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Contents

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ABSTRACT

This review paper aims to provide an overview of core modeling, control, estimation, and planning concepts and approaches for micro aerial robots of the rotorcraft class. A comprehensive description of a set of methods that enable automated flight control, state estimation in GPS–denied environments, as well as path planning techniques for autonomous exploration is provided, and serves as a holistic point of reference for those interested in the field of unmanned aerial systems. Further discussion for other applications of aerial robots concludes this manuscript.

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Introduction

Autonomous aerial systems have stood at the forefront of robotics research over the last few years, and currently enjoy a continuously expanding range of applications wherein they are actively utilized. Some examples include those of consumer and recreational use (Rao *et al.*, 2016), industrial inspection (Yoder and Scherer, 2016), precision agriculture (Lottes *et al.*, 2017; Liebisch *et al.*, 2017), search and rescue (Balta *et al.*, 2017), security surveillance (Bolkcom, 2004), and more. Recent advances in control, onboard sensing and processing, alongside a set of contributions related to the problems of Simultaneous Localization And Mapping (SLAM) and path planning, have paved the way for aerial robots to become capable of conducting the aforementioned tasks autonomously, reliably, and efficiently. Figure 1.1 presents indicative applications of aerial robots.

The term aerial robots refers to a very large set of flying machines that are characterized by varying levels of autonomy in order to accomplish tasks of differentiated complexity. Historically and within the jargon of the aerospace community, robotic flying systems are commonly referred to as Unmanned Aerial Vehicles (UAVs), while the overall set-up that further consists of the human machine interface and communication components is often called Unmanned Aerial System (UAS). More commonly and due to their military roots,

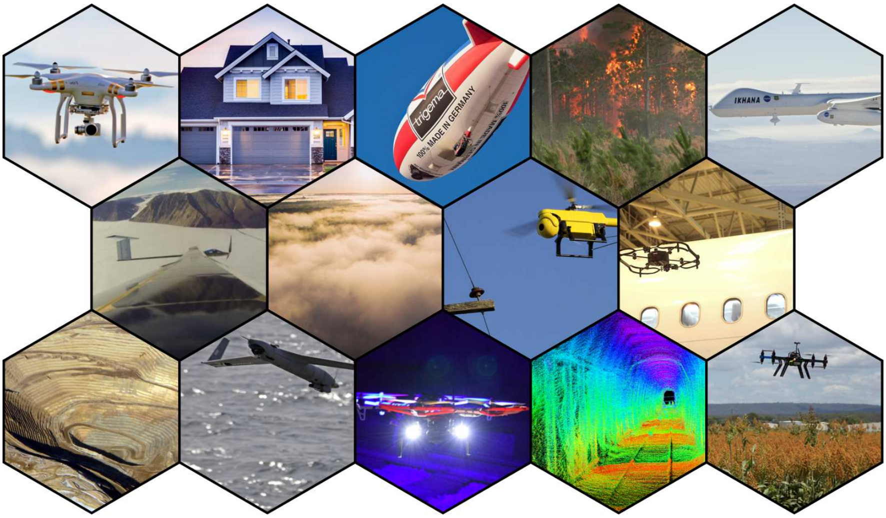

Figure 1.1: Indicative applications of aerial robots, namely (from top–left to bottom–right): a) aerial photography, b) real estate, c) marketing, d) disaster response, e) government use, f) environmental monitoring, g) meteorology, h) infrastructure inspection, i) structural monitoring, j) mine inspection, k) maritime applications, l) subterranean exploration, m) mapping, and n) precision agriculture.

UAVs are also called drones - the term that has largely dominated how such systems are referred to by the general public. In this chapter we will employ the terms “aerial robots” and “Micro Aerial Vehicles (MAVs)” in order to emphasize on the increasingly advanced levels of autonomy and the small scale of the systems discussed. Aerial robots are at the cutting edge of robotics research and integrate breakthrough contributions in the fields of system design (Oettershagen *et al.*, 2016), state estimation and perception (Leutenegger *et al.*, 2015b), control systems (Mahony *et al.*, 2012), path planning and decision making (Popović *et al.*, 2017) and more. The American Institute of Aeronautics and Astronautics (AIAA) provides the following generic definition of a UAV (Leutenegger *et al.*, 2016) as : *an aircraft which is designed or modified, not to carry a human pilot and is operated through electronic input initiated by the flight controller or by an onboard autonomous flight management control system that does require flight controller intervention.*

Following the general trends in the robotics community, aerial robots tend to become increasingly more complex as a result of the effort to enable advanced decision making and autonomy based on onboard perception of the environment and using only roughly and abstractly defined mission goals. Figure 1.2 presents an indicative modern application of aerial robots, that of autonomous subterranean exploration on the basis of multi-modal sensor fusion and intelligent planning.

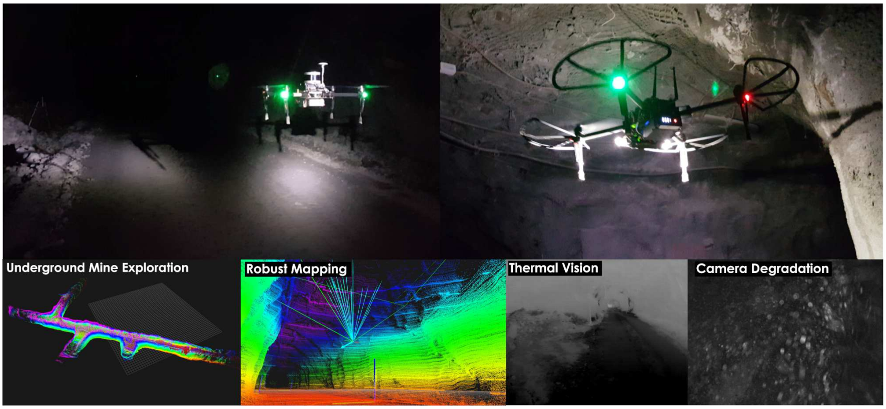

Figure 1.2: Indicative modern application of aerial robots that requires the harmonic coordination of control, perception and planning loops: subterranean exploration inside sensing-degraded and geometrically constrained drift-, raiser- and cave-like environments.

Aerial robots possess the unique and critical capability to gently fly over terrain that other robots struggle to roll, crawl or walk over or swim through. This explains their wide adoption and the steadily rising set of applications within which they find use. However, MAVs correspond to particularly complex systems especially due to the imposed constraints in payload and endurance, alongside their often agile and complex dynamics. Therefore, the design process of autonomous aerial robots requires increased attention and thorough selection of one or more existing and proven or novel flying concepts, electronic components, and algorithms. The design engineer must assess specific optimization challenges and trade–offs relevant to the mission profile and iteratively make optimal design choices while treating the system as a whole.

In this chapter, we review a set of fundamental topics in relation to autonomous aerial robots, namely a) modeling of flight dynamics, b) model–based control, c) state estimation and localization for GPS–denied navigation, as well as d) path planning for autonomous exploration and mapping. Further discussion on other applications and research fields of aerial robots follows. The focus of the chapter is on small rotorcraft–type systems and particularly on multirotors. The reason to constrain the discussion to these types of systems is related to their dominant position in a very large variety of critical applications and their prominence especially within the civilian domain. The main equations of flight are derived followed by an explanation of how the principles of model predictive control can be utilized for the purposes of robust flight of such Micro Aerial Vehicles and improve upon traditional control approaches. Then, a case of GPS–denied localization that relies on the fusion of vision and IMU information is detailed, followed by an elaboration on how sampling–based planning principles can be applied for the purposes of collision-free navigation and autonomous exploration. All sections are preceded with an overview of the state of the art. By the end of the chapter the reader will be able to understand these core functionality loops for autonomous aerial robots and spring–board further investigations within this exciting field.

Section 2 provides a very brief historical overview for UAVs. Sections 3 and 4 detail the aspects of modeling and control for multirotor micro aerial vehicles. Subsequently, Section 5 overviews the problem of GPS–denied localization, followed by Section 6 that describes methods for autonomous path planning. Section 7 overviews further applications and research fields for aerial robotics. Finally, conclusions are drawn in Section 8.

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