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Mobile Pollution Data Sensing Using UAVs

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ABSTRACT

Nowadays, the impact of global warming is causing societies to become more aware and responsive to environmental problems. As a result, pollution sensing is gaining more relevance. In order to have a strict control over air quality, the use of mobile sensors is becoming a promising alternative to traditional air quality stations. Mobile sensors allow to easily perform measurements in many different places, thereby offering substantial improvements in terms of the spatial granularity of the data gathered. Pollution monitoring near large industrial areas or in rural areas where transportation facilities are poor or inexistent can complicate the mobile sensing approach. To address this problem, in this paper we propose endowing Unmanned Aerial Vehicles (UAVs) with pollution sensors, allowing them to become autonomous air monitoring stations. The proposed solution has the potential to quickly cover a target region at a low cost, and providing great flexibility.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and embedded systems; C.2.1 [**Computer-Communications Networks**]: Network Architecture and Design—*Wireless communication*

General Terms

Design, Measurement

Keywords

Mobile sensing, multicopters, UAVs, environmental monitoring.

1. INTRODUCTION

The growing influence of pollution in our lives has caused environmental organizations and governmental institutions to prioritize the monitoring of environmental pollutants. To this aim, the European Topic Center on Air Pollution and Climate Change Mitigation (ETC/ACM [1]) brings together 14 European organizations for the analysis and monitoring of climate change. Similarly, the Environmental Protection Agency (EPA [2]) is responsible for tracking the evolution of environmental pollution in the United States. These agencies typically rely on a few professional air quality stations deployed throughout the countries; however, the results provided have a low spatial resolution, being only representative on a limited area near those stations.

Recently, different proposals have attempted to improve the spatial resolution of air quality measurements. Authors such as Adam et al. [3] have used statistical techniques to analyze ozone levels in the city of Quebec. Cheng et al. [7] relied on crowdsensing to propose a system to monitor the concentrations of PM2.5 (particulate matter smaller than 2.5 microns). Other authors have instead relied on mobile sensors. For instance, Liu et al. [16] have relied on mobility to analyze ozone levels in the city of Toronto. Other projects like [6] measured the environmental pollution in the city of Belgrade, Serbia, by relying on Waspmote sensors installed in the public transport system. Finally, Hu et al. [12] relied on a vehicular ad-hoc network to monitor different environmental parameters.

The techniques adopted by the aforementioned authors are mostly applicable to urban areas, where different mobility alternatives are available. However, in rural areas, mobility options are quite more limited. In addition, air quality monitoring is also relevant not only for the people living in these areas, but also because it directly affects crops, animals and insects. For example, McFrederick et al. [17] showed how air pollution undermines the essential process of pollination by interfering with the ability of bees and other insects to follow the scent of flowers to their source. Thus, different solutions for measuring air quality should be sought for such environments.

Our project proposes the use of UAVs, specifically of the multicopter type, as an efficient solution for quickly and easily monitoring air quality in any region where ground mobility is a poor option. To meet the proposed goal, we plan mounting a computing unit endowed with pollution sensors on the UAV to create a flying air quality station. Our solution allows programming the UAV by defining the target region to monitor using a smartphone. The UAV then flies autonomously throughout the target area and returns with the desired data. Again using a smartphone, data is retrieved from the UAV and uploaded to a server for storage and analysis.

The remainder of this paper is organized as follows: in the next section we refer to some related works addressing UAV-based sensing. An overview of the proposed solution and methodology is presented in section 3. Section 4 offers some implementation details by describing the hardware used. Finally, in section 5, we present our conclusions along with some guidelines for future work.

2. RELATED WORKS

UAV-based solutions have experienced a very substancial increase in the last decade, especially in the past five years. Back in 2004, NASA experts defined a wide set of civil applications for UAVs [9], highlighting their potential in the near future in areas such as commercial, Earth Sciences, national security, and land management. This preliminary report was ratified years later by authors such as Hugenholtz et al. [13], who explained how the use of UAVs can revolutionize research methods in the fields of Earth Sciences and remote sensing.

If we focus on the specific area of quadrotor multicopters, authors like Gupte et al. [11] and Colomina y Molina [8] consider that, given their high maneuverability, compactness and ease of use, different applications for these devices are being found in areas such as civil engineering, search and rescue, emergency response, national security, military surveillance, border patrol and surveillance, as well as in other areas such as Earth Sciences, where they can be used to study climate change, glacier dynamics, volcanic activity, or for atmospheric sampling, among others.

In our case, we are more interested in atmospheric sampling to measure air pollution levels. In this research area, Anderson and Gaston [4] highlight the applicability of UAVs in the field of ecology, emphasizing that the spatial and temporal resolutions of the data obtained by traditional methods often do not adapt well to the requirements of local ecological research. Furthermore, when flying at low altitudes and speeds, the use of UAVs offers new opportunities in terms of ecological phenomena measurements by enabling the delivery of data with a finer spatial resolution. In fact, authors such as Zhang and Kovacs [19] explain how the images taken by small UAVs are becoming an alternative to high resolution satellite images, which are much more expensive, to study the variations in crop and soil conditions. Specifically, the use of UAVs is considered a good alternative given its low cost of operation in environmental monitoring, its high spatial and temporal resolution, and its high flexibility in the scheduling of image acquisitions. A good example of this use can be found in the work of Bellvert et al. [5], which shows how, by using a multicopter equipped with a thermal camera, it was possible to obtain a very precise map of water levels in a vineyard, thereby achieving significant advances in the field of precision agriculture.

Regarding the use of UAVs to measure air pollutants, most efforts focused on measuring ozone levels. However, previous works mainly focused on troposphere measurements, and not on land levels where ozone has a negative impact on health. One of the few works on land-level ozone measurements is [14], where an UAV equipped with ozone sensors is able to cover a wide area in an automated manner. Although the authors seek to make land measurements, this approach differs from ours due to the use of a large-sized aircraft that cannot fly at low altitudes, and therefore the values obtained are not as representative in terms of impact on human health. In addition, the associated costs and operational requirements far exceed those of the proposed solution.

Overall, previous studies clearly show that, so far, efforts in terms of sensing platforms have focused mainly on large sized UAVs such as planes or gliders. Our project differs from others by seeking a multicopter-based sensing platform that is open, low cost, with minimum operational requirements, capable of integrating different types of sensors (including ozone), with a secure and versatile communications system, and connected to the cloud for online data analysis. Thus, it may be used by businesses or users with much more limited resources compared to previous cases, where its use was typically limited to government entities.

3. METHODOLOGY AND PROPOSED ARCHITECTURE

To achieve the desired solution, the proposed methodology consists of: (i) clearly defining the design requirements of the target solution; (ii) proposing a high-level overview of the global system architecture; (iii) defining the desired information flow in the scope of the proposed architecture; and (iv) developing an initial prototype meeting all previous requirements and conditions.

3.1 Design requirements

Req. 1: Open multicopter design.

Regarding the multicopter design, we seek an open platform that is easily scalable and reusable by other researchers, and whose cost is reduced. To achieve this objective, the different components used to manufacture the multicopter should be standard components easily found in the market, and that are consistent with the ”open-source” philosophy. This will allow any researcher the modification or replacement of any multicopter component without a negative impact on the overall performance of the device. To achieve this goal the following strategy is proposed: (i) Basic mul-

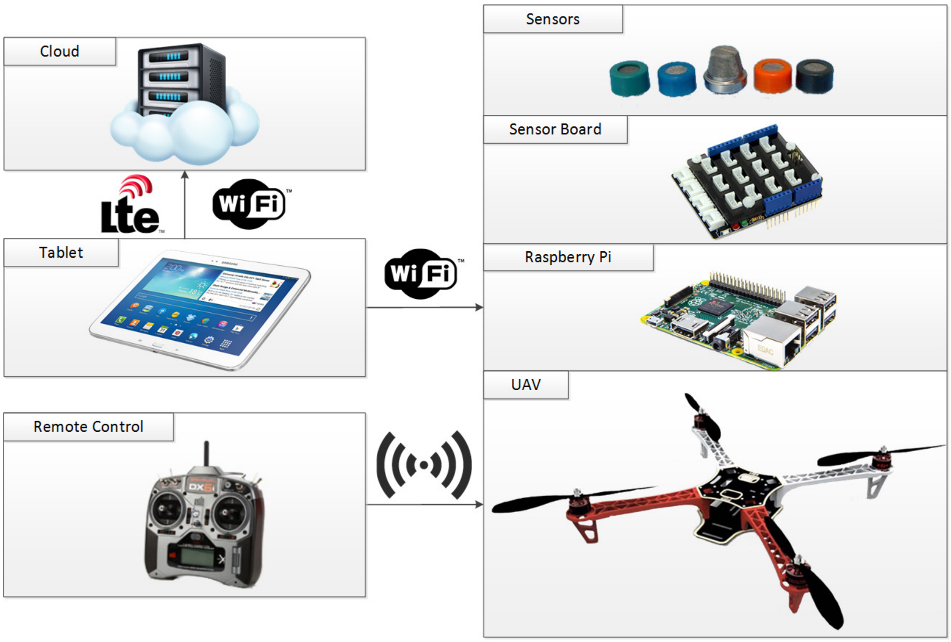

Figure 1: Architecture overview.

ticopter components such as the frame, engines, propellers, electronic speed controllers (ESC) and batteries shall be chosen among models available in the market, easily accessible, and avoiding expensive elements. (ii) The flight controller should be open to possible modifications, and have a serial communications interface following a well-known protocol. (iii) An element offering high-accuracy GPS and compass is required for navigation, and it should be fully compatible with the flight controller. These elements are particularly important to allow the controller to know the location, speed and altitude of the device at any time, and also to fly to predefined positions autonomously. (iv) The remote control used should be universal to allow adapting it to any type of multicopter, programmable to associate different functions to each of the controls dynamically, while integrating aspects such as telemetry on the same radio frequency link.

Req. 2: Integration of an embedded system to provide intelligence to the multicopter.
In order to perform additional tasks not related to flight and navigation, the existing multicopter hardware should be extended through an embedded, low-power device that is able to operate as a fully-featured computer in practical terms. Preferably, it should support the Linux operating system along with all associated tools to provide a platform that is well known and widely used by the open source research community. This embedded system should be linked to the flight controller to manage flights.

Req. 3: Integration of a complete communications system.
The communications system of an UAV is especially critical considering that any failure can cause losing the control of the device, usually resulting in it being crashed or become lost. For this reason, the communications systems adopted should be resilient against attacks, and so its design should target security and robustness.

To allow the UAV being controlled by mobile devices such as smartphones or tablets, it should act as a wireless access point, creating a secure wireless network to which these mobile devices can connect to in order to control the UAV remotely. This network will be complemented by the UAV's native communications system, including remote control and wireless telemetry.

Req. 4: Integration of pollution monitoring sensors.
The multicopter should include different types of sensors including temperature, humidity, and different pollutants such as ozone, carbon monoxide and nitrogen oxides, among others. These sensors should preferably be connected to the embedded system available in the multicopter.

Req. 5: Cloud-based storage, processing and display of collected data.
The data collected by the UAV should be retrieved by a mobile terminal and uploaded to the cloud, where they will be stored along with temporal and geographical information. The server is responsible for data processing tasks such as performing linear unbiased estimations, statistical processes commonly referred to as ordinary Kriging, and cartographic visualization of the data through color maps. This will allow, for example, studying the pollutant levels in a given area at different times, on different days, and at different altitudes.

3.2 Proposed architecture

To meet the requirements defined in the previous section, we propose the architecture shown in Figure 1, which has seven physical elements: (i) an open source multicopter (UAV), (ii) an embedded system based on Raspberry Pi [10], (iii) a GrovePi sensor board [15], (iv) several low-end air pollution sensors, (v) a Android-based device (tablet or smartphone), (vi) a Cloud-based system, and (vii) a remote control.

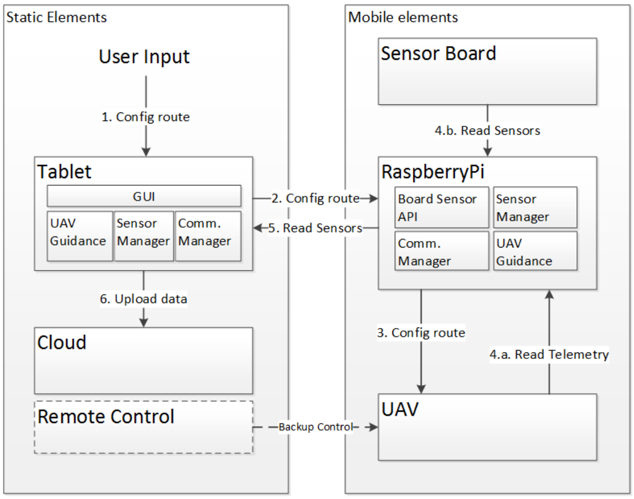

Figure 2: Information flow diagram.

The multicopter (UAV) is deployed with open source and off-the-shelf devices including a Flame Wheel 450 (F450) frame, a Pixhawk 3DR flight controller, and SunnySky X2212-13 motors, among others. By using open standards, it is possible to manage the multicopter using the Raspberry Pi, thereby providing another way for flight guidance.

The Raspberry Pi is the central architectural element in our system. It is mounted directly on the UAV, and connects via WiFi to any Android device while also retrieving pollution information through sensors located in the attached GrovePi Board. Internally, it has three software components: (i) the UAV Guidance component to configure the planned route on the UAV and receive telemetry data, (ii) the Sensor Manager to read pollution data from GrovePi sensors, and (iii) a Communication Manager to handle the wireless communications with the Android-based device and send/receive information.

The Grove Sensor Board (GrovePi) connects directly to the Raspberry Pi GPIO header allowing to add different types of sensors easily through the Grove connector. It has several ports and offers libraries to manage them.

Low-End Sensors are connected to the Grove Sensor Board through Grove connectors, and they can monitor different air pollutants, e.g. CO, CO$_2$, Ozone, PM$_{10}$, PM$_{2.5}$, Air quality, and so forth. They are small, light and cheap.

The Android-based device can be a smartphone or a tablet, and allows users manage the system in a secure manner. It has four software components: (i) the Graphical Interface to configure the UAV's route and manage sensor readings, (ii) the Communications Manager to control the wireless communications via Raspberry Pi, (iii) the UAV Guidance to autonomously manage the UAV's flight, and (iv) the Sensor Manager to manage sensor data received from the GrovePi that are then sent to a Cloud server.

The Cloud-based application processes the collected data with advanced statistics techniques, like Kriging or Cokriging [18], and offers several types of services related to air pollution.

The remote control acts as control backup system. It allows to avoid crashes if the configured route fails, and the UAV is out of control.

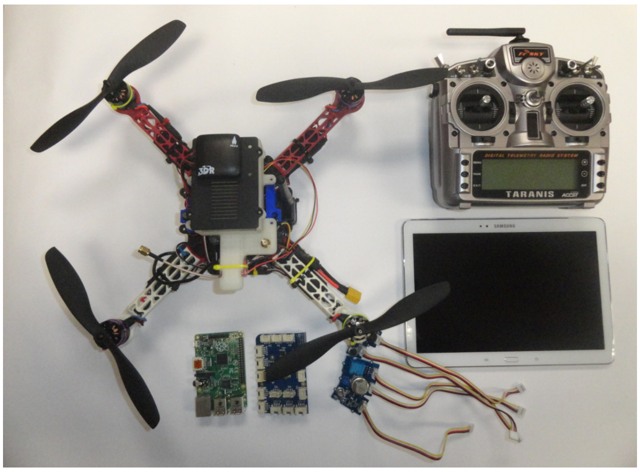

Figure 3: Available hardware devices.

3.3 Expected information flow

Figure 2 illustrates the expected information flow of the proposed prototype.

To start monitoring a particular area, the UAV route should be introduced through the Graphical User Interface (GUI) of the Android-based application (step 1). The user defines different route points, speed, and active sensors. Once the Android device receives the route parameters, it sends all entered settings to the Raspberry Pi (step 2) using the Connection Manager module (via WiFi). The Raspberry Pi then configures the UAV with the received guidance parameters through the UAV Guidance module (step 3).

During the flight, the Raspberry Pi receives telemetry information from the UAV again through the UAV Guidance module (step 4.a), and sensor data from the different sensors via the Sensor Manager module, which in turn relies on the Board Sensor API (step 4.b), storing all received information for future diffusion. If at any time during the flight manual intervention is required, the remote control helps to recover the control over the UAV.

When the UAV returns to the origin, all the collected information is sent to the Android device (step 5) using the Connection Manager module (via WiFi connection). Then, when the smart device has Internet connectivity, either WiFi or Cellular, it sends the collected information to the Cloud-based server via the Sensor Manager module (step 6). Finally, an application running on the cloud analyses the information and offers a detailed report concerning air pollution levels in the target area.

4. PROJECT DETAILS

Currently the project is at an intermediate development stage. Regarding hardware development, it involves the construction of an Open Source UAV, embedding a Raspberry Pi on the UAV, coupling air pollution sensors on the Raspberry Pi, and providing a wireless interface to connect to any Android system. Figure 3 shows the current status of our hardware prototype, showing a fully operational UAV in addition to other elements. The embedding of the Raspberry Pi on the multicopter is pending since it requires creating some parts on a 3D printer and providing a link to the Pixhawk 3DR flight controller. Grove elements, like GrovePi and Grove sensors, are used as an interface between analog air pollution sensors and the Raspberry Pi, and are already operative.

Concerning software components, they are developed on the Raspberry Pi, the Android system, and the Cloud-based application, thereby connecting all hardware components. The Raspberry Pi is the center of our system since it acts as a gateway between the UAV, the sensors, and the Android device. Sensor measurement software was developed in Python and relies on available GrovePi libraries, being also fully operational. Communications with Android devices are also operative, being flight guidance software the only pending element.

The Android system is used mainly as a graphical user interface and a gateway to the Internet; its development is still in an initial stage.

Concerning the cloud-based application, it is fully operational, storing environment pollution levels and analyzing their distribution. It was developed in PHP and runs on an Apache server.

5. CONCLUSIONS AND FUTURE WORK

Professional air quality stations have gained enormous relevance in terms of air pollution and climate change monitoring. However, performing air quality measurements with a high spatial granularity remains nowadays a challenge due to the complexity and costs involved.

In this paper we propose equipping UAVs with pollution sensors to create a low-cost mobile air monitoring station that is especially useful in environments with poor ground accessibility. The envisioned architecture offers simplified management tasks by relying on Android-based mobile terminals to easily define the flight path over the target area, the sensor data to capture, and for sending pollution traces to cloud server for data storage and analysis.

As future work we will complete the proposed prototype and perform test flights to validate our solution.

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