Toward UAV-Based Airborne Computing

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Abstract

In recent years, we have witnessed the significant growth of interest in using unmanned aerial vehicles (UAVs) to facilitate civilian and commercial applications. To design future UAV systems and applications, advanced UAV functions require powerful on-board computing capability. Nevertheless, most existing UAV functions were designed separately and there is a lack of a general framework to exploit airborne computing for all on-board UAV functions. In this article, we present a comprehensive study to address this issue with the goal to adopt UAV-based airborne computing in a unified way. Specifically, we first generalize the motivations to adopt airborne computing from two perspectives: enhancing UAV functions and enabling new UAV applications. We then discuss how to design and implement future UAV-based airborne computing, in which we present some design guidelines and then propose a three-layer reference model that consists of the mission, task, and function layers so as to simplify the analysis and design of future UAV applications. To support the diverse design requirements for future UAV applications, we introduce our recent work on the development of an open networked airborne computing platform, and we demonstrate our latest prototype with experimental results that confirm the viability of our airborne computing platform.

Introduction

With the advances of technologies, unmanned aerial vehicles (UAVs) (a.k.a., drones), have become quite common in our daily lives and will have more impacts in the near future [1]. For example, we are familiar with the scenario that a tourist is using a single drone to capture high-quality videos, and we are used to the drone light shows in various social activities. In the near future, it is expected that the number of civilian and commercial UAVs around the world will be increasing quickly. According to the Federal Aviation Administration (FAA), the number of registered UAVs in the United States passed one million in January 2018, and will reach 4.3 million by 2020. Moreover, it is also expected that more and more UAV applications will emerge, including some that are common to the public, such as using UAVs for entertainment and delivery, and some that are used in special domains, such as using UAVs for land surveys, precision agriculture, emergency response, and so on, as shown in Fig. 1.

To realize a UAV application, it is necessary to design and implement multiple UAV functions. For example, Fig. 1 illustrates that a drone light show application requires a number of functions, including a path planning function to determine the movement of UAVs according to a choreographic design, a positioning function for UAVs to know their accurate positions, some flight control and power management functions for UAVs to move according to the planned path and to land safely. In addition, the application may require communications and networking functions for management and coordination.

In the past few years, many researchers and engineers have tried to address the design of different UAV functions in various domains, such as control [2], communications [3], networking [4], and so on. Certainly, many advanced UAV functions require sophisticated *airborne computing* capabilities. For example, executing a computation-intensive algorithm on-board can help a UAV to achieve high positioning accuracy [5]; running a complicated control algorithm can coordinate a swarm of UAVs [1]; executing an advanced heading control algorithm can significantly increase the capacity of a communication link between two UAVs with directional antennas [6].

Although it is well known that advanced on-board computing capabilities can enhance many UAV functions, these functions (e.g., positioning, image processing, and so on) are usually designed separately and there is a lack of a general framework to exploit airborne computing to flexibly support various computing functions. Consequently, the cost of a UAV with new functions could be higher than necessary. Furthermore, such a common practice may affect the development and adoption of new and important UAV applications.

To address this important issue, in this article, we present a comprehensive study to facilitate UAV-based airborne computing in a unified way. Specifically, we first generalize the motivations to adopt airborne computing from two perspectives: enhancing UAV functions and enabling new UAV applications. For each of these perspectives, we discuss some case studies. We then elaborate on how to facilitate future UAV-based airborne computing. First, we present some design guidelines that can help to fulfill the scalability and flexibility requirements for future wireless communications and network systems [7]. Following the guidelines, we propose a three-layer reference model that consists of the mission, task, and function layers,

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with which we can simplify the analysis and design of UAV applications. Next, to facilitate the diverse requirements of different UAV applications, we propose a networked airborne computing platform. Based on the proposed platform, we develop a novel UAV prototype that carries a powerful processing unit that can execute various airborne computing tasks. Finally, through many experiments using this prototype, we observe insightful results that validate the viability of the proposed airborne computing platform.

The rest of this article is organized as follows. In the following section, we first discuss the motivations to adopt UAV-based airborne computing. Then we elaborate on how to facilitate future UAV-based airborne computing. Following that, we propose a novel networked airborne computing platform. Next we present the latest prototype we developed and some experimental results. Finally, we conclude the article.

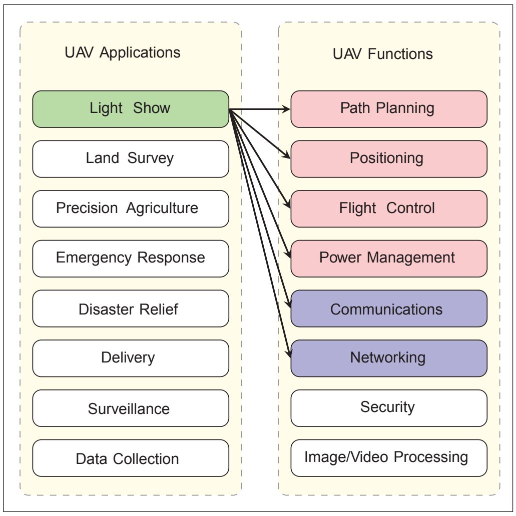

FIGURE 1. UAV applications and functions.

Airborne computing can enhance the performance of many UAV functions, and can enable new and important UAV applications.

Motivations to Adopt UAV-Based Airborne Computing

From the introduction, we can observe that:
- Various computing capabilities have already been included in UAV systems to support different UAV functions.
- All UAV applications require certain computing capabilities, but only some of the computing tasks are performed on-board.

The first observation leads to the first motivation to adopt UAV-based airborne computing, that is, airborne computing can enhance the performance of many UAV functions. Later we will illustrate that UAV-based airborne computing can significantly increase the capacity of wireless communication channels, and can improve the accuracy of positioning.

The second observation motivates to adopt UAV-based airborne computing to enable new and important UAV applications. Below, we will demonstrate that UAV-based airborne computing can facilitate novel data collection applications, and can effectively support the needs of first responders and victims in many emergency response scenarios.

Enhancing UAV Functions

Increasing the Capacity of Communications Channels: In different UAV applications, there are different communications functions that have various requirements. For example, when a UAV is launched to take videos and stream these videos in real-time to the ground station, a high bandwidth communication channel shall be established. However, a UAV may be far away from the ground station, which implies that the channel capacity is insufficient to support video streaming. To address this issue, our previous studies in [6] have demonstrated that, using the airborne computing capability, we can design and implement advanced heading control algorithms so that two UAVs that are a few kilometers away to each other can establish a broadband communication link using controllable directional antennas.

In [8], the authors demonstrated that, using the airborne computing capability, a UAV can optimally provide wireless power to ground nodes, which then use a novel non-orthogonal multiple-access scheme to send sensing data to the UAV simultaneously. Such a system can substantially increase the maximal capacity of a multiple-access channel.

Improving the Accuracy of Positioning: The objective of a positioning function is to determine the accurate location of the UAV at a given time. Depending on specific applications, existing positioning functions can be classified into indoor and outdoor, under which many different schemes have been adopted and investigated. For instance, for outdoor positioning, the dominating positioning scheme is to utilize the global navigation satellite system (GNSS), such as the global positioning system (GPS) developed in the U.S. and the *Beidou* developed in China [5].

Although basic GNSS services can provide the positioning function with low cost, the accuracy is usually in meters, which is not accurate enough to support applications such as elegant drone light shows and land surveys. To address the accuracy issue, many UAV systems are now equipped with the real-time kinematic (RTK) [5] component. Typically, an RTK system consists of two types of nodes: station and rover. An RTK station is deployed on the ground and it uses the waveforms of GNSS signals to determine its position with an accuracy within a few centimeters. Moreover, the station (or stations) will broadcast references to all rovers. On the other hand, each rover also captures the waveforms of GNSS signals as well. In addition, it also needs to receive the references sent by the RTK station. Combining all the aforementioned inputs, airborne computing can determine the position of a UAV with an accuracy in the centimeter level, which enables beautiful light shows and land survey applications.

Facilitating New UAV Applications

Data Collection, Processing, and Distribution in Wireless Networks: In wireless sensor networks (WSNs) or Internet-of-Things (IoT), UAVs can be used as mobile devices to collect data from grounded sensor nodes. In many current designs, most sensor nodes are powered by batteries, which significantly limits the lifetime of WSNs. Recently, the authors in [8] demonstrated that, with sufficient energy capacity and airborne computing capability, a UAV can be sent to power

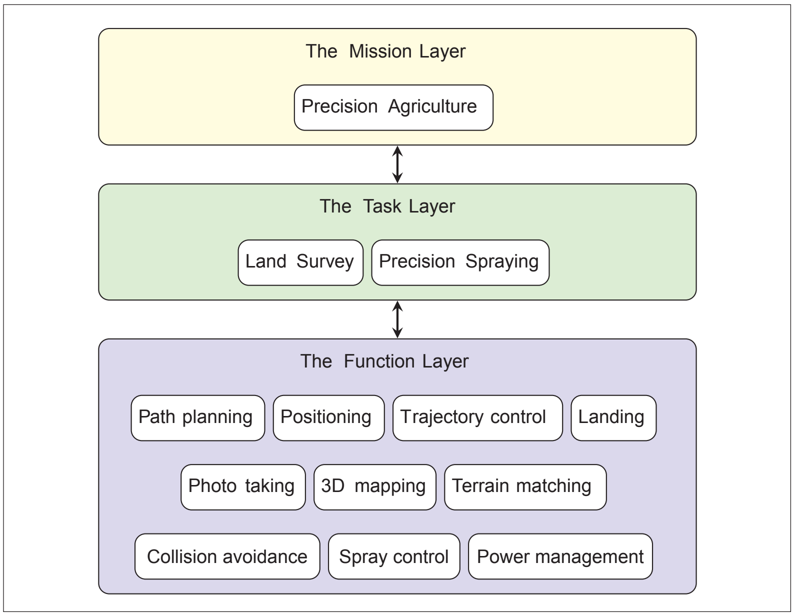

FIGURE 2. A layered view for UAV-based precision agriculture.

ground nodes using the wireless power transfer technology and can also be used as a computing node such that grounded nodes can offload their computing tasks to get desired results without spending too much energy. With advanced computing capability, a UAV can facilitate more applications in various scenarios, such as large-scale content distribution with energy constraints [9].

Emergency Response Based on Real-Time Video Delivery: Helicopters have been used by first responders to observe fire scenes, to search for and rescue people, and so on. Depending on the types of missions, the cost for renting helicopters (including pilots) may vary from a few hundred U.S. dollars to more than US$1,000 per hour. In the past few years, we have been collaborating with emergency response agencies and personnel in Texas on the design and deployment of UAVs for emergency responses, and we have tested our system in realistic scenarios [10]. In one of our designs, we developed a drone-WiFi system that is able to transmit high-resolution videos from one UAV, through a relaying UAV located more than one mile away, to the ground station [6]. Combining the real-time videos (including visible light and infrared) transmitted from UAVs and grounded robots, fire fighters are able to observe the scene, identify the hotspots in the fire, and so on, based on which they can make decisions for the evacuation plan, rescue plan, and fire suppression plan.

To briefly summarize, UAV-based airborne computing can help to enhance many UAV functions and can facilitate many new and important civilian UAV applications, which will benefit humanity.

The Design Guidelines to Facilitate UAV-Based Airborne Computing

In this section, we elaborate on the design guidelines to facilitate UAV-based airborne computing. To better understand how a UAV application can be designed and implemented, we propose a simple layered model that consists of three layers. We then use precision agriculture to demonstrate how to apply the model for the analysis and design of a UAV application.

Guidelines

Certainly, developing a new UAV application is a comprehensive process, let alone UAV-based airborne computing. To facilitate the design efforts, we now summarize a few design guidelines for enabling UAV-based airborne computing in general.

Guideline 1 — Understand the Requirements of the UAV Application: In this step, we must specify a set of requirements in various domains, such as the number of UAVs, the objective of the mission, the goals of control, the communication bandwidth and capacity, the network topology, the delay of transmission and computation, the processing and storage capabilities, and so on.

Guideline 2 — Understand How to Realize the UAV Application by Using a Certain Set of UAV Functions: To this end, we will propose a three-layer reference model below to facilitate the analysis and design of UAV applications.

Guideline 3 — Use a Common Airborne Computing Platform: Over the past decade, we have seen many UAV systems developed for different purposes. However, virtually all of them were designed to fulfill specific missions, which means the system may not be flexible to support other new UAV functions and applications. On the other hand, a common trend in computing, communication, and networking is to adopt a common platform to flexibly support diverse services and applications [7], such as cloud platform for general computing, software-defined radio (SDR) for communication, network function virtualization (NFV) for networking, and multiple-access edge computing (MEC) for emerging 5G and IoT services [7]. To address this issue, we propose and develop an open networked airborne computing platform, which will be discussed later.

Guideline 4 — Understand the Capabilities and Limitations of UAV Components: This includes the flying time, payload capacity, operational environment (indoor or outdoor), communication range, UAV type (quadcopter or fixed-wing), cost, and so on.

Guideline 5 — Understand the Joint Design Opportunities: Being aerial robots controlled through wireless communications, UAVs present various joint design opportunities where communication, control, computing, and networking can benefit each other toward an overall optimized performance for UAV applications [11].

A Layered Model

We now define a three-layer reference model to facilitate the analysis and design of UAV applications. The three layers include the following.

The Function Layer: This layer includes fundamental functions that are essential to UAV applications, such as positioning, flight control, and so on. It can also include more advanced functions, such as path planning, networking, machine learning, security, and so on.

The Task Layer: This layer specifies (a) the requirements of a UAV task; (b) the necessary functions to perform the task; and (c) how these functions are linked so as to collaboratively perform the task.

The Mission Layer: This layer defines a comprehensive mission that consists of one or more tasks. For the latter case, the mission layer also defines how these tasks are relevant to each other.

UAV-Based Airborne Computing for Precision Agriculture

In this subsection, we use a precision agriculture application as an example to demonstrate how to design a UAV application and how to incorporate airborne computing. To simplify the discussions, we will skip the requirement analysis and the detailed implementation.

Analysis and Design: We now apply the proposed three-layer reference model for analysis and design. As illustrated in Fig. 2, there is only one mission in the mission layer, which is straightforward. On the task layer, there are two tasks: land survey and precision spraying. On the function layer, there are a total of ten functions, which will be explained below.

To perform the land survey task, several functions are involved. In particular, we consider there are three stages. In the first stage, we need to first use a *path planning* algorithm to determine how a surveying UAV can fully cover a certain geographical region. Before we launch the surveying UAV, the path information shall be uploaded to the UAV, which will need to activate its *positioning* function to understand where it is and also enable a *trajectory control* scheme to manage the flight direction and speed. Then during the surveying stage, a *photo taking* procedure will be performed, in which the UAV will take photos pointing to the ground and include position information in the metadata of the photos.

In the second stage, after the surveying UAV returns, the photos are downloaded and then a ground station can use a *3D mapping* [12] program to process the photos and generate a 3D map for the field. Next, another *path planning* algorithm shall be executed to determine the 3D path for each agriculture UAV.

In the next stage, after the path information is uploaded to each agriculture UAV, it will activate its *positioning* function as well as the *trajectory control* algorithm accordingly. In addition to these functions, the agriculture UAV may enable a *terrain matching* scheme to improve the performance of spraying, for example, to stop exactly 5 meters on top of a tree, and also may enable the collision avoidance function to guarantee the safety of the UAV and ground units. Finally, the spray control procedure will specify where and how fluids will be sprayed.

For both tasks, there are some common UAV functions, such as *landing* and *power management*.

UAV-Based Airborne Computing: From the discussions above, we can easily identify several UAV functions that require airborne computing, including positioning, trajectory control, landing, power management, terrain matching, collision avoidance, and spray control.

While most of the aforementioned functions have been included in existing systems, more functions can be enabled by exploiting airborne computing. For instance, we may utilize the computing capability of a UAV to further enhance the accuracy and reliability of positioning. On the other hand, we may also utilize airborne computing to construct 3D maps during the flight task. Furthermore, based on the 3D maps, we may be able to design new schemes to dynamically adjust the trajectory of a surveying UAV to improve the 3D maps.

A Networked Airborne Computing Platform

As explained in the last section, it is very important to develop UAV applications on a unified airborne computing platform that seamlessly integrates control, communication, computing, and networking supports. To achieve this goal, in this section, we present an open networked airborne computing platform that includes a UAV-carried generic computing system, a broadband wireless communication system, a full UAV/antenna cooperative control system, and up-to-down applications (APPs) development capabilities to support a full-scale development [10]. Next, we will first present an overview of the proposed platform, and then further explain four important components in our design.

Overview

As shown in Fig. 3, the proposed airborne computing platform has four core units:

- Quadcopter unit (QUAD) for lifting and mobility.
- Control unit (CTRL) for mobility control of the UAV and directional antenna.
- Communication and networking unit (COMM) for long-range broadband communication.
- Computing and storage unit (COMP) for on-board processing and data storage.

In addition, our system provides extendable ports to accommodate extra payloads.

Unlike existing UAV infrastructures that are often designed specifically for a single purpose and oriented to missions that involve a single UAV, both hardware and software in the proposed platform are open for the community and designed in modules that can be easily enhanced, replaced, or extended to facilitate various network-based research development, applications and services. As shown in Fig. 3, applications can access the computing, communication, and control resources through the platform API and focus only on their own research interests without developing the UAV from scratch. In the following, we present more details for each of the units.

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Quadcopter Unit

The quadcopter is chosen as the platform carrier because of its three salient capabilities:

- Hovering mode: Many UAV applications require stationary positioning for tasks such as inspections and precision agriculture.
- Indoor operation: This capability will provide researchers with a more controllable environment, which is especially important during the early development and testing phases.
- Easy operability: Unlike fixed-wing UAVs that need a runway or are thrown by hand, quadcopters facilitate vertical taking off and landing, and thus can fly and land almost everywhere, implying more potential applications. Nevertheless, due to the modular design, the proposed airborne computing can also use other types of UAV such as hexacopter, fixed-wing, or even helicopters according to application needs.

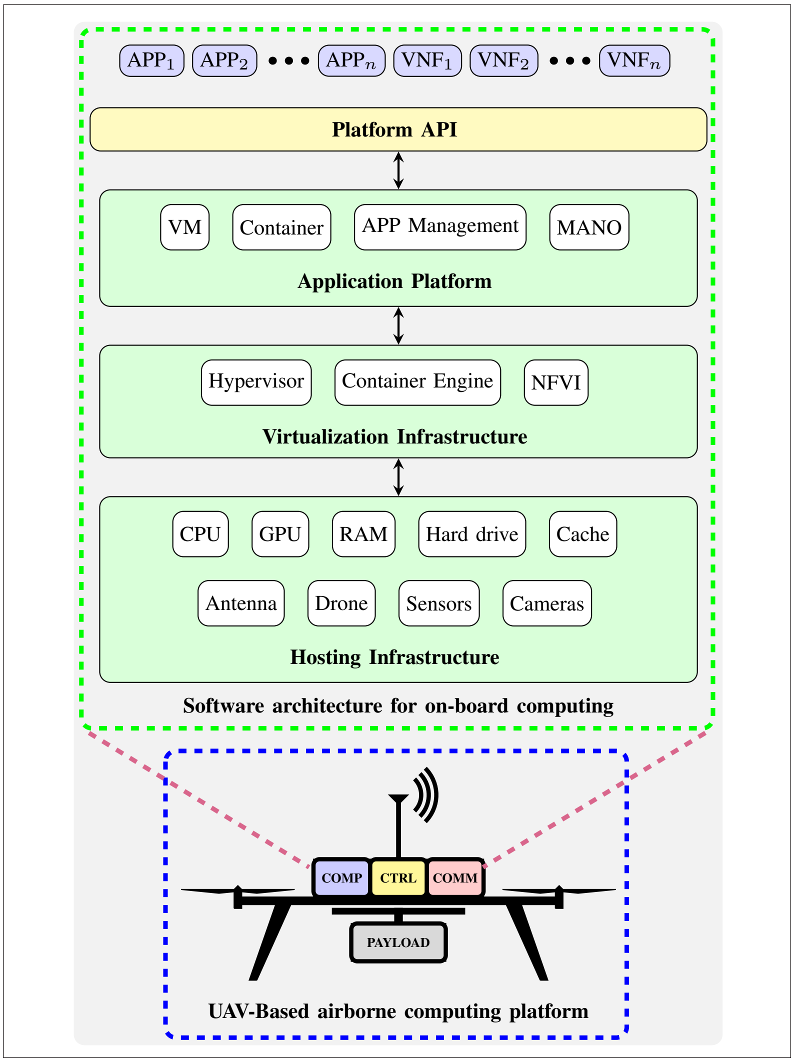

FIGURE 3. A UAV-based airborne computing platform and the software architecture for on-board computing.

Control Unit

The CTRL has three sub-units: autopilot control, antenna control, and cooperative mobility control. In particular, the *autopilot control* sub-unit translates higher-level UAV navigation and control command signals received from the cooperative mobility control sub-unit to motor PWM control signals. This sub-unit allows an individual UAV to maintain stability and perform desired trajectories, based on information feedback from on-board sensors such as GPS and an inertial measurement unit (IMU).

The *antenna control* sub-unit responds to configurations received from the cooperative mobility control sub-unit and the COMM. This sub-unit supports the control of phase-array or directional antennas for directional networking, with the advantage of reduced power consumption, extended distance, and reduced interference. It also allows adaptive antenna gain control for different communication range configurations for both directional and omni-directional communications.

The *cooperative mobility control* sub-unit modifies UAV mobility to address networking and cooperative UAV application needs. When no cooperative functionality is needed, this sub-unit receives ground station/remote pilot commands and directly sends them to the UAV autopilots.

Communication and Networking Unit

This unit supports air-to-air (A2A), air-to-ground (A2G), and ground-to-air (G2A) communication needs. We use a commercial off-the-shelf (COTS) WiFi access point to provide A2G/G2A communications, and a COTS WiFi router with directional antenna to achieve A2A communication. In particular, we use the Ubiquiti Nanostation Loco M series (Nanostation: https://www.ubnt.com/airmax/nanostationm), which can provide broadband and long-range communication functionality (e.g., 2.4GHz/5GHz band, directional antenna, legacy IEEE 802.11 protocol, proprietary time-division multiple access (TDMA)-based protocol, and so on).

Besides using WiFi, the UAV can also connect to the ground cellular infrastructure. Moreover, SDR can also be used to support other communication and networking protocols.

Computing and Storage Unit

The COMP not only offers computing and storage capabilities for many computationally intensive tasks, but also supports other units, for example, the real-time path planning for control unit and virtual network functions (VNFs) for communication unit.

By leveraging virtualization technologies, this unit allows users to easily test and/or design their APPs regardless of which operating system (OS) they are built upon. The virtualization also provides powerful resource management capabilities and security support, and permits concurrent execution of multiple APPs.

The architecture of the COMP is illustrated in Fig. 3, which consists of three layers and a platform API to host APPs and VNFs. The *hosting infrastructure layer* contains all hardware resources that can be utilized by users for their designs, including computing (CPU, GPU) and storage (RAM, hard drive, cache) resources, peripheral devices like sensors and cameras, as well as a drone for lifting and mobility and directional antenna for A2A communication. Built upon this layer, the *virtualization infrastructure layer* provides support to virtualize physical resources including computing, storage, memory, applications and network functions. Examples include the hypervisor, container engine, and NFV infrastructure (NFVI), hosting VMs, containers, and NFV management and organization (MANO), respectively. The *application platform layer* manages software and hardware resources, and facilitates users to design their APPs and/or VNFs.

With COMM connecting multiple UAVs and COMP providing virtualized computing and storage resources, the proposed airborne computing platform can function as a cloud to provide cloud services for surrounding mobile users, which is similar to the emerging MEC [13] for cellular network. Such a computing network not only will present the same capabilities as MEC, such as high data-rate and low-latency, but also will have additional attractive advantages. For instance, it will be able to provide on-demand computing services to mobile users anytime and anywhere, even in the absence of communication infrastructure. The computing

UAV function	Type of computing	Performance
Real-time object detection	Deep learning based object detection	0.78 sec to detect objects in a 105 KB image
3D mapping	Image processing based 3D model construction	32 min to reconstruct a 3D model using 77 1.6MB images
Long-range communication	Reinforcement learning based antenna heading control	30 Mb/s data rate at 1 km distance

TABLE 1. A summary of computing tasks and performance results.

and storage capabilities of the proposed platform can be further extended by connecting to the public cloud.

Prototype and Experimental Results

In this section, we present a prototype with strong computing capability based on our platform. Using the prototype, we will discuss three experiments that can demonstrate the potentials of UAV-based airborne computing.

Overview of the Prototype

We now briefly describe the latest prototype [14] we develop based on our airborne computing platform, as shown in Fig. 4. For the quadcopter, we choose DJI Matrice 100 (https://www.dji.com/matrice100) because it is designed for professional developers with build-in battery and adjustable arm torque, and we design an expansion bay to include components for communication and computing. The directional WiFi system, Nanostation Loco M, is used for the A2A communication, for which we design a system to control the heading of the directional antenna.

The prototype uses an NVIDIA Jetson TX2 as the computing unit because it has better performance than other similar products [15], such as Snapdragon (Qualcomm) and Aero (Intel). The TX2 is featured with 256 CUDA cores for GPU processing, four ARM A57 CPU, 8 GB LPDDR4 RAM, and 32 GB eMMC for storage. As shown in Fig. 4, a carrier board is also developed to fit TX2 in the expansion bay of the quadcopter, and to provide external interfaces, including HDMI, UART, micro USB, GPIO, and two camera ports. The schematics and PCB layout are open-source and available at our project website [10].

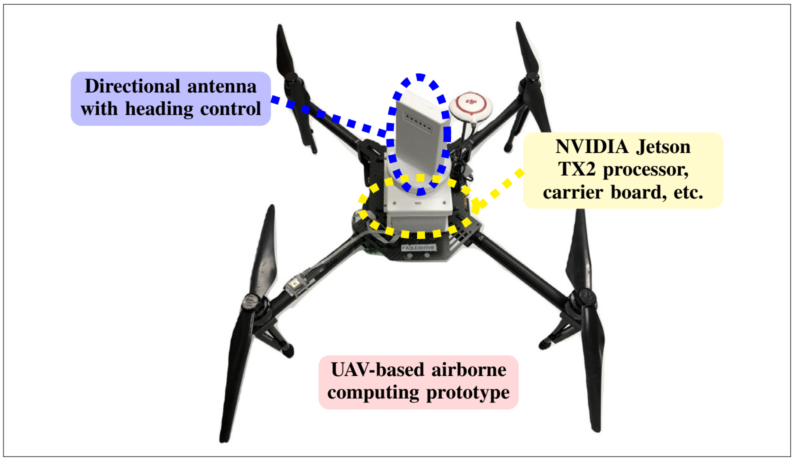

FIGURE 4. A UAV-based airborne computing prototype.

Experimental Results

To verify the proposed airborne computing platform and the prototype, we conduct many interesting experiments. Due to limited space, we explain only a few results next. A summary of these results is shown in Table 1.

Real-Time Object Detection: Object detection, if performed on-board the UAV in real-time, will significantly benefit many applications, including emergency response, trajectory monitoring, infrastructure inspection, and so on. Existing studies on UAV-based object detection process images offline at the ground station. To test the on-board computing capability of our prototype, we implemented the YOLO (https://pjreddie.com/darknet/yolo/), a state-of-the-art real-time object detection system, over the prototype. The results are presented in Fig. 5. Processing a UAV image of size 105 KB takes around 0.78 seconds.

3D Mapping: In land surveys, precision agriculture, and many other applications, 3D maps of target areas are constructed to facilitate decision making. The Structure from Motion (SfM) is a common approach used in these applications to reconstruct 3D models [12]. However, due to its high computational cost, it is performed offline after all images are collected. The proposed airborne computing platform has the potential to bring 3D mapping from offline to online. As a preliminary investigation, we test the efficiency of an SfM-based 3D reconstruction application, called OpenDroneMap (http://opendronemap.org/), on a single UAV prototype. This application takes around 32 minutes to reconstruct the 3D model shown in Fig. 5 from 77 2D UAV images of size 1.6 MB per image. We believe that the performance can be further improved by optimizing the program and by utilizing the computing resources from multiple UAVs.

Long-Distance Broadband Aerial Communication using Directional Antenna Control: In emergency and other applications, long-distance and broadband A2A communication channels need to be established to transmit high-throughput monitoring data streams. The robustness of such a communication channel is challenging to achieve, considering the loss of GPS signals, the imperfect and unknown communication environment, uncertain and varying UAV movement patterns, and various disturbances. We reduce this problem to the communication and control co-design problem of two interacting directions:

- Distributed alignment of directional antennas to achieve a channel with optimized communication performance.
- Utilizing communication signal measurement (such as received signal strength indicator) as additional measurement signals for better antenna control.

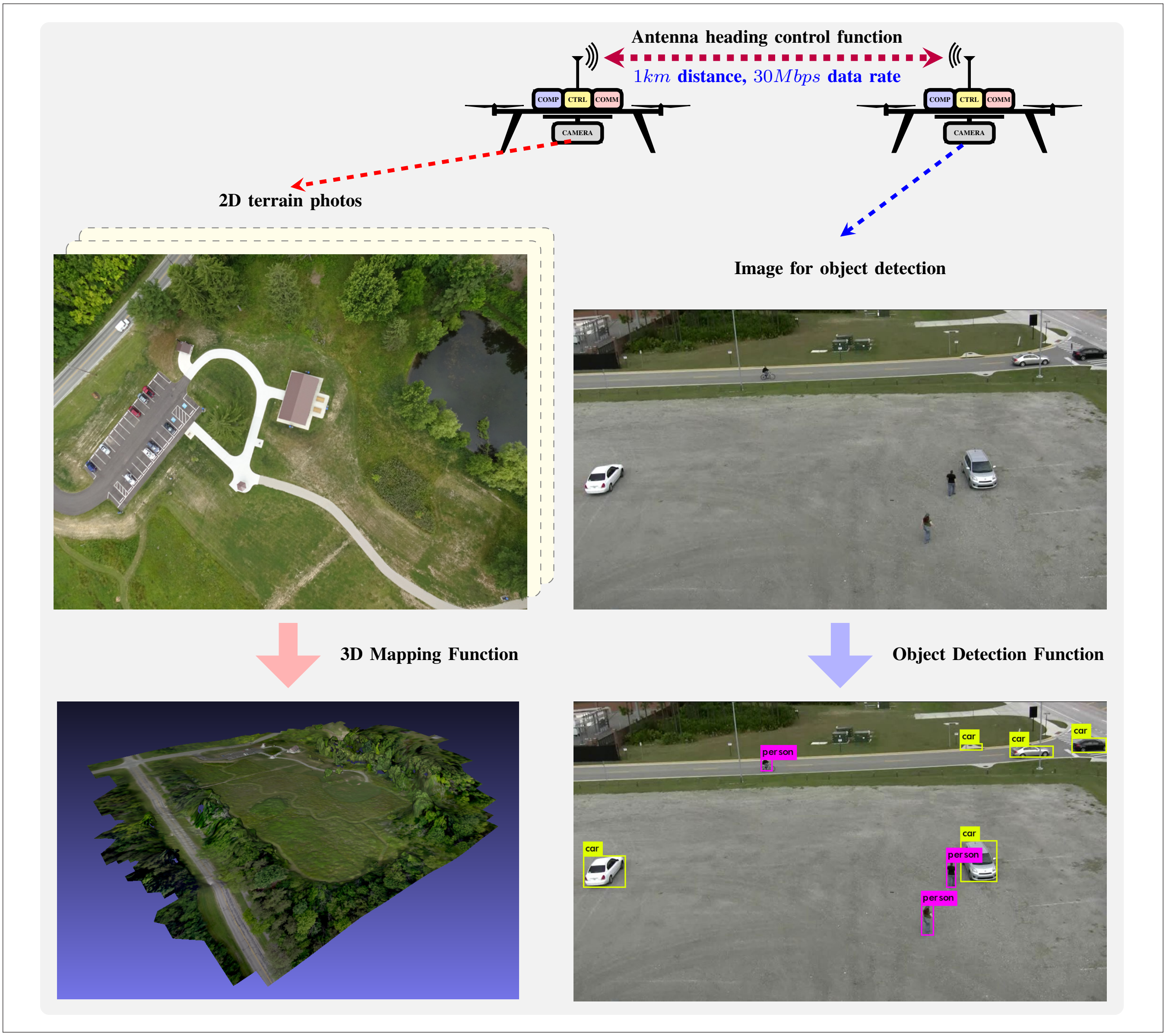

FIGURE 5. Examples of airborne computing: 3D mapping, image-based object detection, and long-range broadband communications.

Advanced UAV computing capabilities make such communication and control co-design functions feasible. Recently, we use the prototype to implement a learning and uncertainty exploited solution that integrates reinforcement learning, uncertainty quantification, stochastic optimal control, and adaptive observer design [14]. The solution demonstrates an improved performance over the GPS-based antenna heading alignment, achieving a communication channel of 30 Mb/s data rate at 1 km distance.

Conclusion

In this article, we have systematically investigated how to develop and utilize on-board computing capabilities to enable UAV-based airborne computing, which can facilitate the design and implementation of future UAV applications. Specifically, we first generalized the motivations to adopt UAV-based airborne computing by using two categories: enhancing UAV functions, and enabling new UAV applications. We then elaborated on several important design guidelines for facilitating UAV-based airborne computing. In particular, we proposed a three-layer reference model to simplify the analysis and design of UAV applications and to help understand how to apply airborne computing. To flexibly support diverse UAV functions and applications, we also proposed and developed an open networked airborne computing platform. Based on the proposed platform, we developed a prototype with powerful processing capability and we also demonstrated insightful experimental results that confirm the applicability of the proposed airborne computing platform.

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Biographies

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