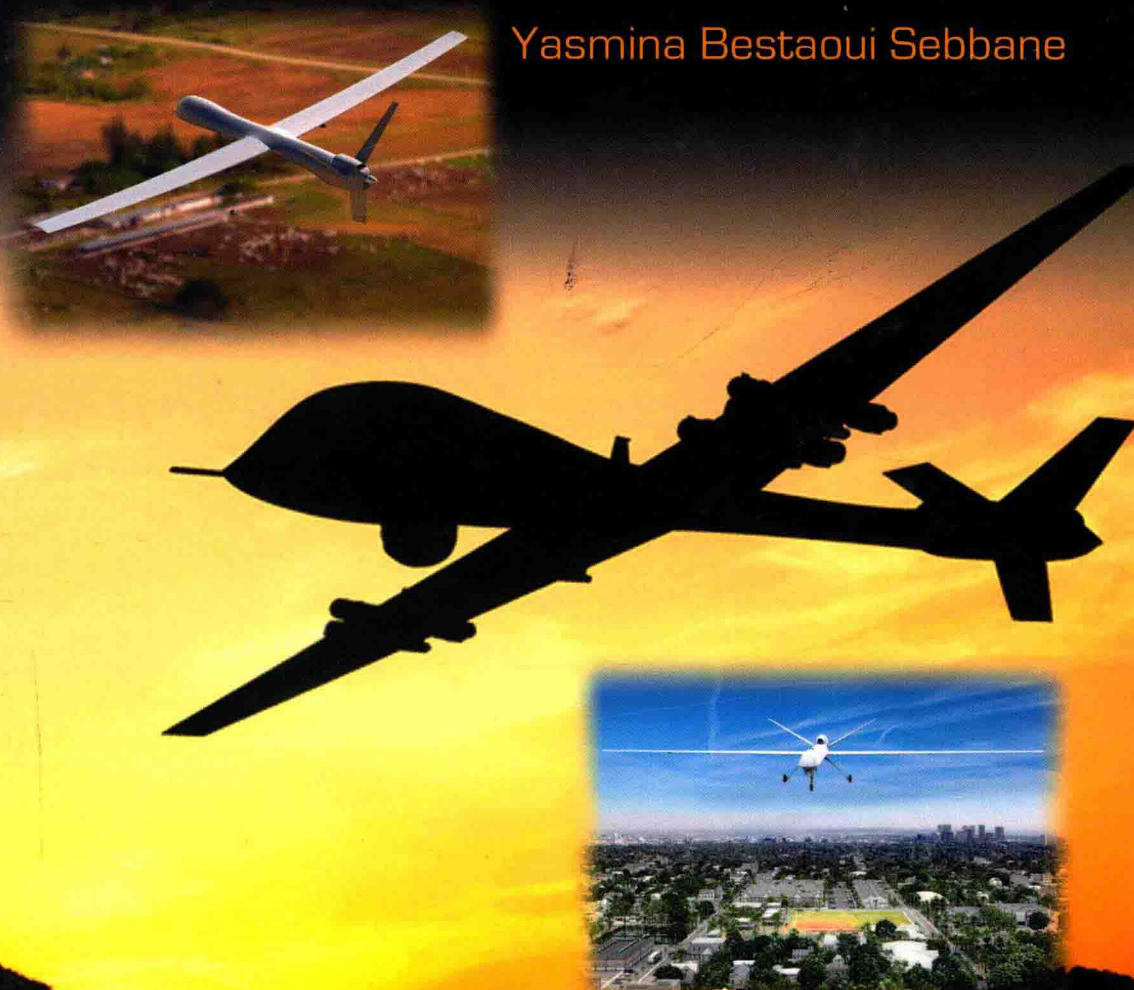
SMART AUTONOMOUS AIRCRAFT

Flight Control and Planning for UAV

Yasmina Bestaoui Sebbane



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Dedication

To my family

Preface

Smart autonomous aircraft have become the new focus of academic research and education, due to their important application potential. They offer new opportunities to perform autonomous missions in field services and tasks such as search and rescue, observation and mapping, emergency and fire fighting, hurricane management.

A smart autonomous aircraft does not require any human intervention during its mission. Without a pilot onboard, an aircraft either must be controlled from the ground by a radio-control ground pilot or it must have its own intelligence to fly autonomously. Autonomy is defined as the ability of a system to sense, communicate, plan, make decisions and act without human intervention. To that end, the goal of autonomy is to teach machines to be smart and act more like humans. Intelligence is necessary for:

1. Mission planning to chart its own course using navigation with guidance and tracking control, while achieving optimal fuel consumption.
2. Path planning and waypoint generation accounting for changing weather and air traffic en route.
3. Mode switching and control reconfiguration decisions for implementation through the use of a flight control system.
4. Staying within the flight envelope of the aircraft.
5. Taking the corrective action to avoid an obstacle or to evade a threat, in the presence of external abnormal conditions.
6. Taking the corrective action by reconfiguring the set of controls to safely continue to fly or land the aircraft, in the presence of internal abnormal conditions.
7. Interpreting the data from a variety of sources to execute these functions.

The objective of this book is to give an interdisciplinary point of view on autonomous aircraft. It aims to develop models and review different methodologies of control and planning used to create smart autonomous aircraft. Some case studies are examined as well.

The topics considered in this book have been derived from the author's research and teaching duties in smart aerospace and autonomous systems over several years. The other part is based on the top literature in the field. This book is primarily geared at advanced graduate students, PhD students, and researchers. It assumes at least an undergraduate-level background in engineering.

Author

Professor Yasmina Bestaoui Sebbane earned a PhD in control and computer engineering from École Nationale Supérieure de Mecanique, Nantes, France, in 1989 (currently École Centrale de Nantes) and the Habilitation to Direct Research in Robotics, from University of Évry, Évry, France, in 2000.

She has been with the Electrical Engineering Department of the University of Evry since 1999. From 1989 to 1998, she was with the Mechanical Engineering Department of the University of Nantes. From September 1997 to July 1998, she was a visiting associate professor in the Computer Science Department at the Naval Postgraduate School, Monterey, California, USA.

Her research interests include control, planning and decision making of unmanned systems particularly unmanned aerial vehicles and robots. She has authored two other books: *Lighter than Air Robots*, Springer, ISCA 58, 2012 and *Planning and Decision Making for Aerial Robots*, Springer, ISCA 71, 2014.

She also has published eight book chapters, forty journal papers and eighty fully refereed conference papers. She is the coordinator of the Master SAAS: Smart Aerospace and Autonomous Systems, in cooperation with Poznan University of Technology, Poland.

Dr. Yasmina Bestaoui Sebbane is an AIAA senior member and IEEE senior member and was an associate editor of the *IEEE Transactions on Control Systems Technology* from January 2008 to December 2012. She is cited in *Who's Who in the World* and *Who's Who in Engineering.*

Contents

1 Introduction

1.1 CURRENT UAV PRESENTATION

An unmanned aircraft is defined by the US Department of Defense [22] as an aircraft that does not carry a human operator and is capable of flight under remote control or autonomous programming. Unmanned aircraft are the preferred alternatives for missions that are characterized as dull, dirty or dangerous. Unmanned aerial vehicles (UAV) provide a great degree of flexibility in mobility and response time [5, 6, 7]. This contributes towards lower mission costs compared to manned aircraft and enables acquisition of information in a time frame not previously possible [36]. The AIAA defines an UAV 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 not require flight controller intervention. During the last decade, significant efforts have been devoted to increasing the flight endurance and payloads of UAV resulting in various UAV configurations with different sizes, endurance levels and capabilities. UAV platforms typically fall into one the following four categories: fixed wing UAV, rotary wing UAV, airships or lighter than air UAV and finally flapping wing UAV. This book is devoted to fixed wing UAV.

The civilian applications can be divided into four categories:

1. Scientific and research related: environmental monitoring [21], climate monitoring, pollution monitoring [26], pollutant estimation [56],
2. Security related: surveillance [16, 37], communications [29], pipeline inspection,
3. Contractor supplied flight services: structure inspection [39, 44, 46], agriculture and farm management [47, 53, 63], bridge monitoring [10],
4. Safety related: weather and hurricane monitoring [55].

Unmanned aircraft typically have complementary sensors that can provide aircraft location along with imagery information and that support mission planning and route following [8, 15, 17]. Both multi-spectral and hyper-spectral cameras are now available for small UAV. The aircraft are used to collect relevant sensor information and transmit the information to the ground control station for further processing. For example, advanced sensors are contributing to precision agriculture which uses the technology to determine crop nutrient levels, water stress, impacts from pests and other factors that affect yield. Advances in platform design, production, standardization of image georeferencing and mosaiking and information extraction work flow are required to provide reliable end products [64].

The characteristics of UAV are:

1. Operation in large, outdoor environments.
2. Motion in 3 dimensions meaning that the planning space must be 4 dimensions.
3. Uncertain and dynamic operating environment.
4. Presence of moving obstacles and environmental forces that affect motion such as winds and changing weather conditions.
5. Differential constraints on movement.

On the basis of gross weight, operational altitude above ground level (AGL) and mission endurance, UAV can be described broadly as:

1. Group 1 : Micro/Mini tactical (< 10 kg)
2. Group 2 : Small tactical (10 to 20 kg)
3. Group 3 : Tactical (< 500 kg)
4. Group 4 : Persistent (> 500 kg and Flight Level $< FL180$)
5. Group 5 : Penetrating (> 500 kg and Flight Level $> FL180$)

Civilian applications deal mainly with group 1 to group 3. **Unmanned aerial systems** (UAS) are systems of systems. These systems make use of a large variety of technologies. These technologies are not always traditionally aviation-related. Some of them are related to robotics, embedded systems, control theory, computer science and technology. Many of these technologies have crossover potential.

Unmanned aircraft rely predominantly on guidance, navigation and control sensors, microprocessors, communication systems and ground station command, control and communications (C3). Microprocessors allow them to fly entire missions autonomously with little human intervention [42]. The principal issues for communication technologies are flexibility, adaptability, security and controllability of the bandwidth, frequency and information/data flows. The key aspects of the off-board command, control and communications are: man-machine interfaces, multi-aircraft command, control and communications, target identification, downsizing ground equipment.

Navigation is concerned with determining where the aircraft is relative to where it should be, guidance with getting the aircraft to the destination and control with staying on track. Situation awareness is used for mission planning and flight mode selection which constitutes the high level control elements. For inhabited aircraft, the pilot provides the intelligence for interpreting the data from a variety of sources to execute these functions. Much of this data is used in pre-flight or pre-mission planning and is updated onboard as the mission proceeds. As the mission segments are executed and abnormal events are encountered, flight mode switching takes place; this constitutes the mid-level control element. On an inhabited aircraft, the pilot flies the aircraft and makes necessary mode switching and control reconfiguration decisions for implementation through the use of the flight control system. This constitutes the low-level control element and is used to execute the smooth transition between modes of flight, for example transition from takeoff to level flight to landing and stay within the **flight envelope** of the aircraft. External abnormal conditions cause the pilot to take corrective actions, such as avoiding a collision or an obstacle or evading a threat. Internal abnormal conditions can also occur, such as a failure or a malfunction of a component onboard the aircraft. Once again, the pilot provides the intelligence to take the corrective action by reconfiguring the set of controls to safely continue to fly or land the aircraft.

Without a pilot onboard the aircraft, the onboard computing architecture must provide the environment for re-usability and reconfigurability. The high level supervisory controller receives mission commands from the command and control post and decomposes them into sub-missions which will then be assigned to connected function modules. Upon reception of start and destination points from the supervisory controller, the route planner generates the *best* route in the form of waypoints for the aircraft to follow. A database of the terrain in the form of a digitized map should be available to the route planner.

Currently, automated functions in unmanned aircraft include critical flight operations, navigation, takeoff and landing and recognition of lost communications requiring implementation of return-to-base procedure [54, 60]. Unmanned aircraft that have the option to operate autonomously today are typically fully preprogrammed to perform defined actions repeatedly and independently of external influence [14]. These systems can be described as self-steering or self-regulating and can follow an externally given path while compensating for small deviations caused by external disturbances. Current autonomous systems require highly structured and predictable environments. A significant amount of manpower is spent directing current unmanned aircraft during mission performance, data collection and analysis and planning and re-planning [9].

An unmanned aircraft system (UAS) is a system whose components include the necessary equipment, network and personnel to control the unmanned aircraft [5]. Unmanned technology innovations are rapidly increasing. Some UAS platforms fly throughout areas of operations for several hours at multiple altitudes. These missions require accurate and timely weather forecasts to improve planning and data collection and to avoid potential weather related accidents [62]. Accurate weather reporting also supports complementary ground and flight planning synchronization.The UAS replaces the onboard pilot's functionality with several distinctive integrated capabilities. From a decision-making perspective, these include a remote-human operator, coupled with an information technology based system of components that enable autonomous functionality. The latter element is significant since it must compensate for the many limitations that arise as a result of operating with a remote pilot [25]. As UAS endurance is increasing, weather predictions must be accurate so that potential weather related incidents can be avoided and coordinated flight and ground operations can be improved [34]. UAS have the potential to be more cost-effective than current manned solutions. UAS can be more effective than manned aircraft at dull, dirty and dangerous tasks. They are also capable of missions that would not be possible with manned aircraft.

1.2 AUTONOMOUS AIRCRAFT

In the context of humans and societies, autonomy is the capacity of a rational individual to make an informed, uncoerced decision and/or to give oneself his own rules according to which one acts in a constantly changing environment [33]. Technical systems that claim to be autonomous will be able to perform the necessary analogies of mind functions that enable humans to be autonomous. Moreover, like in human and animal societies, they will have to abide by rule set or law systems that govern the interaction between individual members and between groups.

Research and development in automation are advancing from a state of automatic systems requiring human control toward a state of autonomous systems able to make decisions and react without human interaction [2]. Advances in technology have taken sensors, cameras and other equipment from the analog to the digital state, making them smaller, lighter and more energy efficient and useful.

Autonomy is a collection of functions that can be performed without direct intervention by the human. Autonomy can be defined as an unmanned system ability of sensing, perceiving, analyzing, communicating, planning, decision-making and acting to achieve its goals [40, 41]. Autonomy is a capability enabled by a set of technologies such as sensing, intelligence, reliability and endurance [50].

Different levels of autonomy can be considered [22, 58]:

1. Human makes all decisions
2. Computer computes a complete set of alternatives
3. Computer chooses a set of alternatives
4. Computer suggests one alternative
5. Computer executes suggestion with approval
6. Human can veto computer's decision within time frame
7. Computer executes then reports to human
8. Computer only reports if asked
9. Computer reports only if it wants to
10. Computer ignores the human.

In today's technology, the last five levels of autonomy have not yet been attained.

An integrated suite of information technologies is required to achieve autonomous capabilities. The four elements of the decision cycle: ***observe, orient, decide, act (OODA)***, are the same actions that any human would perform in achieving an objective in daily life. For an autonomous system,