Autonomous Flying Robots

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Unmanned Aerial Vehicles and Micro Aerial Vehicles

Springer

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Front cover: The 6-rotor MAV which Chiba university MAV group developed is shown here and its size is one meter diameter, 1 kg for weight, 1.5 kg for payload and 20 minutes for flying time. In order to achieve a fully autonomous flight control, the original autopilot unit has been implemented on this MAV and the model based controller has been also installed. This MAV will be used for industrial applications.

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Preface

The advance in robotics has boosted the application of autonomous vehicles to perform tedious and risky tasks or to be cost-effective substitutes for their human counterparts. Based on their working environment, a rough classification of the autonomous vehicles would include unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), autonomous underwater vehicles (AUVs), and autonomous surface vehicles (ASVs). UAVs, UGVs, AUVs, and ASVs are called UVs (unmanned vehicles) nowadays. In recent decades, the development of unmanned autonomous vehicles have been of great interest, and different kinds of autonomous vehicles have been studied and developed all over the world. In particular, UAVs have many applications in emergency situations; humans often cannot come close to a dangerous natural disaster such as an earthquake, a flood, an active volcano, or a nuclear disaster. Since the development of the first UAVs, research efforts have been focused on military applications. Recently, however, demand has arisen for UAVs such as aero-robots and flying robots that can be used in emergency situations and in industrial applications. Among the wide variety of UAVs that have been developed, small-scale HUAVs (helicopter-based UAVs) have the ability to take off and land vertically as well as the ability to cruise in flight, but their most important capability is hovering. Hovering at a point enables us to make more effective observations of a target. Furthermore, small-scale HUAVs offer the advantages of low cost and easy operation.

The Chiba University UAV group started research of autonomous control in 1998, advanced joint research with Hirobo, Ltd. in 2001, and created a fully autonomous control helicopter for a small-scale helicopter for hobbyists. There is a power-line monitoring application of UAV called SKY SURVEYOR. Once it catches power line, regardless of the vibration of the helicopter, with various onboard cameras with a gross load of 48 kg for a cruising time of 1 hour, catching of the power line can be continued. In addition, it has a payload of about 20 kg. Although several small UAVs are helicopters — Sky Focus-SF40 (18 kg), SST-eagle2-EX (7 kg), Shuttle-SCEADU-Evolution (5 kg), and an electric motor-based Lepton (2 kg) for hobbyists, with gross loads of 2–18 kg — fully autonomous control of these vehicles is already possible. Cruising time, depending on the helicopter's class, is about 10–20 min, with payloads of about 800 g – 7 kg. These devices are what automated the commercial radio-controlled helicopters for hobbyists, because they can be flown freely by autonomous flight by one person, are cheap and simple systems, and can apply chemical sprays, as in orchards, fields, and small-scale gardens. In the future they can also be used for aerial photography, various kinds of surveillance, and rescues in disasters.

GH Craft and Chiba University are conducting further research and development of autonomous control of a four-rotor tilt-wing aircraft. This QTW (quad tilt wing)-UAV is about 30 kg in gross load; take-off and landing are done in helicopter mode; and high-speed flight at cruising speed is carried out in airplane mode. Bell Helicopter in the United States completed development of the QTR (quad tilt rotor)-UAV, and its first flight was carried out in January 2006; however, the QTW-UAV had not existed anywhere in the world until now, although the design and test flight had been attempted. The QTW-UAV now is already flying under fully autonomous conditions. Moreover, Seiko Epson and Chiba University tackled autonomous control of a micro flying robot, the smallest in the world at 12.3 g, with the micro air vehicle (MAV) advantage of the lightest weight, and have succeeded with perfect autonomous control inside a room through image-processing from a camera. The XRB by Hirobo, Ltd., about 170 g larger than this micro flying robot, has also successfully demonstrated autonomous control at Chiba University. Flying freely with autonomous control inside a room has now been made possible.

We have also been aggressively developing our own advanced flight control algorithm by means of a quad-rotor MAV provided by a German company (Ascending Technologies GmbH) as a helicopter for hobbyists. We have chosen this platform because it offers good performance in terms of weight and payload. The original X-3D-BL kit consists of a solid airframe, brushless motors and associated motor drivers, an X-base which is an electronic card that decodes the receiver outputs and sends commands to motors, and an X-3D board that incorporates three gyroscopes for stabilization. The total weight of the original platform is about 400 g including batteries, and it has a payload of about 200 g. The flight time is up to 20 min without a payload and about 10 min with a payload of 200 g. The X-3D-BL helicopter can fly at a high speed approaching 8 m/s. These good characteristics are due to its powerful brushless motors that can rotate at very high speed. Furthermore, the propellers are directly mounted on the motors without using mechanical gears, thereby reducing vibration and noise. Also, our original 6-rotor MAVs for industrial applications such as chemical spraying have been developed, and their fully autonomous flight has already been successful.

For industrial applications, a power-line monitoring helicopter called SKY SURVEYOR has been developed. A rough division of the system configuration of SKY SURVEYOR consists of a ground station and an autonomous UAV. Various apparatuses carry out an autonomous control system of a sensor and an inclusion computer, and power-line monitoring devices are carried in the body of the vehicle. The sensors for autonomous control are a GPS receiver, an attitude sensor, and a compass, which comprise the autonomous control system of the model base. The flight of the compound inertial navigation of GPS/INS or a 3D stereo-vision base is also possible if needed. The program flight is carried out with the ground station or the embedded computer system by an orbital plan for operation surveillance, if needed. For attitude control, an operator performs only position control of the helicopter with autonomous control, and so-called operator-assisted flight can also be performed. In addition, although a power-line surveillance image is recorded by the video camera of the UAV loading in automatic capture mode and is simultaneously transmitted to the ground station, an operator can also perform posture control of the power-line monitoring camera and zooming at any time.

We have been studying UAVs and MAVs and carrying out research more than 10 years, since 1998, and we have created many technologies by way of experimental work and theoretical work on fully autonomous flight control systems. Dr. Farid Kendoul worked 2 years in my laboratory as a post-doctoral research fellow of the Japan Society for the Promotion of Science (JSPS post-doctoral fellow), from October 2007 to October 2009. He contributed greatly to the progress in MAV research. These factors are the reason, the motivation, and the background for the publication of this book. Also, seven of my graduate students completed Ph.D. degrees in the UAV and MAV field during the past 10 years. They are Dr. Jinok Shin, Dr. Daigo Fujiwara, Dr. Kensaku Hazawa, Dr. Zhenyo Yu, Dr. Satoshi Suzuki, Dr. Wei Wang, and Dr. Dasuke Nakazawa. The last three individuals — Dr. Suzuki, Dr. Wang, and Dr. Nakazawa — along with Dr. Kendoul are the authors of this book.

The book is suitable for graduate students whose research interests are in the area of UAVs and MAVs, and for scientists and engineers. The main objective of this book is to present and describe systematically, step by step, the current research and development in, small or miniature unmanned aerial vehicles and micro aerial vehicles, mainly rotary wing vehicles, discussing integrated prototypes developed within robotics and the systems control research laboratory (Nonami Laboratory) at Chiba University. In particular, this book may provide a comprehensive overview for beginning readers in the field. All chapters include demonstration videos, which help the readers to understand the content of a chapter and to visualize performance via video. The book is divided into three parts. Part I is “Modeling and Control of Small and Mini Rotorcraft UAVs”; Part II is “Advanced Flight Control Systems for Rotorcraft UAVs and MAVs”; and Part III is “Guidance and Navigation of Short-Range UAVs.”

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First I would like to express my gratitude to the contributors of some of the chapters of this book. Mr. Daisuke Iwakura, who is an excellent master's degree student in the MAVs research area, in particular, contributed Chapter 13. Also, I express my appreciation to Mr. Shyaril Azrad and Ms. Dwi Pebrianti for their contributions on vision-based flight control. They are Ph.D. students in MAV research in my laboratory. Dr. Jinok Shin, Dr. Daigo Fujiwara, Dr. Kensaku Hazawa, and Dr. Zhenyo Yu made a large contribution in UAV research, which is included in this book. I also appreciate the contributions of Dr. Shin, Dr. Fujiwara, Dr. Hazawa, and Dr. Yu. During the past 10 years, we at Chiba University have been engaged in joint research with Hirobo Co., Ltd., on unmanned fully autonomous helicopters; with Seiko Epson on autonomous micro flying robots; and with GH Craft on QTW-UAV. I thank all concerned for their cooperation and support in carrying out the joint research. I am especially grateful to Hirobo for providing my laboratory with technical support for 10 years. I appreciate the teamwork in the UAV group. I will always remember our field experiments and the support of each member. I thank you all for your help and support. Lastly, I would like to thank my family for their constant support and encouragement, for which I owe a lot to my wife.

Contents

Part I Modeling and Control of Small and Mini Rotorcraft UAVs

Part II Advanced Flight Control Systems for Rotorcraft UAVs and MAVs

Part III Guidance and Navigation of Short-Range UAVs

Chapter 1
Introduction

Abstract This chapter contains a non-technical and general discussion about unmanned aerial vehicles (UAVs) and micro aerial vehicles (MAVs). This chapter presents some fundamental definitions related to UAVs and MAVs for clarification, and discusses the contents of this monograph. The goal of this chapter is to help the reader to become familiar with the contents of the monograph and understand what to expect from each chapter.

Video Links:

Auto-take off and Landing
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/1.avi
Cooperation between UAV, MAV and UGV
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/2.mpg
Formation flight control of two XRBs
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/3.mpg
Fully autonomous flight control of QTW-UAV
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/4.wmv
Fully autonomous hovering of micro-flying robot by vision
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/5.mpg
GPS_INS fusion flight control
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/6.avi
Operator assistance flight control
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/7.avi
Promotion video of UAVs and IMU sensor
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/8.avi
Power line inspection by Skysurveyor
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/9.avi
Rotation control of Eagle; onboard camera & ground camera views
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/10.mpg
UAV application by Skysurveyor
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/11.avi
Vision based auto-take off, hovering and auto-landing
http://mec2.tm.chiba-u.jp/monograph/Videos/Chapter1/12.avi

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1.1 What are Unmanned Aerial Vehicles (UAVs) and Micro Aerial Vehicles (MAVs)?

In recent years, there has been rapid development of autonomous unmanned aircraft equipped with autonomous control devices called unmanned aerial vehicles (UAVs) and micro aerial vehicles (MAVs). These have become known as "robotic aircraft," and their use has become wide spread. They can be classified according to their application for military or civil use. There has been remarkable development of UAVs and MAVs for military use. However, it can be said that the infinite possibilities of utilizing their outstanding characteristics for civil applications remain hidden. Figure 1.1 shows that there was a large number of registered UAVs in Japan in 2002. This was because of the many unmanned helicopters used for agricultural–chemical spraying, as can be seen in Table 1.1. Figure 1.2 shows the country-wise R&D expenditure and Fig. 1.3 indicates the application of UAVs for civil and military purposes.

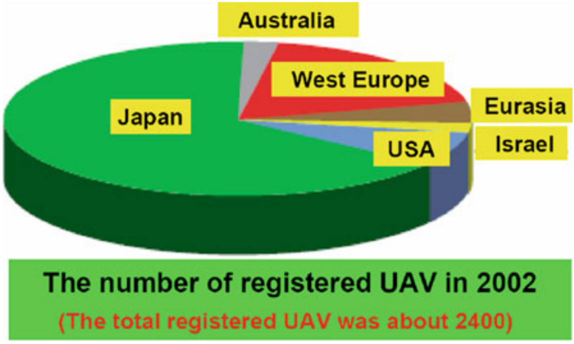
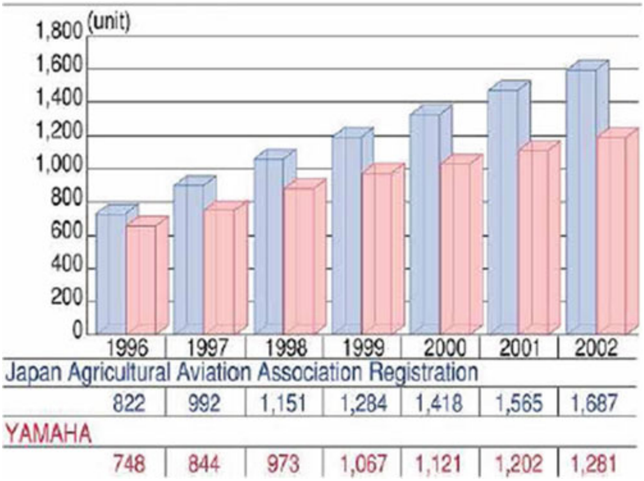


Fig. 1.1 Registered UAVs

Table 1.1 Number of registered UAVs in Japan



	1996	1997	1998	1999	2000	2001	2002
Japan Agricultural Aviation Association Registration	822	992	1,151	1,284	1,418	1,565	1,687
YAMAHA	748	844	973	1,067	1,121	1,202	1,281

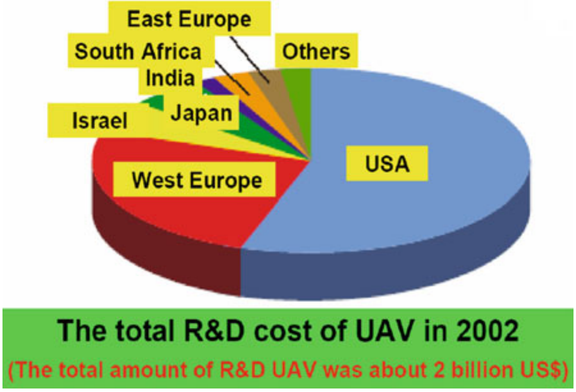


Fig. 1.2 Country-wise R&D expenditure on UAVs

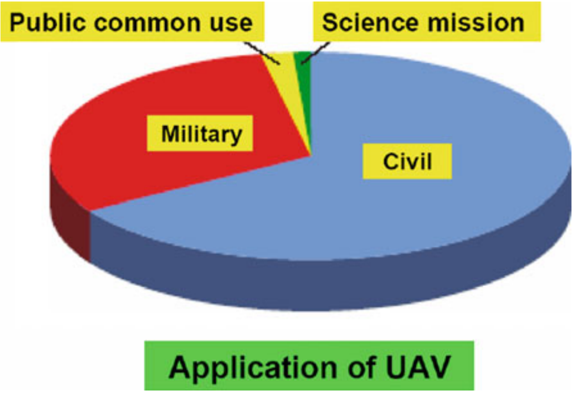


Fig. 1.3 Application of UAVs for civil and for military use in 2002

UAVs offer major advantages when used for aerial surveillance, reconnaissance, and inspection in complex and dangerous environments. Indeed, UAVs are better suited for dull, dirty, or dangerous missions than manned aircraft. The low downside risk and higher confidence in mission success are two strong motivators for the continued expansion of the use of unmanned aircraft systems. Furthermore, many other technological, economic, and political factors have encouraged the development and operation of UAVs. First, technological advances provide significant leverage. The newest sensors, microprocessors, and propulsion systems are smaller, lighter, and more capable than ever before, leading to levels of endurance, efficiency, and autonomy that exceed human capabilities. Second, UAVs have been used successfully in the battlefield, being deployed successfully in many missions. These factors have resulted in more funding and a large number of production orders. Third, UAVs can operate in dangerous and contaminated environments, and can also operate in other environments denied to manned systems, such as altitudes that are both lower and higher than those typically traversed by manned aircraft. Several market studies [1–3] have predicted that the worldwide UAV market will expand significantly in the next decade. These studies also estimated that UAV spending will more than triple over the next decade, totaling close to $55 billion in the next 10 years [3]. As stated in [2, 4], over the next 5–7 years, the UAV market in the U.S. will reach $16 billion, followed by Europe, which is spending about $3 billion. In US for example, development budgets increased rapidly after 2001, as shown in Fig. 1.4, and UAV research and development was given a powerful push [5]. On the other hand, the R&D budgets in Europe have increased slowly, as seen in Fig. 1.5. Today, there are several companies developing and producing hundreds of UAV designs. Indeed, major defense contractors are involved in developing and producing UAVs. At the same time, newer or smaller companies have also emerged with innovative technologies that make the market even more vibrant, as seen in Fig. 1.6. U.S. companies currently hold about 63–64% of the market share, while European companies account for less than 7% [2]. As shown in Table 1.2, in 2005, some 32 nations were developing or manufacturing more than 250 models of UAVs, and about 41 countries were operating more than 80 types of UAVs, primary for reconnaissance in military applications [5]. Table 1.2 lists the results of an investigation that tracked

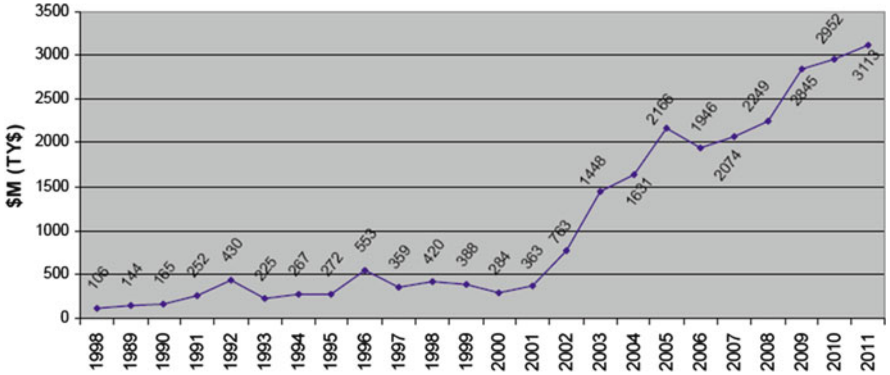


Fig. 1.4 Annual funding profile of the U.S. Department of Defense [5]

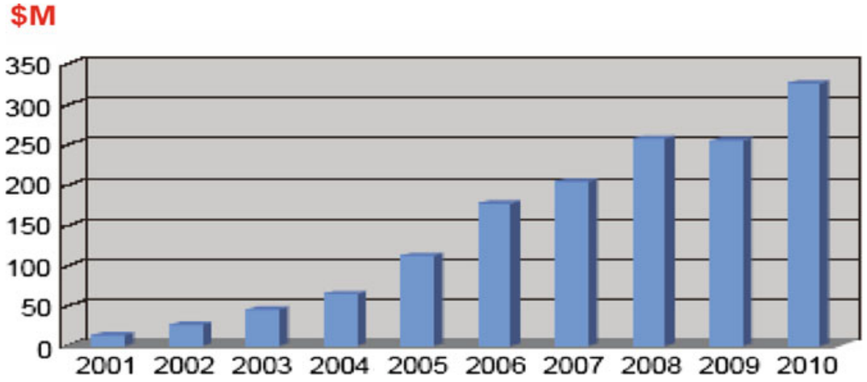


Fig. 1.5 Annual funding profile in Europe

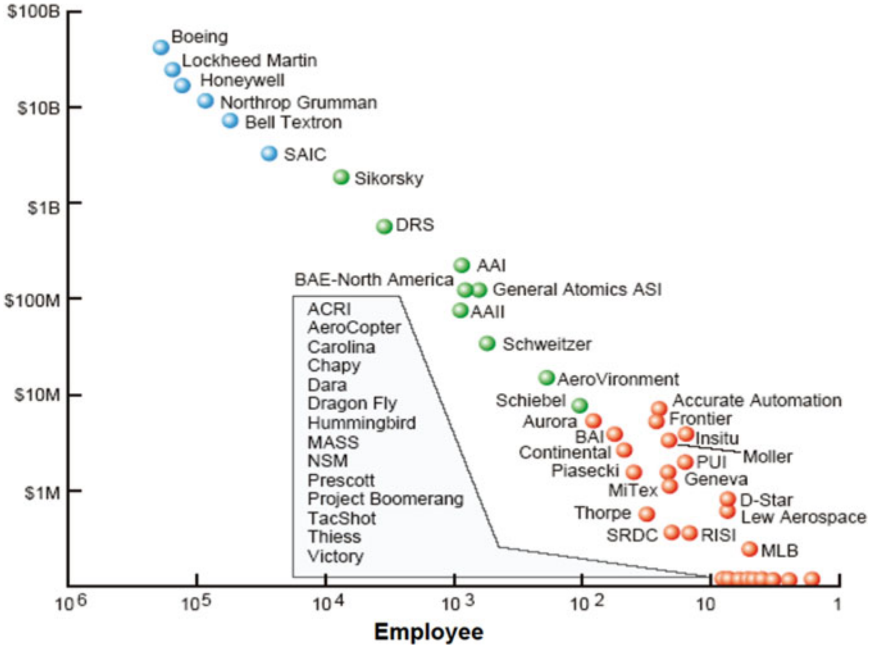


Fig. 1.6 The scale of the U.S. companies developing and manufacturing UAVs

and recorded the exporters, users, manufacturers, and developers of UAVs around the world. In some countries, including the group of seven (G7) industrialized countries and Russia, every category has a “Yes.” Although their use varies, except for Japan and some other countries, the majority of the research and development is supported by defense expenditures. However, the civil UAV market is predicted to emerge over the next decade, starting first with government organizations requiring surveillance systems, such as coast guards, border patrol organizations, rescue teams, police, etc. Although armed forces around the world continue to strongly invest in researching and developing technologies with the potential to advance the capabilities of UAVs, commercial applications now drive many unmanned technologies. Among these technologies, some apply equally to manned aircraft like platform technologies (airframe, materials, propulsion systems, aerodynamics, etc.) and payload technologies (mission sensors, weapons, etc.). Other technologies are specific to UAVs in the sense that they compensate for the absence of an onboard pilot and thus enable unmanned flight and autonomous behavior. Indeed, UAVs rely predominantly on

- *Navigation sensors and microprocessors*: Sensors now represent one of the single largest cost items in an unmanned aircraft and are necessary for navigation and mission achievement. Processors allow UAVs to fly entire missions autonomously with little or no human intervention.

Table 1.2 Current exporters, operators, manufacturers, and developers of UAVs [5]

MTCR member	UA exporter	UA operator	UA manufacturer	UA developer
Argentina	No	Yes	Yes	Yes
Australia	Yes	Yes	Yes	Yes
Austria	Yes	No	Yes	Yes
Belgium	No	Yes	Yes	Yes
Brazil	No	No	No	No
Canada	Yes	No	Yes	Yes
Czech Republic	No	Yes	Yes	Yes
Denmark	No	Yes	No	No
Finland	No	Yes	No	No
France	Yes	Yes	Yes	Yes
Germany	Yes	Yes	Yes	Yes
Greece	No	No	No	Yes
Hungary	No	No	No	Yes
Iceland	No	No	No	No
Ireland	No	No	No	No
Italy	Yes	Yes	Yes	Yes
Japan	Yes	Yes	Yes	Yes
Luxembourg	No	No	No	No
The Netherlands	No	Yes	No	No
New Zealand	No	No	No	No
Norway	No	No	No	Yes
Poland	No	No	No	No
Portugal	No	No	No	Yes
Russia	Yes	Yes	Yes	Yes
South Africa	Yes	Yes	Yes	Yes
South Korea	No	Yes	Yes	Yes
Spain	No	No	Yes	Yes
Sweden	No	Yes	Yes	Yes
Switzerland	Yes	Yes	Yes	Yes
Turkey	Yes	Yes	Yes	Yes
Ukraine	Yes	Yes	Yes	Yes
United Kingdom	Yes	Yes	Yes	Yes
United States	Yes	Yes	Yes	Yes

- *Communication systems (data link)*: The principal issues for communication technologies are flexibility, adaptability, security, and cognitive controllability of the bandwidth, frequency, and information/data flows.
- *Ground Station Command, Control, and Communications (C3)*: There are several key aspects of the off-board C3 infrastructure that are being addressed, such as man–machine interfaces, multi-aircraft C3, target identification, downsizing ground equipment, voice control, etc. Advancing the state of the art in all of the areas discussed above will allow a single person to control multiple aircraft.

- *Aircraft onboard intelligence (guidance, navigation, and control)*: The intelligence that can be “packed” into a UAV is directly related to how complicated a task that it can handle, and inversely related to the amount of oversight required by human operators. More work needs to be done to mature these technologies in the near term to show their utility and reliability. The reader can refer to [5] for more details on forecasting trends in these technologies over the coming decades.

1.2 Unmanned Aerial Vehicles and Micro Aerial Vehicles: Definitions, History, Classification, and Applications

Before any discussion on UAV technologies, it is necessary to provide clarifications related to the terminology, classification, and potential applications of UAVs.

1.2.1 Definition

An uninhabited aircraft is defined using the general terms UAV (uninhabited aerial vehicle or unmanned aerial vehicle), ROA (remotely operated aircraft), and RPV (remotely piloted vehicle) [4]. A pilot is not carried by an uninhabited aerial vehicle, but the power source, which provides dynamic lift and thrust based on aerodynamics, is controlled by autonomous navigation or remote-control navigation. Therefore, neither a rocket, which flies in a ballistic orbit, nor a cruise missile, shell, etc. belong in this category. An unmanned airship that flies in the air with a help of gas is also not included in this category.

On the other hand, the AIAA defines a 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.” Although there is no strict definition of the difference between a UAV and MAV, according to a definition by DARPA (Defense Advanced Research Projects Agency) of the U.S. Department of Defense, an MAV has dimensions (length, width, or height) of 15 cm or less.

1.2.2 Brief History of UAVs

The first UAV was manufactured by the Americans Lawrence and Sperry in 1916. It is shown in Fig. 1.7. They developed a gyroscope to stabilize the body, in order to manufacture an auto pilot. This is known as the beginning of “attitude control,” which came to be used for the automatic steering of an aircraft. They called their

Fig. 1.7 First UAV in the world, 1916

Fig. 1.8 UAVs in the 1960s and 1970s (Firebee)

device the “aviation torpedo” and Lawrence and Sperry actually flew it a distance that exceeded 30 miles. However, because of their practical technical immaturity, it seems that UAVs were not used in World War I or World War II.

The development of UAVs began in earnest at the end of the 1950s, taking advantage of the Vietnam War or the cold war, with full-scale research and development continuing into the 1970s. Figure 1.8 shows a UAV called Firebee. After the Vietnam War, the U.S. and Israel began to develop smaller and cheaper UAVs. These were small aircraft that adopted small engines such as those used in motorcycles or snow mobiles. They carried video cameras and transmitted images to the operator’s location. It seems that the prototype of the present UAV can be found in this period.

Fig. 1.9 Predator in military use

Fig. 1.10 Civil use UAV by NASA (Helios)

The U.S. put UAVs into practical use in the Gulf War in 1991, and UAVs for military applications developed quickly after this. The most famous UAV for military use is the Predator, which is shown in Fig. 1.9. On the other hand, NASA was at the center of the research for civil use during this period. The most typical example from this time was the ERAST (Environmental Research Aircraft and Sensor Technology) project. It started in the 1990s, and was a synthetic research endeavor for a UAV that included the development of the technology needed to fly at high altitudes of up to 30,000 m, along with a prolonged flight technology, engine, sensor, etc. The aircraft that were developed in this project included Helios, Proteus, Altus, Pathfinder, etc., which are shown in Figs. 1.10–1.12. These were designed to carry out environmental measurements.

Fig. 1.11 Civil use UAV by NASA (Proteus)

Fig. 1.12 Civil use UAV by NASA (Altus)

1.2.3 Classification of UAV Platforms

During recent decades, significant efforts have been devoted to increasing the flight endurance and payload of UAVs, resulting in various UAV configurations with different sizes, endurance levels, and capabilities. Here, we attempt to classify UAVs according to their characteristics (aerodynamic configuration, size, etc.). UAV platforms typically fall into one of the following four categories:

- Fixed-wing UAVs, which refer to unmanned airplanes (with wings) that require a runway to take-off and land, or catapult launching. These generally have long endurance and can fly at high cruising speeds, (see Fig. 1.13 for some examples).
- Rotary-wing UAVs, also called rotorcraft UAVs or vertical take-off and landing (VTOL) UAVs, which have the advantages of hovering capability and high maneuverability. These capabilities are useful for many robotic missions, especially

in civilian applications. A rotorcraft UAV may have different configurations, with main and tail rotors (conventional helicopter), coaxial rotors, tandem rotors, multi-rotors, etc. (see Fig. 1.14 for some examples).

- Blimps such as balloons and airships, which are lighter than air and have long endurance, fly at low speeds, and generally are large sized (see Fig. 1.15 for some examples).

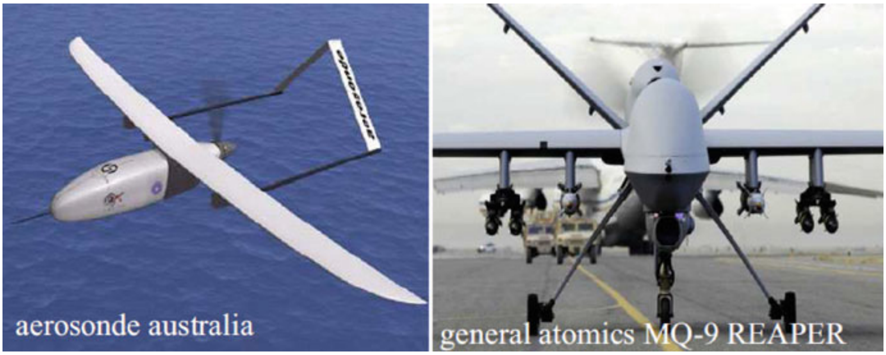


Fig. 1.13 Some configurations of fixed-wing UAVs

Fig. 1.14 Examples of rotary-wing UAVs

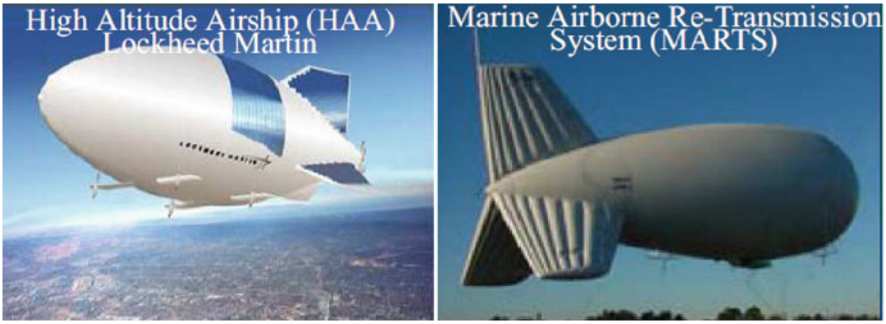


Fig. 1.15 Examples of airship-based UAVs

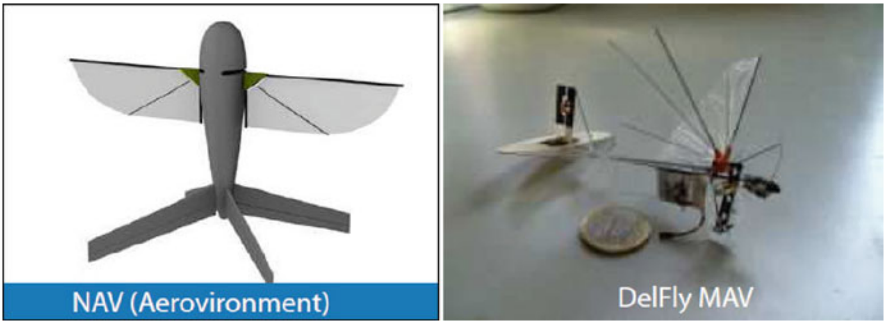


Fig. 1.16 Micro flapping-wing UAVs

- Flapping-wing UAVs, which have flexible and/or morphing small wings inspired by birds and flying insects, see Fig. 1.16.

There are also some other *hybrid* configurations or *convertible* configurations, which can take-off vertically and tilt their rotors or body and fly like airplanes, such as the Bell Eagle Eye UAV. Another criterion used at present to differentiate between aircraft is size and endurance [5]:

- High Altitude Long Endurance (HALE) UAVs, as for example, the *Northrop-Grumman Ryan's Global Hawks* (65,000 ft altitude, 35 h flight time, and 1,900 lb payload).
- Medium Altitude Long Endurance (MALE) UAVs, as for example *General Atomics's Predator* (27,000 ft altitude, 30/40 h flight time, and 450 lb payload).
- Tactical UAVs such as the *Hunter*, *Shadow 200*, and *Pioneer* (15,000 ft altitude, 5–6 h flight time, and 25 kg payload).
- Small and Mini man-portable UAVs such as the *Pointer/Raven (AeroVironment), Javelin* (*BAI*), or *Black Pack Mini* (*Mission Technologies*).
- Micro aerial vehicles (MAV): In the last few years, micro aerial vehicles, with dimensions smaller than 15 cm, have gained a lot of attention. These include the *Black Widow* manufactured by *AeroVironment*, the *MicroStar* from *BAE*, and many new designs and concepts presented by several universities, such as the *Entomopter* (*Georgia Institute of Technology*), *Micro Bat* (*California Institute of Technology*), and *MFI* (*Berkeley University*), along with other designs from European research centers (Fig. 1.17).

Currently, the main research and development for UAV platforms aims at pushing the limits/boundaries of the flight envelope and also the vehicle's size. Indeed, most ongoing ambitious projects (or prototypes in development) are about (1) unmanned combat air vehicles (UCAV) with high speed and high maneuverability or (2) micro aerial vehicles (MAVs) with insect-like size and performance.