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Design of autonomous smartphone based quadrotor and implementation of navigation and guidance systems,☆,☆☆

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ABSTRACT

This work discusses the design of a novel smartphone-based autopilot for quadrotor aerial platforms and the results of its flight tests. The proposed solution consists of two different layers, a low-level navigation and control layer and a high-level human-robot communication layer. The low-level navigation system uses nonlinear complementary filters for position, velocity and attitude estimation based on low-cost sensors. The structure of the filter allows a straightforward implementation without need of high performance signal processing. A nonlinear flight controller is used for the quadrotor stability and trajectory tracking. This controller demonstrates also the ability of the guidance system in the high-level layer to provide effective waypoint navigation capabilities for the quadrotor drone. The waypoints can be defined remotely using a human-robot interface that is able to receive commands and to send information to a human operator throughout a web-based social network, i.e. *Twitter*. The performances of the proposed solution are evaluated by means of flight tests and are compared to the results derived from a more traditional approach (i.e. PX4 controller) used for quadrotor tracking and control.

1. Introduction

Nowadays the big challenge in the improvement of aerial platforms is not their implementation, but rather the development of inexpensive, upgradeable, reconfigurable, and compact hardware structures and control systems with commercial off-the-shelf (COTS) products [1]. Recent works proposed different approaches aiming to obtain autonomous navigation capabilities of an Unmanned Aerial Vehicle (UAV) using monocular camera [2], Red, Green, Blue and Depth (RGB-D) camera [3], or using multiple cameras approach [4]. Other UAVs were equipped with a laser scanner [5], or a combination between two approaches, *i.e.*, the use of cameras and laser scanners, [6–8]. However, these solutions result in heavy platforms, and they do not provide a way to cut the gap between the use of complex algorithms and its use by an average person for daily applications [9].

Among the developed solutions, some researches are proposing aerial robots based on *Android* smartphones for estimating flight condition data and implementing the control algorithms necessary for performing complex tasks [9–13]. This solution can provide a reduction of the development time and costs because of the integration of different hardware components (*i.e.* flight control system computing unit, dynamics sensors and communication devices) in a commercial product characterized by certified performance and operating life requirements.

The higher computational power Central Processing Unit (CPU), the wide and powerful communication capabilities and the high-quality camera in smartphone allow one the implementation of complex automatic control, guidance and navigation solutions in autonomous flight operations, and in fact, lead to operate the aerial robot in a multi agent network easily [10,14]. Furthermore, the wide and well-structured framework of *Android* Application Programming Interface (API) enhances and simplifies significantly the implementation of the aerial robot functionalities.

The main contribution of this work is the development of a smartphone based quadrotor using custom-built structure and avionics with off-the-shelf motors and batteries. Unlike other works that use additional computer beside the smartphone, the guidance, navigation, and control systems of this drone were implemented inside the smartphone itself based on the information provided by the onboard sensors. The proposed solution was implemented in two different layers, a high-level human-robot communication layer and a low-level navigation and control layer.

The quadrotor concept here described is used to develop the

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preliminary implementation of highly automated drone with the capability to share information and receive commands in multi-agent system. Such characteristics are very powerful capability in different operating scenarios, in which low-altitude drones, like quadrotors, can be effectively employed to speed-up operations, *i.e.* search & rescue and security & monitoring applications [15–18]. In order to perform this control capability, it was decided to implement for the drone the capability to connect to a *Twitter* account. This account receives commands from different agents could be placed at a much greater distance comparing to other typical platforms and allows both autonomous navigation and control of the quadrotor [19]. The agents commands are published on this account and the drone itself can upload the acquired data. A demonstration of this concept is given in this work considering a single human agent communicating with the drone *Twitter* account in order to control its flight.

Both localization and planning in robot navigation requires good estimation of the robot's current position and a position of a target location [20]. Therefore, the work in this paper proposes an integrated filtering approach to provide high rate estimates for vehicle's velocity, position, orientation components based on nonlinear complementary filters inspired by the works described in [21–23]. Unlike the complex filtering approaches using Kalman techniques [10,24–29], the simple structure of complementary filters allows handy and direct implementation without the need of high performance signal processing in limited computational resources. The gains in the adopted filters were computed offline using an auxiliary design system to achieve robustness in most flight conditions [11]

Another strong innovation aspect in using smartphone is the touch-screen interface that is currently exploited in this project to provide different human-machine interface functionalities. First of all, in the current implementation of this project, this screen is used from the operator before to start the quadrotor flight to set the autonomous flight mission profile and generate the set of waypoints to be reached during the flight. Then a dedicated application was developed to calibrate the inertial sensors whenever the quadrotor mission is launched in a different environment. An utility was finally implemented on the graphical user interface for tuning of the control system parameters.

An important issue that must be mentioned here regarding *Android* OS is its real-time capabilities. One of the implementation directions that is adopted in order to make Android possible to be used in Open Real-Time environments is reported in [30]. In this approach, it was possible to have bounded memory management, real-time scheduling, and better synchronization mechanism within the Virtual Machine (VM). For task scheduling, the real-time VM was capable of mapping each task natively on the operating system where it will be scheduled.

This paper is organized as follows. The quadrotor structure and the hardware architecture are described in Section 2. Then a description of the ground control station and the established communications are explained in Section 3. The real-time implementation of the quadrotor's App is illustrated in Section 4 and the overall architecture of the GNC system is described in Section 5. Section 6 provides the adopted navigation system using nonlinear complementary filters. Then the quadrotor model and the nonlinear attitude and position controller are introduced in Section 7. The reactive supervisory system and the guidance system are then introduced in Section 8. Then the experimental tests used to demonstrate the quadrotor performances in-door and out-door flights are discussed in Section 9. Finally, some conclusive remarks on the work are given in Section 10.

2. Quadrotor architecture

This section discusses the architecture of the smartphone based quadrotor, points out its features and compares the smartphone based approach with traditional controllers used for quadrotor drones.

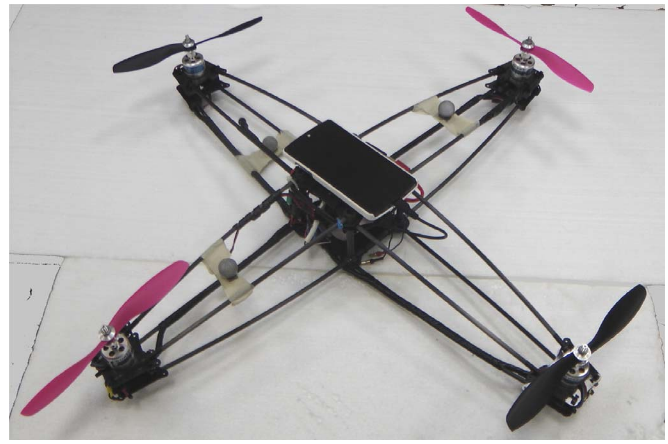

Fig. 1. The smartphone quadrotor prototype.

Table 1
The quadrotor components and related weights.

Part	Specifications	Weight (gram)
Structure	Carbon fiber tubular structure (tubes diameter 600 mm)	250
4 × BLDC Motors	DualSky XM400 Kv:1180*RPM*/*V*130*W*	4 × 50
4 × *APC* propellers	10" × 4.5"	4 × 10
Li-Po battery	3 cells 11.1 *V* 2650 mAh	225
4 × ESC	20 *A* (30 Max)	4 × 15
Smartphone	Nexus 5	130
IOIO-OTG board	mini-USB connection	50
Power module	outputs 5.3*V*, 2.25*A*	15
Wires and screws	–	170
Total weight		1150

2.1. Smartphone based quadrotor

The quadrotor drone developed in this work is shown in Fig. 1 and the list of its hardware components and related weights are summarized in Table 1. It is based on a *Google Nexus 5* smartphone [31] acting as computing unit for the flight control system. Its airframe is a carbon fiber tubular structure providing a light-weight and high-stiffness mechanical layout. The quadrotor has a total weight of 1150 g including the smartphone and the total maximum thrust generated by the four rotors is approximately 2.5 kg.

The motors in the vehicle are pretty powerful. Therefore imbalances in propellers and high speed rotations can generate a lot of vibrations that increase the noise affecting the measurements provided by the inertial sensors. These vibrations are an important issue that should be taken in account in the structure design. In fact, this noise affects the accuracy of the quadrotor state variables estimation provided by the quadrotor autopilot. This is the reason why the smartphone and its sensors are isolated from the quadrotor structure vibrations with the a well designed damping system.

The smartphone is built around *Qualcomm Snapdragon 800* 2.26 GHz quad-core processor that provides a much higher computational power than commercial control boards for civil UAV (*e.g.* PixHawk [32] and Naza [33]) according to the discussion given in [34]. An *Adreno 330* 450 Mhz Graphics Processing Unit (GPU) is then used to increase the smartphone computational speed. The *Broadcom BCM4339 5G Wi-Fi combo chip* is then used for standard wireless Local Area Network (LAN) communication. The inertial sensors in smartphone include a three-axis gyrometers, a three-axis accelerometer and a three-axis magnetometer (compass). This sensors set provides sufficient bandwidth to accurately capture the dynamics of the quadrotor. The smartphone is equipped also with a low-frequency GPS receiver, and low-frequency pressure