Chapter 1: Introduction[1]

This Chapter justifies the rationale for publishing this edited book. It starts with a non technical, general discussion about unmanned aerial vehicles (UAVs). Then, it presents some fundamental definitions related to UAVs for clarification purposes, and discusses the contents of the book in a very concise way. It paves the way for what is included in subsequent Chapters and how the material, even though it is divided in parts, ties together in a rather unified and smooth way. The goal is to help the potential reader become familiar with the contents of the book and with what to expect reading each Chapter.

1.1 Introduction

UAVs, also called unmanned aircraft systems, have recently reached unprecedented levels of growth in diverse military and civilian application domains.

UAVs were first introduced during World War I (1917), registering the long involvement of the US military with unmanned vehicles [12]. Those early UAVs were very unreliable and inaccurate, and, at that time, their usefulness, their ability to change the battlefield and their overall impact on military applications was not recognized by most military and political leaders.

Only a handful of individuals did envision and predicted their future potential and overall impact on military applications. If it were not for that small group of people who kept alive (over the post World War I years) the concept of an unmanned vehicle pushing for political support and funding, nothing would have been possible today.

Even though UAVs were used in Vietnam, it was only after Operation Desert Storm (1991) and the conflict in the Balkan Peninsula in the early 1990's when interest in UAVs gained momentum. As such, in 1997, the total income of the UAV global market, including the Vertical Take-Off

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and Landing (VTOL) segment, reached $2.27 billion dollars [4], a 9.5% increase over 1996. In the middle 1990's the demand for VTOL vehicles was limited, but since then, commercially available products and market share started to increase.

Focusing only on the year 2000, one year before 9/11, Figure 1.1 illustrates the total year funding of the US DOD [3]; as shown in the Figure, 15% of the funding was allocated to VTOL vehicle design.

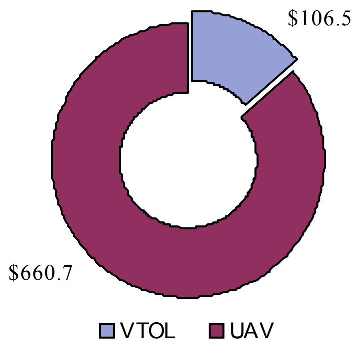

Fig. 1.1. US Government funds ($M) for R&D in UAVs / VTOLs – year 2000.

The critical event that changed completely the perception about UAVs and put them on the everyday life map, on front covers, made them first subject in media coverage and TV documentaries, was the terrorist attack on 9/11. The events on 9/11, coupled with the war in Afghanistan and Operation Iraqi Freedom where UAVs were successfully used in the battlefield and they were deployed successfully for a multitude of missions, resulted in skyrocketed funding and the largest number of production orders [10].

As stated in [10], over the next 8-10 years (until 2015), the UAV market in the US, as a whole, will reach $16 billion, with Europe as a continent playing the role of the second but distant competitor, spending just about €2 billion. US companies hold currently about 63%-64% of the market share, while European companies account for less than 7% [10]. This data is verified in [12] where it is stated that from 1990 to 1999, the US DOD total investment in UAV development, procurement and operations was a bit over $3 billion; but as shown in Table 1.1, the FY03-09 Presidential Budget for related UAV programs reaches $16.2 billion [12]. As a follow up of the data shown in Table 1.1, and just for comparison purposes, Table 1.2 illustrates the revised FY06 President's budget for UAS operations and maintenance [15].

Program	FY03*	FY04*	FY05*	FY06*	FY07*	FY08*	FY09*	Total*
Predator	227.9	358.0	329.4	355.0	241.4	266.5	374.2	2152.4
Pioneer	29.1	36.3	17.7	9.9	10.7	11.2	11.4	126.3
Hunter	33.9	29.2	28.2	28.1	26.0	24.6	25.2	195.2
Global Hawk	510.5	624.2	625.7	688.8	869.6	800.5	730.6	4849.9
Shadow 200	179.0	132.0	124.8	89.0	90.5	93.6	90.2	799.1
ER/MP	0.0	23.1	33.6	71.0	85.7	140.0	168.7	522.1
Fire Scout/VTUAV	38.6	4.0	0.0	0.0	0.0	180.0	270.0	492.6
UCAV (AF & Navy)	171.3	347.8	573.3	530.3	361.7	914.7	1226.1	4125.2
BAMS	0.0	25.1	224.4	187.1	322.1	415.2	440.3	1614.2
GH Maritime Demo	189.4	76.4	57.3	59.2	61.9	56.5	56.9	557.6
UCAR	33.0	49.4	75.9	107.7	84.2	86.2	47.0	483.4
Various Small UAV	51.6	52.4	55.0	55.0	55.0	55.0	55.0	379.0 estimated
Grand Total	**1455.7**	**1761.6**	**2139.1**	**2158.0**	**2199.6**	**3016.9**	**3459.5**	**16190.4**

* All budget figures are given in millions of dollars and roll up RDT&E, procurement, and O&S together.

Table 1.1. Presidential Budget for UAV Programs in $M, FY 04 (Credit: taken from [12], Table 2.4–1).

UAS Program FY06PB ($M)	FY05	FY06	FY07	FY08	FY09	FY10	FY11	Total
Predator (Air Force)	71.9	160.4	175.1	103.0	115.1	116.6	119.2	861.3
Pioneer (USMC)	8.7	10.4	7.7	6.7	3.9	9.5	11.2	58.0
Hunter (Army)	27.9	30.0	30.1	29.8	28.1	9.7	1.1	156.7
Global Hawk (Air Force)	20.0	19.5	68.7	71.3	94.3	108.5	113.5	495.7
Shadow (Army)	29.2	36.2	38.0	34.8	34.0	44.3	45.7	262.3
Fire Scout/VTUA (Navy)	0.0	0.0	0.0	TBD	TBD	TBD	TBD	0.0
BAMS UA (Navy)	0.0	0.0	0.0	0.0	0.0	0.0	31.3	31.3
GH Maritime Demo (Navy)	9.6	18.9	19.1	20.0	20.0	20.0	20.0	127.6
Total	**167.3**	**275.4**	**338.7**	**265.6**	**295.4**	**308.6**	**342.0**	**1992.9**

*Does not include 2005 supplemental request for OIF, OEF, and Operation UNIFIED ASSISTANCE

Table 1.2. FY06 President's Budget for UAS Operations and Maintenance in $M (Credit: taken from [15], Table 2.6–3).

An additional independent study conducted by the Teal Group, a defense and aerospace market analysis firm based in Fairfax, VA [14], claims that UAVs will continue to be the most dynamic growth sector of the world aerospace industry. Their market study that was previewed during the Unmanned Systems North America 2006 Conference, estimates that UAV spending will more than triple over the next decade, totaling close to $55 billion in the next ten years [14]. The same study [14], points out that the US will account for 77% of the worldwide RDT&E spending on UAV technology over the next decade, and about 64% of the procurement. These US expenditures represent higher shares of the aerospace market than for worldwide defense spending in general, with the US accounting for about 67% of total worldwide defense RDT&E spending and 37% of procurement spending, according to forecasts in International Defense Briefing, another Teal Group competitive intelligence service.

Another conclusion that the Teal Group has reached [14] is that a civil UAV market will slowly emerge over the next decade, starting first with government organizations requiring surveillance systems similar to military UAVs such as coast guards, border patrol organizations and similar national security organizations.

A rapidly evolving and dynamic sector of the overall UAV market is the VTOL vehicle segment. America as a continent accounts for 68% of all VTOL vehicles developed worldwide, while Europe and Asia contribute 22% and 10%, respectively, as shown in Figure 1.2 [13]. Moreover, most of VTOL vehicles manufactured in the American continent are contributed by the US. The US alone manufactures 66% of the total number of VTOLs worldwide as shown in Figure 1.3, with most VTOLs being used for military applications.

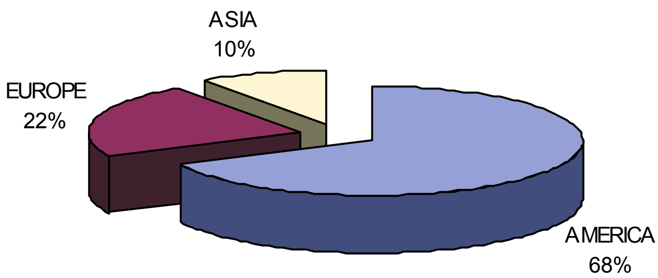

Fig. 1.2. VTOL regional division.

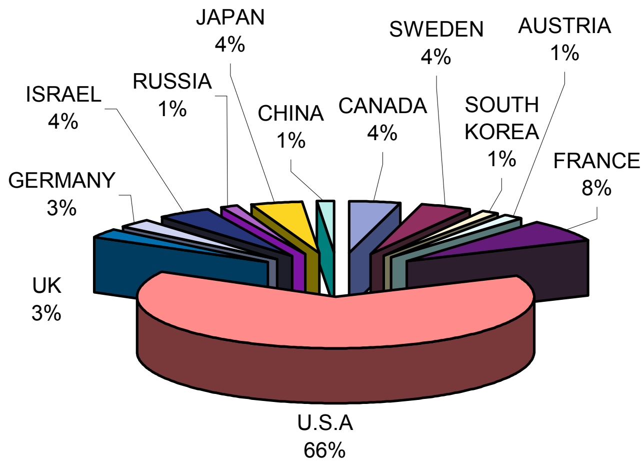

Fig. 1.3. Percentages of VTOL models produced over the world.

It is essential to state that unmanned airplanes are basically used for military applications; however VTOL applications extend to the non-military domains as well. VTOL military applications include surveillance and reconnaissance, combat uses and testing for new weapon systems. Non-military applications include pipelines and power lines inspection and surveillance, border patrol, rescue missions, region surveillance, oil and natural gas search, fire prevention, topography and natural disasters, as well as agricultural applications (mostly in Japan).

As the field matures, the tendency shifts to smaller, more flexible and versatile UAVs. From that perspective, and regardless of application and type of UAV under consideration, the US Army states that "the role of small unmanned aerial vehicles as a critical component for providing unprecedented situational awareness, is rapidly increasing" [11].

Certainly, this brief introduction supports the claim that the future of UAVs is bright and that this area will continue to grow. Therefore, it is important to concentrate in thrust areas related to the current state of the art in research and development, register application domains but also discuss challenges and limitations that need be overcome to improve functionality and utilization of unmanned aerial systems.

Before any further discussion, it is necessary to provide clarifications related to the UAV terminology.

1.2 Clarifications and Related Definitions

In general, an aircraft is any flying vehicle/machine in all possible configurations: fixed-wing, rotary-wing or rotorcraft, helicopters, VTOL vehicles, or short take-off and landing (STOL).

As stated in [8] [9], an aircraft may be either heavier or lighter than air, with balloons and airships belonging to the latter category. Moreover, the term unmanned aerial vehicle (also known as a drone) refers to a pilotless aircraft, a flying machine without an on-board human pilot. As such, 'unmanned' refers to total absence of a human who directs and actively pilots the aircraft. Control functions for unmanned aircraft may be either on-board or off-board (remote control).

A fixed-wing UAV refers to an unmanned airplane that requires a runway to take-off and land, or catapult launching.

A helicopter refers to an aircraft that takes off and lands vertically; it is also known as a rotary aircraft with the ability to hover, to fly in very low altitudes, to rotate in the air and move backwards and sideways. It is capable of performing non-aggressive or aggressive flights.

A helicopter may have different configurations, with a main and a tail rotor (most common), with only a main rotor, with tandem configuration, with coaxial but opposite rotary rotors, as well as with one, two or four rotors.

1.3 Objectives and Outline of the Book

The main objective of the book is to register current research and development in small / miniature unmanned aerial vehicles, fixed- or rotary-wing ones discussing integrated prototypes developed within research laboratories. It aims at describing advances in UAVs, highlighting challenges that need be overcome when dealing with such flying machines, as well as demonstrating their wide applicability to diverse application domains.

Even though this is not a comprehensive edited Volume of contributed Chapters (since it does not include research results from every group working in this area), it does offer a wide perspective of important problems and research questions that need be addressed and solved.

The book is unique in at least one aspect: even though it consists of contributed Chapters from different individuals and groups, material is presented in a rather unified way, classified per topic discussed, assuring continuity in reading.

The book is divided in five Parts:

- Part I consists of Chapters 1 and 2. Both Chapters are introductory motivating and guiding the reader gradually in to the field of UAVs. A historical overview of the evolution of such vehicles, starting from Ancient Greece to the most recent models shows that the idea of a flying machine is a very old one, and provides proof of the tremendous progress in the field.

- Part II focuses on modeling and control fundamentals of small fixed-wing airplanes and small rotorcraft. It includes four Chapters:

  - Chapter 3 provides fundamental background information related to the derivation of the basic equations of motion of a traditional airplane. It explains how the airplane's position and orientation are determined with respect to an Earth-fixed inertia reference frame, derives the aerodynamic forces that act on the airplane, defines the corresponding control angles, and concludes with derivation of the open-loop dynamics. This Chapter is the basic one a designer or control engineer needs to understand before proceeding in controller design, testing and implementation.
  - Chapter 4 focuses on low-level controller design of miniature helicopters for autonomous flights. After summarizing major contributions to small helicopter control, the Chapter describes a general model suitable for small / miniature helicopter non-aggressive flights and compares three different controllers, a PID, a Linear Quadratic Regulator (LQR) and an $\boldsymbol{H}_\infty$ controller in terms of their practical implementation to achieve autonomous, self-governing flights.
  - Chapter 5 presents a tutorial–like approach to studying, designing, implementing and testing controllers for small unmanned helicopters performing autonomous non-aggressive flights, putting emphasis on hovering and cruising. It describes simplified, decentralized single input single output, PID and PID-like fuzzy logic controller designs with optimized gains, and a complete design of a multiple inputs multiple outputs linear quadratic regulator (LQR) controller. The presented approach is general enough to be applicable to a wide range of small unmanned helicopters. Chapters four and five are complementary and 'loosely coupled'. Taken together, they offer a comprehensive perspective to small helicopter controller design.

  - Chapter 6 takes advantage of progress in low-power processors and miniature sensors to design and control a miniature quadrotor. This is a rather difficult problem in the field of miniature flying robots (MFR) that are used in search and rescue missions, after earthquakes, explosions, collapsed buildings, etc, since such a MFR should fit through small openings, maneuver around pillars and destructed wall structures.

- Part III is devoted to autonomous navigation, discussing approaches that contribute to improving UAV autonomicity, a key requirement dictated by the US DOD [12] [15]. This part is composed of four Chapters:

  - Chapter 7 concentrates in micro air vehicle (MAV) obstacle and terrain avoidance building on the notion of utilizing useful but imperfect map information to plan nominal paths through city or mountain terrain. The focal point is that MAVs utilize sensory information to detect and avoid obstacles unknown to the path planner (due to maps being outdated, inaccurate, etc.).
  - Chapter 8 focuses on UAV vision-based navigation and target tracking, demonstrating that the addition of a camera to a UAV allows the vehicle to perform a variety of tasks autonomously. This Chapter presents vision systems developed and tested at the Georgia Institute of Technology using the GTMax unmanned research helicopter. On top of discussing the vision-based navigation system, the Chapter includes demonstrations of an automated search routine for stationary ground targets, as well as a ground target tracking architecture for mobile targets.
  - Chapter 9 describes how vision-based techniques for single UAV localization may be extended to deal with the problem of multi-UAV relative position estimation. The approach is built on the assumption that if different UAVs identify using their cameras common objects in the scene, then, the relative pose displacement between the UAVs can be computed from these correspondences.
  - Chapter 10 derives and tests an evolutionary algorithm based path planner for cooperating UAVs. The scenario under consideration assumes that several UAVs are launched from the same or different but known initial locations. Then, the main goal is to produce 3-D trajectories that ensure a collision free operation with respect to mission constraints. The path planner produces curved routes that are represented by 3-D B-Spline curves. An off-line and an on-line path planner are derived. Both off-line

and on-line path planning problems are formulated as optimization problems, with a differential evolution algorithm serving as the optimizer.

- Part IV refers to diverse applications using UAVs; it includes seven Chapters:

  - Chapter 11 talks about robust non-linear filters for attitude estimation of micro UAVs. It proposes a suite of non-linear attitude observers that fuse angular velocity and orientation measurements in an analogous manner to that of a complementary filter for a linear system. By exploiting the natural geometry of the group of rotations an attitude observer is derived that: requires only accelerometer and gyro outputs; it is suitable for implementation on embedded hardware, and, provides robust attitude estimates as well as estimating the gyro biases on-line.
  - Chapter 12 refers to autonomous solar UAV for sustainable flights. A methodology is presented that is suitable for the global design of a solar powered airplane intended to achieve continuous flight on Earth.
  - Chapter 13 illustrates how integrating optic flow sensing for lateral collision avoidance with a novel MAV platform results in a vehicle that is well suited for flight in near-Earth environments. A novelty is a fixed-wing MAV with hovering capabilities.
  - Chapter 14 is on the topic of dynamic localization of air-ground wireless sensor networks. It presents a method for relative and absolute localization based on potential fields. The relative localization algorithm assumes that distance measurements between sensor nodes are available. For absolute localization, it is assumed that some nodes have GPS absolute position information.
  - Chapter 15 focuses on the problem of decentralized formation tracking of multi-vehicle systems with consensus-based controllers. The problem is stated as multiple vehicles are required to follow spatial trajectories while keeping a desired inter-vehicle formation pattern in time. The Chapter considers vehicles with nonlinear dynamics to follow very general trajectories that can be generated by some reference vehicles. The key idea is to combine consensus-based controllers with the cascaded approach to tracking control, resulting in a group of linearly coupled dynamical systems. The method is general and may be used for both unmanned ground and unmanned aerial vehicles.

- ➢ Chapter 16 describes a complete system including hardware in the loop tuning for a volcanic gas sampling UAV developed at the University of Catania, Italy.
- ➢ Chapter 17 presents two detailed designs on on-board processing systems for small / miniature helicopters with very strict payload limitations. Designs are general and generic enough that may be used across aerial and ground platforms.

- Part V concludes the book. It includes only one Chapter:

  - ➢ Chapter 18 summarizes the book, gives the road map to future developments and designs, talks about the road to complete autonomy and highlights what may be next.

The contributed Chapters reflect mostly current research findings, with the background information needed for completeness purposes. References are included at the end of each Chapter for additional information.

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