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Indoor low-cost localization system for controlling aerial robots

Milton C.P. Santos[a,*], Lucas V. Santana[b], Alexandre S. Brandão[c], Mário Sarcinelli-Filho[d], Ricardo Carelli[e]

[a] Federal Institute of Espírito Santo, Rodovia ES-080, Km 93, São João de Petrópolis, Santa Teresa - ES 29660-000, Brazil
[b] Federal Institute of Espírito Santo, Av. Filogónio Peixoto, 2220 - Aviso, Linhares - ES 29901-291, Brazil
[c] Federal University of Viçosa, Viçosa - Minas Gerais 36570-900, Brazil
[d] Department of Electrical Engineering, Federal University of Espírito Santo (UFES), Av. Fernando Ferrari, 514, 29075-910 Vitória - ES, Brazil
[e] Institute of Automatics (INAUT), National University of San Juan (UNSJ), Av. San Martin Oeste 1109, 5400 San Juan, Argentina

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ABSTRACT

This paper presents a low-cost localization system to guide an Unmanned Aerial Vehicle (UAV) in indoor flights, considering an environment with invariant texture and typical indoor illumination. The first contribution of the paper is the proposal of a system to estimate the position and orientation of the UAV, through a multi-sensor fusion scheme, dealing with data provided by a RGB-D sensor, an inertial measurement unit (IMU), an ultrasonic sensor and optical flow-based velocity estimates. A second contribution of the paper is the proposal of a high-level control system to guide the UAV in path-following tasks, involving two controllers: a kinematic one, responsible for generating reference velocities for the vehicle, and a PD one, responsible for tracking such reference velocities, thus characterizing a cascade controller. Experiments with such a localization and control systems, during which abrupt disturbances are applied, were carried out to check the effectiveness of the developed capture and control systems, whose results validate the proposed framework.

1. Introduction

In the last few years there have been an increasing development of rotorcraft Unmanned Aerial Vehicles (UAV), motivated by their capability to fly in indoor and outdoor environments (Ferrick, Fish, Venator, & Lee, 2012) and their advantages over other flying machines, such as the possibility of to take off and land in the vertical, to hover, to move ahead and aside, and to change its direction of flight and to stop their motion abruptly (Pedro Castillo Garcia & Lozano, 2005). These features allow rotorcraft machines, mainly the smaller ones, to fly in indoor environments, such as offices and labs (Tournier, Valenti, How, & Feron, 2006). Another meaningful aspect associated to rotorcraft UAVs, still in terms of navigation, is that they are more versatile than ground vehicles, for making possible to get a global view of the workspace, what is fundamental in tasks like surveillance or inspection, for instance.

Traditional navigation systems based on wireless-transmitted information, such as Global Positioning System (GPS), are widely used to ensure a self-positioning task. However, indoor environments remain inaccessible to external positioning systems, limiting the navigation ability of the satellite-based GPS systems (Flores Colunga, Zhuo, Lozano, & Castillo, 2014). Most indoor applications use commercially available devices with infrared light to localize the UAV through computer vision, as the VICON system (http://www.vicon.com) and the CODA system (http://www.codamotion.com). The ETH Zurich Flying Machine Arena is an example of an indoor research space built specifically for the study of autonomous systems and aerial robotics (Lupashin, Schollig, Hehn, & D'Andrea, 2011; Lupashin et al., 2014). There a VICON system generates position data for small quadrotors accomplishing different tasks (Hehn & D'Andrea, 2011; Hehn, Ritz, & D'Andrea, 2012; Lupashin & D'Andrea, 2011; Schoellig, Siegel, Augugliaro, & D'Andrea, 2014; Willmann et al., 2012). Another famous example is the GRASP Laboratory (Michael, Mellinger, Lindsey, & Kumar, 2010), where quadrotors fly precisely through narrow gaps, automatically perch on inverted surfaces, and execute aggressive formation flights (Mellinger, Michael, & Kumar, 2014; Turpin, Michael, & Kumar, 2012).

However, the VICON system can be much expensive. An alternative is to use visual markers, such as in Santana, Brandão, and Sarcinelli-Filho (2016), where the position and orientation of the UAV are estimated through the extraction of features from images of known markers in the environment, using a camera onboard the UAV. Other

* Corresponding author.
E-mail addresses: milton.santos@ifes.edu.br (M.C.P. Santos), lucas@ifes.edu.br (L.V. Santana), alexandre.brandao@ufv.br (A.S. Brandão), mario.sarcinelli@ufes.br (M. Sarcinelli-Filho), rcarelli@inaut.unsj.edu.ar (R. Carelli).

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studies, in turn, propose similar solutions, although using different camera arrangements, such as monocular vision (Weiss et al., 2013), stereo vision (Acgtelik, Bachrach, He, Prentice, & Roy, 2009) and RGB-D (Flores Colunga et al., 2014; Huang et al., 2011). Despite being low-cost solutions, these equipments have disadvantages, such as the sensitivity to light changes, the high processing cost, and the requirement of external markers.

An interesting approach was recently adopted in Huang et al. (2011), where a method that performs the fusion of data provided by a RGB camera with a depth map is proposed for mapping tasks. Following this approach, in order to reduce costs and not to require markers in the environment, this paper proposes a new low-cost localization platform to carry out experiments with UAVs in indoor environments.

The first results with this platform are in Santos, Santana, Martins, Brandão, and Sarcinelli-Filho (2015), where it is presented a method based on polynomial functions to localize the UAV in the environment. In such work a simple algorithm to guide the UAV to accomplish path-following tasks is also proposed, based on a waypoint navigation approach. An imitation is that the UAV orientation is not controlled. As a sequence of such work, after detecting the UAV and estimating its 3D position (x, y, z), a strategy for obstacle avoidance was developed, as well as a method to allow tracking the UAV, using position provided by a fusion filter (Santos, Santana, Brandao, & Sarcinelli-Filho, 2015).

This paper presents the final version of the aforementioned low cost platform, discussing all the details of the proposed localization system. It is shown how to get the UAV states (position and orientation), through a fusion scheme that considers data provided by different sensors, as well as how the model used to design a controller to guide the UAV (feedback linearization through inverse dynamics is the control strategy adopted) is identified. An algorithm to supervise the orientation of the vehicle is also presented, and a solution for the orientation drift is proposed. Besides this, a comparison is made between the proposed UAV detection algorithm and the method of Hu (1962). With this new platform to localize the UAV, it is possible to perform different tasks, considering different applications, and validate controllers as well. Thus, the first meaningful contribution of this article is the development of a low-cost, simple and efficient platform to estimate the UAV localization in an indoor environment, independently of illumination and visual markers.

In the sequel, the paper also proposes a controller to guide an UAV in path-following tasks, which is validated using the proposed localization framework. Regarding a path-following controller, the main objective is to make the "cross-track" error (ρ), the distance from the UAV to the path, and the heading error $|\psi_d - \psi|$ ($|\cdot|$ means absolute value) as close to zero as possible (to get $\rho \to 0$ and $|\psi_d - \psi| \to 0$ along the navigation). Nonlinear control techniques are popular for path-following applications (Sujit, Saripalli, & Sousa, 2014). In this case, good estimates of the position (x, y, z) and orientation (ψ) of the UAV are essential to guide it along the desired path (Chen, Chang, & Agate, 2013). A current problem in the development of this specific navigation strategy is that the robot should keep a fixed velocity along the path being followed, with the possibility of a null velocity, to allow the UAV to hover over the path being followed, if desired. Thus, path-following can be a smooth convergent task (Aguiar, Hespanha, & Kokotovic, 2005), ideal for applications involving capturing images of the working environment, for instance.

However, when the path-following controllers are based only on the robot kinematics, changes in the velocity of the vehicle is either not allowed (Rhee, Park, & Ryoo, 2010) or limited (Nelson, Barber, McLain, & Beard, 2007; Park, Deyst, & How, 2007). Therefore, the control objective, namely to keep the path error close to zero when the vehicle travels at a fixed velocity along the path, is not well accomplished (the velocity change demands a nonzero acceleration time, thus resulting in a difference between the velocity commanded by the kinematic controller and the velocity effectively developed by the UAV). In such a context, this paper proposes to add a simple dynamic controller in cascade with the kinematic one, to guide the UAV to perform path-following tasks as well as positioning tasks (in this case by setting the velocity of the vehicle to zero), which is its second meaningful contribution. Notice that this second class of tasks is perfectly compatible with rotorcraft UAVs, which are able to hover in a predefined 3D position.

Therefore, this paper proposes an indoor and low-cost platform to validate controllers based on different navigation strategies. Such platform includes a RGB-D system, which detects and estimates the posture and position of different types of objects. Commonly, this detection is performed using Hu (1962) moments. However, a new approach based on polynomial functions is here proposed. Both approaches are compared, in the specific case of detecting a Parrot Ar.Drone 2.0 quadrotor. After estimating the UAV position and orientation, based on the data provided by the RGB-D sensor, a multi-sensor fusion approach, using the information provided by the RGB-D system and the information provided by the sensors onboard the vehicle, is proposed, to decrease possible drift errors embedded in the measurements provided by inertial navigation systems (INS). Such a data fusion scheme is implemented in two steps. The first one is performed by the autopilot onboard the Parrot Ar.Drone 2.0, and the data outputted is the fusion of the information provided by an IMU, an ultrasonic sensor that gives information about the altitude of the vehicle and velocity estimates in the directions x and y. The second data fusion step involves the fusion of the result of the first data fusion step and the information provided by the RGB-D sensor. In addition, a cascade controller is designed to execute two navigation tasks, namely path-following and positioning.

To address such topics, the paper is hereinafter split as follows: Section 2 presents the AR.Drone quadrotor, the UAV used in this work, whereas Section 3 presents the indoor platform, showing how to detect the UAV and the necessary conversions to calculate its 3D position and orientation. The method designed to perform the sensory data fusion to improve the estimation of the position and velocities of the UAV is shown in Section 4. In the sequel, Section 5 presents the nonlinear controller proposed to control the position of the vehicle, using the sensory data delivered by the estimation subsystem proposed. Finally, experimental results obtained using the proposed data capture and position-estimate subsystem and the proposed controller in connection with a Parrot Ar.Drone 2.0 Power Edition® quadrotor are presented in Section 6, which is followed by some conclusions.

2. The AR.Drone quadrotor

The experimental rotorcraft machine chosen to validate our proposals is the Parrot AR.Drone 2.0 Power Edition quadrotor, which is shown in Fig. 1.

It is an autonomous aerial vehicle commercialized as a hi-tech toy,

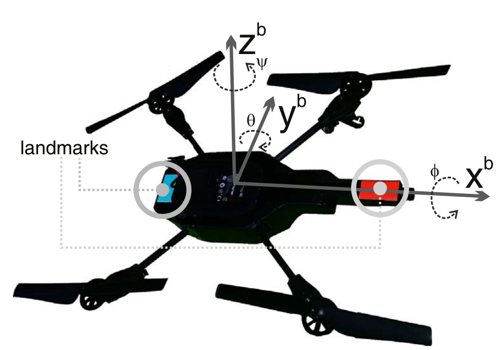

Fig. 1. The AR.Drone 2.0 Power Edition quadrotor and the body coordinate system $\langle b \rangle$. The visual markers are used to estimate its orientation (ψ). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)