services using drones: A prototype system exploiting a quadcopter for autonomous drug shipments,” in *2015 IEEE 39th Annual Computer Software and Applications Conference*, vol. 2, July 2015, pp. 920–927.
- [173] S. Sawaditang, D. Niyato, P. S. Tan, and P. Wang, “Supplier cooperation in drone delivery,” in *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*, Aug 2018, pp. 1–5.
- [174] C. Yuan, Z. Liu, and Y. Zhang, “Fire detection using infrared images for uav-based forest fire surveillance,” in *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*. IEEE, 2017, pp. 567–572.
- [175] N. Nigam, S. Bieniawski, I. Kroo, and J. Vian, “Control of multiple uavs for persistent surveillance: Algorithm description and hardware demonstration,” in *AIAA Infotech@ Aerospace Conference and AIAA Unmanned... Unlimited Conference*, 2009, p. 1852.
- [176] J. Nygård, P. Skoglar, M. Ulvklo, and T. Högström, “Navigation aided image processing in uav surveillance: Preliminary results and design of an airborne experimental system,” *Journal of Robotic Systems*, vol. 21, no. 2, pp. 63–72, 2004.

- [177] J. Faigl, P. Váňa, R. Pěnička, and M. Saska, “Unsupervised learning-based flexible framework for surveillance planning with aerial vehicles,” *Journal of Field Robotics*, vol. 36, no. 1, pp. 270–301, 2019.
- [178] H. Kim and J. Ben-Othman, “A collision-free surveillance system using smart uavs in multi domain iot,” *IEEE Communications Letters*, vol. 22, no. 12, pp. 2587–2590, 2018.
- [179] S. d’Oleire Oltmanns, I. Marzolf, K. Peter, and J. Ries, “Unmanned Aerial Vehicle (UAV) for Monitoring Soil Erosion in Morocco,” *Remote Sensing*, vol. 4, no. 11, pp. 3390–3416, 2012.
- [180] M. A. Ma’sum, M. K. Arrofi, G. Jati, F. Arifin, M. N. Kurniawan, P. Mursanto, and W. Jatmiko, “Simulation of intelligent unmanned aerial vehicle (uav) for military surveillance,” in *2013 International Conference on Advanced Computer Science and Information Systems (ICACSIS)*, Sep. 2013, pp. 161–166.
- [181] D. Orfanus, E. P. D. Freitas, and F. Eliassen, “Self-organization as a supporting paradigm for military uav relay networks,” *IEEE Communications Letters*, vol. 20, no. 4, pp. 804–807, 2016.
- [182] S. J. Kim, G. J. Lim, and J. Cho, “Drone relay stations for supporting wireless communication in military operations,” in *International Conference on Applied Human Factors and Ergonomics*. Springer, 2017, pp. 123–130.
- [183] T. Long, M. Ozger, O. Cetinkaya, and O. Akan, “Energy neutral internet of drones,” *IEEE Communications Magazine*, vol. 56, no. 1, pp. 22–28, 2018.
- [184] A. Y. Javaid, W. Sun, V. K. Devabhaktuni, and M. Alam, “Cyber security threat analysis and modeling of an unmanned aerial vehicle system,” in *2012 IEEE Conference on Technologies for Homeland Security (HST)*. IEEE, 2012, pp. 585–590.
- [185] C. Lin, D. He, N. Kumar, K. Choo, A. Vinel, and X. Huang, “Security and privacy for the internet of drones: Challenges and solutions,” *IEEE Communications Magazine*, vol. 56, no. 1, pp. 64–69, 2018.
- [186] N. Ammour, H. Alhichri, Y. Bazi, B. Benjdira, N. Alajlan, and M. Zuair, “Deep learning approach for car detection in uav imagery,” *Remote Sensing*, vol. 9, no. 4, p. 312, 2017.
- [187] Y. Xu, G. Yu, Y. Wang, X. Wu, and Y. Ma, “Car detection from low-altitude uav imagery with the faster r-cnn,” *Journal of Advanced Transportation*, vol. 2017, 2017.
- [188] T. Liu, H. Y. Fu, Q. Wen, D. K. Zhang, and L. F. Li, “Extended faster r-cnn for long distance human detection: Finding pedestrians in uav images,” in *2018 IEEE International Conference on Consumer Electronics (ICCE)*. IEEE, 2018, pp. 1–2.
- [189] H. Huang, J. Deng, Y. Lan, A. Yang, X. Deng, and L. Zhang, “A fully convolutional network for weed mapping of unmanned aerial vehicle (uav) imagery,” *PloS one*, vol. 13, no. 4, p. e0196302, 2018.
- [190] V. Moskalenko, A. Moskalenko, A. Korobov, and V. Semashko, “The model and training algorithm of compact drone autonomous visual navigation system,” *Data*, vol. 4, no. 1, p. 4, 2019.
- [191] K. Peng, J. Du, F. Lu, Q. Sun, Y. Dong, P. Zhou, and M. Hu, “A hybrid genetic algorithm on routing and scheduling for vehicle-assisted multi-drone parcel delivery,” *IEEE Access*, vol. 7, pp. 49 191–49 200, 2019.
- [192] S. K. Datta, J. Dugelay, and C. Bonnet, “Iot based uav platform for emergency services,” in *2018 International Conference on Information and Communication Technology Convergence (ICTC)*, Oct 2018, pp. 144–147.
- [193] T. X. Tran, A. Hajisami, P. Pandey, and D. Pompili, “Collaborative Mobile Edge Computing in 5G Networks: New Paradigms, Scenarios, and Challenges,” *IEEE Communications Magazine*, vol. 55, no. 4, pp. 54–61, April 2017.