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A Survey of Small-Scale Unmanned Aerial Vehicles: Recent Advances and Future Development Trends

Guowei Cai*,§, Jorge Dias*,†,¶, Lakmal Seneviratne*,‡,‖

*Khalifa University Robotics Institute (KURI), Khalifa University, Al Saada Street, Abu Dhabi 127788, UAE
†Institute of Systems and Robotics, University of Coimbra, Portugal
‡Department of Informatics, King's College London, UK

This paper provides a brief overview on the recent advances of small-scale unmanned aerial vehicles (UAVs) from the perspective of platforms, key elements, and scientific research. The survey starts with an introduction of the recent advances of small-scale UAV platforms, based on the information summarized from 132 models available worldwide. Next, the evolvement of the key elements, including onboard processing units, navigation sensors, mission-oriented sensors, communication modules, and ground control station, is presented and analyzed. Third, achievements of small-scale UAV research, particularly on platform design and construction, dynamics modeling, and flight control, are introduced. Finally, the future of small-scale UAVs' research, civil applications, and military applications are forecasted.

Keywords: Dynamics modeling; flight control; guidance navigation and control; flapping-wing; fixed-wing; platform design; rotorcraft; unmanned aerial vehicle (UAV).

1. Introduction

An unmanned aerial vehicle (UAV) is defined as a space-traversing vehicle that flies without a human crew on board and that can be remotely controlled or can fly autonomously [144]. Over the past three decades, the popularity of UAVs or UASs (unmanned aircraft systems, initiated by US Department of Defense in 2005 from the perspective of system) has kept growing at an unprecedented rate. To date, there are over 1000 UAV models being developed in over 50 countries, serving as indispensable assistant for human operators in a broad range of military and civil applications. According to a UAV market forecast conducted by the Teal Group (a leading UAS market research firm), the worldwide UAV expenditures over the next decade will increase annually from the current 5.2 billion to 11.6 billion, and the total amount in the next decade will reach to an incredible 89 billion: UAVs' future is absolutely unlimited.

Among different types of UAVs, small-scale UAVs, which further consist of small tactical, miniature, and micro UAVs (specific definitions are to be given in Sec. 2), are gaining top interest and popularity because:

- Small-scale UAVs are a powerful tool for scientific research due to attractive features such as low cost, high maneuverability, and easy maintenance. Significant progresses in various research areas (e.g., dynamics modeling, flight control, guidance, and navigation) have been made and further benefit autonomy enhancement of UAVs.
- Small-scale UAVs can be implemented in a myriad of civil applications. Typical cases include: (1) emergency monitoring, (2) victim search and rescue, (3) aerial filming, (4) geological survey, (5) weather forecast, (6) pollution assessment, (7) fire detection, and (8) radiation monitoring.
- The role of small-scale UAVs to warfare and defense is unique: for close-range surveillance and reconnaissance

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Email Addresses: §*guowei.cai@kustar.ac.ae*, ¶*jorge.dias@kustar.ac.ae*, ‖*lakmal.seneviratne@kustar.ac.ae*

Table 1. List of acronyms.

Acronyms			
AGL	Altitude above ground level	IEEE	Institute of Electrical and Electronics Engineering
AHRS	Attitude and heading reference system	IMU	Inertial measurement unit
CIFER	Comprehensive identification using frequency responses	LADAR	Laser detection and ranging
CFD	Computational fluid dynamics	LIDAR	Light detection and ranging
COTS	Commercial-of-the-shelf	LOS	Line-of-sight
CNF	Composite nonlinear feedback	LQG	Linear quadratic gaussian
DARPA	Defense Advanced Research Projects Agency	LQR	Linear quadratic regulation
EKF	Extended Kalman filter	MAV	Micro aerial vehicle
FCS	Flight control system	MEMS	Micro-electro-mechanical-systems
FHSS	Frequency hopping spread spectrum	MIMO	Multi-input, multi-output
FOG	Fiber optic gyro	MPC	Model predictive control
GCS	Ground control station	NATO	North Atlantic Treaty Organization
GNC	Guidance, navigation, and control	PID	Proportional-integral-differential
GNSS	Global navigation satellite system	RTOS	Real-time operating system
GPS	Global positioning system	SBC	Single board computer
GTOW	Gross take-off weight	SISO	Single-input, single-output
GUI	Graphical user interface	UAV	Unmanned aerial vehicle
IARC	International Aerial Robotics Competition	UAS	Unmanned aircraft system

in confined battlefield or urban environment, small-scale UAVs that can operate intelligently are an ideal choice for collecting information with zero injury involved.

Numerous documents in the literature can familiarize one with the state-of-the-art development of small-scale UAVs. For rudimentary level, some introductory documents such as [5, 7] can bring readers a basic understanding of UAV's development on various essential issues such as design, operation, sensing, development, automation and autonomy, safety assessment and deployment. From the technical and scientific perspective, the leading-edge research on small-scale UAVs is commonly documented in topic basis, such as autopilot system [15], flapping-wing platform design [33, 123], flapping aerodynamics modeling [4], system identification [41], rotorcraft UAV flight control [65], rotorcraft UAV GNC (guidance, navigation, and control) [49] and path planning [60], fixed-wing UAV path following [132], etc. Besides, some strategic documents such as the unmanned systems integrated roadmap series [121] can help readers predict the future of small-scale UAVs in military and defense applications. However, most aforementioned documents focus on certain subset(s) or specific area (s), and it is indeed rare to find a compact document that can provide a fairly comprehensive review of the evolvement and advances of small-scale UAVs. The absolute necessity has ignited our motivation and driven us to complete this survey work. The contributions of our study are threefold: (1) to present a big picture on the recent development and advances of small-scale UAVs, (2) to provide a comprehensive overview of small-scale UAV research and highlight benchmark results among the huge amount of documented work, and (3) to help readers identify the focuses in small-scale UAVs' future development.

The rest of this paper is organized as follows: in Sec. 2, 132 small-scale UAV models that are commercially available worldwide are classified into three categories: small tactical, miniature, and micro. Associated analyses based on the collected information are provided. Section 3 addresses the evolvement and advances of the key elements belonging to a small-scale UAV, which include onboard processing units, navigation sensors, mission-oriented sensors, communication modules, and ground control station (GCS). Section 4 reviews the representative research results achieved for small-scale UAVs. The small-scale UAVs developed for research purposes are regrouped into three categories: rotorcraft, fixed-wing, and flapping-wing. For each category, the advances are addressed from three perspectives: platform design and construction, dynamics modeling, and flight control. In Sec. 5, the future development trends of small-scale UAVs in research, civil applications, and military applications are predicted. Finally, in Sec. 6, a number of conclusions are drawn. For ease of understanding, all acronyms are summarized in Table 1 before proceeding to the next section.

2. Small-Scale UAV Platforms

A variety of characteristics can be used to classify UAVs, and there is currently no widely acknowledged common method

Table 2. Detailed specifications of small-scale UAVs.

Specs	Small tactical	Miniature	Micro
Size	< 10 m*	< 5 m*	< 15 cm
GTOW	$10 - 25$ kg	< 10 kg	< 100 g*
Speed	< 130 m/s	< 50 m/s	< 15 m/s
Altitude	< 3500 AGL	< 1200 AGL	< 100 AGL*
Range	< 50 km	< 25 km	< 10 km
Endurance	Up to 48 h	Up to 48 h	Up to 20 min

[37]. Our method is a synthesis of (1) the classification adopted in the latest unmanned systems integrated roadmap [121], (2) the classification addressed in [5], and (3) DARPA's definition on micro aerial vehicles (MAVs). Most essential UAV characteristics, including size, gross take-off weight (GTOW), speed, maximum altitude, operational range, flight endurance, as well as purpose of use, have been taken into account. More specifically, based on our classification small-scale UAVs consist of the following three types:

- Small tactical UAVs (also addressed as close-range UAVs),
- Miniature UAVs, and
- Micro UAVs.

Their detailed specifications are provided in Table 2, in which size is quantified by wing- or rotor-span, range is designated under the line-of-sight (LOS) condition, AGL stands for altitude above ground level, and values with "$*$" are determined according to our analysis but not official release. To gain an in-depth understanding on the current status of small-scale UAVs, a comprehensive survey has been completed among over 500 UAS manufacturers listed in [73]. As a result, 132 small-scale UAV models have been located and listed systematically in Tables 3 and 4. Additional information shown in these two tables contains (1) place of origin (Asia, Europe, North America, South America are abbreviated to AS, EU, NA, and SA, respectively) and (2) operational principles (hybrid, flapping-wing, coaxial, duct-fan, single-rotor, and multi-rotor are abbreviated to HB, FW, RC, RD, RM, and RS, respectively).

2.1. *Small tactical UAVs*

Small tactical UAVs feature top performance among the aforementioned three UAV types. Besides, they generally possess highest GTOW and largest wing- or rotor-span. Interested readers are referred to [5, 37] to quantify the differences between small tactical UAVs and larger types (e.g., tactical, high altitude long endurance, medium altitude long endurance, etc.) in terms of the specifications listed in Table 2. Small tactical UAVs are mainly deployed to mobile army battle groups, serving for military operations such as reconnaissance, target designation, monitoring, and airfield security [5]. Besides, they can be also employed in various civil missions such as ship-to-shore surveillance, power-line inspection, and traffic monitoring.

Our survey shows that 18 UAVs, as listed in Tables 3 and 4, fall into the small tactical category. Based on the associated information, the current status of small tactical UAVs can be outlined as follows:

- 13 of the 18 (72%) models are fixed-wing UAVs, which indicates that fixed-wing type's dominance in this category.
- The ratio of civil-to-military models is 11:7, showing the strong demand and cheerful potential of small tactical UAVs in civil applications.
- Besides the conventional fixed-wing and single-rotor types, a number of creative UAV models (such as hybrid V-BAT developed by MLB) have been manufactured, aiming to optimize the aerodynamics or extend the flight envelope. Representative examples for fixed-wing, single-rotor, hybrid, and coaxial small-scale UAVs are displayed in Fig. 1.
- To date, small-scale UAVs are primarily manufactured in three regions: Asia (AS), Europe (EU), and North America (NA). Among them, NA is currently taking lead: 60% (for military applications) and 55% (for civil applications) models are produced in NA. Despite the availability of 18 models, very few records have been found regarding their practical implementations.

2.2. *Miniature UAVs*

Miniature UAVs, compared with the former type, possess reduced traveling speed and payload, and thus operate in a more confined space with decreased flight endurance. Most miniature UAV modules feature foldable and detachable design, which makes them capable of being backpacked by single operator. As such, miniature UAVs are particularly suitable to mobile battle groups for conducting reconnaissance, surveillance, and target-designation. The most well-known case might be the RQ-11B Raven ("R" and "Q" stand for reconnaissance and UAV, respectively), which has been broadly deployed to US Air Force, US Navy, US Marine Corp., and US Special Ops Command. On the other hand, to civil customers miniature UAVs achieve the best tradeoff among cost, maneuverability, weight, payload requirement, and difficulty in maintenance. Miniature UAVs can be conveniently integrated into various civil applications on aerial photography and sensing, communication relay, and newly emerging goods and post delivery. According to our review, up to 113 miniature UAV models (with representative examples shown in Fig. 2) are currently available in the

Table 3. Classification of small-scale UAVs developed for military applications.

Type (region)	Platform (manufacturer)		
Small (AS)	Huma (GIDS)	Orbiter 3 (AeroNautics)	
Small (EU)	ZALA 421-16E (ZALA Aero)		
Small (NA)	CYBird (CyberTechnology)	Honet-maxi (AdaptiveFlight)-RS	ScanEagle (Insitu-Boeing)
	V-BAT (MLB)-HB		
Mini (AS)	AeroSeeker (AeroSeeker)-RM	ALADIN (EMT)	Baaz/Guardian (OM UAV)
	BirdEye-series (IAI)	EWZ-S8 (EWATT)-RM	Fancopter (EMT)-RM
	FireBee (Kadet)	Ghost (IAI)	Mosquito (IAI)
	Orbiter (AeroNautics)	Scout (GIDS)	Skylark ILE (Elbit Systems)
	Vision MK (Integrated Dynamics)		
Mini (EU)	AR4-Light Ray (TEKEVER)	Bayraktar (Baykar)	BlackStar (BlueBear)
	Condor (Bosh Tech)-RS	Copter 1b (SurveyCopter)-RS	CyberQuad (EPS)-RM
	CyberEye/ZYGO (EPS)	Tracker (SurveyCopter)-RS	GULL (Warrior)-HB
	HoverEye (Bertin-Tech)-RS	Ideon (BSK-defense)	Malazgirt VTOL (Baykar)-RS
	NX110m (Novadem)	SurveyCopter4 (Cassidian)-RS	Swiper (Bosh Tech)
	TRACKER (Cassidian)	T-series (Enics)	UX-SPYRO (UAVISION)
	Vigilant (UAVSI)	X1-series (Sky-Watch)-RM	ZALA 421-08 (ZALA Aero)
	ZALA 421-21 (ZALA Aero)-RM		
Mini (NA)	Aeryon Series (Aeryon Lab)-RM	Coyote/Manta (Sensintel)	Desert Hawk (Lockheed Martin)
	Dragonfly (Dragonfly)-RM	FH-series (Flint Hills)-RS	Honet (AdaptiveFlight)-RS
	MK-series (VanGuard)-RS	Phantom (VeraTech)-HB	Phoenix-series (UAV Solutions)-RM
	RQ-11B Raven (AeroVironment)	SA-100 Mink (Scion UAS)-RS	SKATE (urora)
	Talon-series (UAV Solutions)	T-Hawk (Honeywell)-RD	Tiger Moth (Lite Machines)-RC
Mini (SA)	BRV-01/02 (BRVANT)	Gyro-series (Gyrofly)-RMy	
Micro (EU)	Black Hornet (Prox Dynamics)		

worldwide market. The current status of miniature UAVs can be summarized as follows:

- For military applications, the ratio of fixed-wing to rotorcraft is 30:22, whereas the ratio in the civil side slightly increases to 34:27. These near-to-1:1 ratios indicate that fixed-wing and rotorcraft types are both essential for either military or civil usage, partially due to the diversity of missions.
- The civil-to-military ratio is (61:52), which again reflects the popularity of miniature UAVs in civil applications.
- Multi-rotor UAVs, which mainly consist of quad, hex, octo, and Y-six styles, are rapidly occupying the market and expressing a golden prospect. Among the surveyed miniature rotorcraft UAVs, 45% and 70% multi-rotor UAV models are manufactured for military and civil applications, respectively. Such significant increase is gained only within the past decade. Besides, their rapid prevalence has been proven by some business successes. For instance, in an announcement given by the Parrot Inc., over 500,000 AR.Drone (a quad-rotor UAV released in January 2010) units have been sold worldwide until December 2013.
- For now the majority of miniature UAVs are manufactured in three regions, that is, AS, EU, and NA.

2.3. *Micro UAVs*

Micro UAV development was initiated by a DARPA's 35 million USD program "micro air vehicles (MAVs)" launched in 1997. The primary aim was to develop a UAV prototype that has a wing- or rotor-span no greater than 15 cm, fly up to 2 h, and carry a day-night imager for operations in combat or urban environments, particularly within buildings. Such requirements have been recently relaxed somewhat (e.g., in terms of size and endurance), partially due to the relatively negative results obtained during the "Phase 1" study ended in 2001.

Black Widow MAV, a flying wing developed by AeroVironment, can be regarded as one of the earliest fixed-wing micro UAV prototypes. In 1999, Black Widow MAV successfully demonstrated its capability of 20 min flight and real-time image (color video resolution) transmission. Its follow-on, named WASP, was further enhanced in terms of wing-structure optimization and battery usage, and further deployed to US Marine Corp., and US Special Ops Command. However, the wingspan of the newest version of WASP is extended to 33 cm, which shifts it out of MAV category according to the above definition.

Another famous case in flapping-wing MAV design is AeroVironment's Nano Hummingbird prototype, which is a

Table 4. Classification of small-scale UAVs developed for civil applications.

Type (region)	Platform (manufacturer)		
Small (AS)	AL-20 (AeroLand)	Black Eagle 50 (Steadicopter)-RS	EWZ-I (EWATT)-RS
Small (EU)	HE series (Helipse)-RS	IT180-series (Infotron)-RC	
Small (NA)	AID-H (AIDrones)-RS	Bricans UAV (Brican)	CH-50 (X.Y. Aviation)
	Flexrotor (Aerovel)-HB	Penguin-series (UAVFactory)	T-15E/16XL (Arcturus)
Mini (AS)	AL-4 (AeroLand)	Hexa/Curiosity (OM UAV)-RM	PARS (RTS Ideas)-RM
	Phantom Series (DJI)-RM	Rover (Integrated Dynamics)	KARI UAV (SmartUAV Dev)-HB
	YU-YAN (Zero Tech)	Zeros-series (Zero Tech)-RM	
Mini (EU)	Aibot X6 (Airbotix)-RM	AID-M (AIDrones)-RM	AR100-B (AirRobot)
	AT-series (Advanced UAV)-RS	Atmos/Argos (CATUAV)	Basal1 (CATUAV)-RM
	Bramor C4EYE (C-Astral)	CoaX (Skybotix)-RC	CSV-series (Tasuma)
	CyberHawk (CyberHawk)	E100/300 (Elimco)	Firefly(AscTech)-RM
	Fulmar (AeroVision)	HEF-series (HighEye)	L-A/M-series (Lehmann Avi)
	MD4-series (Microdrones)-RM	Microdrone (Danish Avi)-RM	MikroKopter (Microkopter)-RM
	MX-SIGHT (UAV Serv & Sys)	Pioneer/Photobot (Unmanned)	Pteryx UAV (Trigger)
	QuestUAV (QuestUAV)	SARAH (Flying-Cam)-RM	Scancopter (Fly-n-sense)-RM
	Scout B1-100 (AeroScout)-RS	Sensefly-series (Danish Avi)	Spy Owl (UAS-Europe)
	SR-series (RotoMotion)-RS	S90 & U130 (Novadem)-RM	W200 (Embention)
Mini (OA)	RQ-84Z (Hawkeye)		
Mini (NA)	Aeromapper (Aeromao)	AR.Drone (Parrot)-RM	AZTEK/ATImapper (AeroSight)
	Boomerang/Devilray (Attopilot)	BRAVO 300 (Crescent)-RM	EASE (CyphyWorks)-RD
	FixedWing (3DRobotics)	G/H/HD-65 (AutoCopter)-RS	Heliplane (Challis)-RS
	IRIS/Y6/X8 (3DRobotics)-RM	Maveric (Prioria)	MP-series (Micropilot)
	PARC (CyphyWorks)-RM	Q4 Drone (TOR robotics)	ResolutionUAS (Atiak)
	Skystinger/Axo (IAT Tech)	Saitis (IAT Tech)-RM	UX5/X100 (Trimble)
	Zephyr (marcusuav)		
Mini (SA)	Carcara-series (Santos Lab)	IMK-8 (IDETEC)-RM	Siro 110 (IDETEC)

ScanEagle Hornet Maxi

V-BAT (Hybrid UAV) IT180 (Coaxial UAV)

Fig. 1. Representative examples of small tactical UAVs.

RQ-11B Raven EBee (Flying Wing)

FlyingCam Dragonfly (Multi-Rotor)

Fig. 2. Representative examples of miniature UAVs.


Black Hornet Hubsan quadcopter

Fig. 3. Representative examples of micro UAVs and MAVs.

result of a two-phase study over five years with four million USD expenditure. Nano Hummingbird is able to perform controlled hovering flight with only one pair of two flapping wings [123]. However, from the public perspective, this effort is currently ceased at this proof-of-concept stage.

The only micro UAV, which truly meets the requirements listed in Table 2 and currently in service, is the Black Hornet developed by Prox Dynamics and shown in Fig. 3. Its main features include single-rotor design with 10.2 cm rotor span, 16 g GTOW, cruise speed up to 10 m/s, real-time video and image transmission, and endurance up to 25 min. It has been deployed to the British Army in Afghanistan since August 2012.

Finally, it should be noted that the recent technology boosting has successfully shrunk many radio-controlled (RC) hobby models into MAV category (e.g., Hubsan micro quadcopter shown in Fig. 3). Their all-in-one onboard design and good attitude stabilization property forecast their potential in being upgraded to MAVs with full autonomy.

3. Advances of Small-Scale UAV's Elements

Prior to addressing any details, let us first have an overview of the general configuration of a UAS, which is shown in Fig. 4. Basically, a complete UAS mainly consists of four parts: (1) a baseline aircraft, (2) optional manual control backup, which is realized via RC link for crash avoidance, (3) a GCS system for remotely monitoring the UAV's in-flight status and intervene the UAV's operation if needed, and (4) an onboard flight control system (FCS) acting as the UAV's brain. Among them, the last two parts are particularly important in terms of functionality. As shown in Fig. 4, a FCS is an systematic integration of seven elements, including:

- Onboard processing units consist of two types: flight control processing unit and mission-oriented processing unit. The former is compulsory for any UAV and mainly responsible for (1) in-flight data collection, analysis, and synthesis, (2) GNC algorithms execution, (3) communication with GCS, and (4) data logging, whereas the latter is optional but commonly possesses advanced computational power for interacting with mission-oriented sensors and high-level tasks such as advanced sensing, task management, and mission planning.
- Navigation sensors provide measurement of the UAV's in-flight status in different spatial coordinates.
- Mission-oriented sensors are the companion to the navigation sensors, providing ground crew additional information (e.g., real-time and first-person-view visional information) required by certain specific missions.
- Communication modules are the rover side of the wireless communication links between the UAV and the GCS. Small-scale UAVs are commonly equipped with more than one communication modules for different types of information exchange (e.g., in-flight data and image data).
- Power source provides electricity to the UAV system in air. Solo or separate power solution is dependent of the specific UAV configuration.
- Data storage is for onboard in-flight or image data storage, and normally required to be immune to strong vibration or shock.
- Optional RC link is the onboard terminal of the RC communication to realize piloted control backup.

In what follows, an overview on the recent technological advances of five key elements, including (1) onboard processing units, (2) navigation sensors, (3) mission-oriented sensors, (4) communication modules, and (5) GCS, is presented.

3.1. *Onboard processing units*

The evolvement of onboard processing units of small-scale UAVs is mainly reflected by the transition from single board computer (SBC) stack to all-in-one board integration, with the year 2005 as the rough watershed between these two stages.

Development of small-scale UAVs before 2005 can be regarded as its dormant state. According to our survey, over 80% of UAS manufacturers were not founded during this period. Instead, many pioneer work on autopilot system construction had been carried out in the academic circle. Among over 20 SBCs with variant form factors, the most popular choice for both flight control and more complex sensor-based processing was the SBC based on the PC/104 and PC/104-plus standard, because of its optimal balance on the following four elements: (1) form factor (96 cm × 90 cm, ISA-bus and PCI-bus compatible), (2) extreme environment design (robust pin-hole connection), (3) expendability (optional function extension board via pin-hole connection), and (4) sufficient processing speed (range roughly from 300 MHz to 1.5 GHz). It should be highlighted that the SBC principally act as a normal desktop or laptop but featuring highly shrunk size and improved anti-vibration capacity. However, in terms of interaction

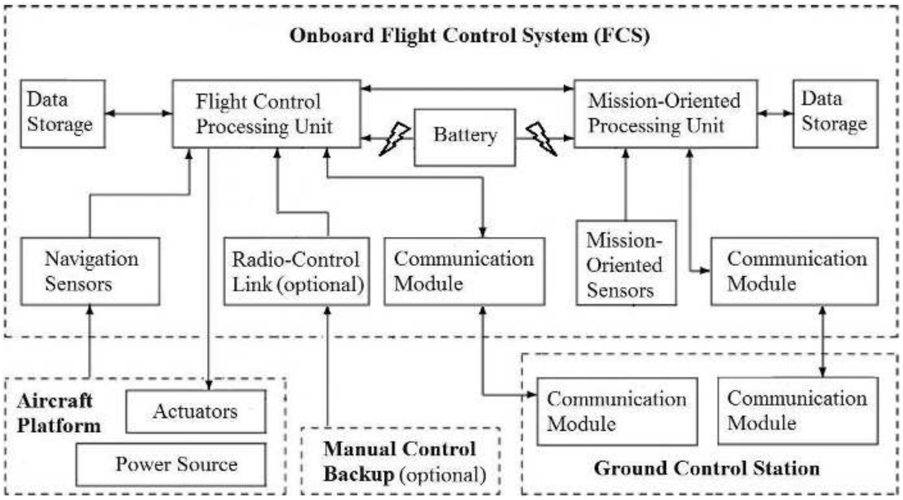

Fig. 4. Block diagram of a typical unmanned aerial system.

with various types of sensors, additional boards are commonly needed to be attached to SBC motherboard. For instance, most PC-104(-plus) SBC motherboards are not compatible with sensors outputting analog signals. Therefore, acquiring analog data is commonly realized by the attachment of a PC-104(-plus) data acquisition card. Interested readers can refer to some representative UAV construction work completed by research groups at National University of Singapore [12], Carnegie Mellon University [59], Chiba University [64], and Georgia Institute of Technology [71]. Despite its recently decreased popularity, its application can be still seen in some small-scale UAVs with strict requirement on reliability. For instance, the ScanEagle, a small tactical UAV developed by Insitu-Boeing, still adopts PC/104(-plus) SBC as part of its FCS.

There are basically three reasons that drive the direct integration of the microprocessor into the autopilot system: (1) the unsuitability of the miniature SBC to the recently born miniature UAVs, particularly for multi-rotor vehicles, (2) the rapid enhancement in IC's computational power (e.g., ARM Cortex-A17 with over 2 GHz processing capacity), and (3) more flexible choice (e.g., over 20 models for just ARM-based microprocessor). The initiation can be traced back to two end-of-life products: Kestrel autopilot (Procerus Technologies) for fixed-wing UAVs, and SPB400 coupled with MNAV-100CA (Crossbow) for both fixed-wing and rotorcraft UAVs. However, the prevalence and success were not formally witnessed until the emergence of high-end hobbyist autopilot systems such as ArduPilot, PixHawk, and DJI Phantom series between 2010 and 2012.

3.2. *Navigation sensors*

There are mainly five types of fundamental sensors belonging to this category: (1) accelerometer, (2) gyroscope, (3) magnetometer, (4) GNSS (global navigation satellite system, typically GPS) receiver, and (5) peripheral sensors (e.g., barometer, odometer, airspeed sensor). Based on these, the three prevalent sensor suits are:

- Inertial Measurement Unit (IMU): formed by accelerometers and gyroscopes (and optionally magnetometers) that are mounted along three strictly orthogonal axes and a microprocessor, providing acceleration and angular rate measurements.
- Attitude and Heading Reference System (AHRS): formed by accelerometers, gyroscopes, magnetometers, and a microprocessor, providing attitude (roll and pitch) and heading estimates besides the raw acceleration and angular rate information.
- GPS-aided AHRS: an integration of AHRS, necessary peripheral sensors, and GNSS receiver that utilizes GNSS's drift-free signals to correct the accumulated error of a pure AHRS, and provide the complete navigation solution, including: position, velocity, attitude and heading, as well as raw sensor measurements, at a sufficient rate.

Their physical and mathematical principles can be referred to textbooks such as [10, 16, 67]. To date, there are over 50 manufacturers worldwide dedicated to the navigation sensor business. A very comprehensive list of the manufacturers who can produce navigation sensor suits for small-scale UAVs, together with the key specifications of their mainstream models, is given in [72]. Our survey indicates that the following analysis and benchmark work can bring readers a prompt understanding on the evolvement of the navigation sensors for small-scale UAVs:

- Industrial-grade (defined quantitatively in [16, 66]), MEMS-based AHRS or GPS-aided AHRS have become the primary choice in small tactical and miniature UAV

construction. The main disadvantages of MEMS accelerometers and gyroscopes are their relatively large bias stability and angular random walk. However, they can be significantly mitigated via a systematic calibration described in [66], and further corrected by GNSS's drift-free signals in calculating the navigation solution. It should be noted that during the last decade a number of tactical-grade (defined quantitatively in [16]) AHRS or GPS-aided AHRS, featuring (1) low-end fiber optic gyro (FOG) utilization, (2) affordable weight and price, and (3) enhanced navigation accuracy, have emerged in the market for small-scale UAV construction.
- MEMS sensor miniaturization has evolved significantly from miniature- to micro- and even to nano-level. According to our survey, currently the smallest industrial-grade GPS-aided AHRS is the surface-mounted VN-200, which has a tiny volume of 22 mm × 24 mm × 3 mm, developed by VectorNAV in 2012.
- Extended Kalman filtering (EKF) has become the standard sensor fusion algorithm in AHRS or GPS-aided AHRS construction. Although the navigation sensor fusion topic gained significant popularity over the last two decades and many other algorithms, which are chronologically summarized in [39], were proposed, few records have been documented regarding their commercial utilization. Two cases found in our survey include (1) the Spatial FOG (Artificial Intelligence inspired algorithm) developed by Advanced Navigation, and ArduIMU (Direct Cosine Matrix algorithm) developed by 3D Robotics.
- In 2011, AeroVironment's Nano Hummingbird prototype (sponsored by DARPA) demonstrated the navigation capability of a nuclear magnetic resonance quantum gyro, which initiated a new era of the navigation sensing technology for small-scale UAVs.

3.3. *Mission-oriented sensors*

Mission-oriented sensors can be basically classified into two categories: passive and active sensors.

Passive sensors primarily refer to various kinds of imagers or cameras, which further consist of the following three types: (1) electro-optical cameras, (2) low-light-level (LLL) cameras, and (3) thermal imagers. More specifically,

- Electro-optical cameras (also called daylight or visible light cameras) are the most natural and popular choice. They use electronics to pivot, zoom, and focus the image, and operate in the visible light spectrum [7]. The rapid advances of electro-optical cameras is expressed by the fact that almost all small-scale UAVs are currently equipped with one of the following daylight cameras: single, stereo, omnidirectional, and optic flow. Among them, the first configuration is particularly prevalent in military- and civil-based aerial monitoring missions, whereas all the four types have been adopted in the academic community for research on vision-based state estimation and perception.
- Low-light-level (LLL) cameras operate in the same manner as the standard optical cameras, but are fed an amplified level of light [5]. This kind of cameras are generally costly and particularly utilized in military-based night surveillance and reconnaissance.
- Infrared (IR) cameras function using IR or heat radiation or heat radiation. They are commonly utilized in battlefield, defense, and home security applications, but have recently extended their usage to some civil applications such as vegetation monitoring.

Active sensors used by small-scale UAVs are mainly miniature laser devices for detection and ranging. Other common terms include: LIDAR (light detection and ranging), LADAR (laser detection and ranging), laser radar, and laser range finder. They use a laser beam to determine the distance to an object or designate a target [7]. Despite its enhanced precision, active sensors, compared with the passive counterparts, are less commonly used in either military or civil applications, mainly because they are relatively heavy, energy consuming, and vulnerable to atmospheric-condition changes. However, research on guidance and navigation based on active sensors have been actively conducted over the past decades, driven by the researchers' enthusiasm on pushing the autonomy of small-scale UAVs to a higher level.

3.4. *Communication modules*

Communication between small-scale UAVs and GCS can be theoretically established via three ways: by laser, by fibre-optics, and by radio. Currently, the only system known in practical operation is radio-based communication, most directly or via relay [5].

As for the frequency bands, as introduced in [5], there are three main systems available: (1) The International Telecommunication Union (ITU) designation that features the coverage of extremely low frequencies from 3 Hz up to the microwave bands, (2) The Institute of Electrical and Electronics Engineering (IEEE) designation that covers the original band ranges developed in World War II, and (3) the most recent NATO and EU designation. Among them, the IEEE designation (specified in Table 5) is most commonly adopted. According to it, small-scale UAVs generally operate in L band (405 to 425 MHz, 915 MHz, and 1.35 to 1.39 GHz) S band (2.45 GHz), and C band (5.8 GHz), all of which are primarily suitable for LOS operations.

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Table 5. IEEE frequency band designations.

Band	Frequency range
HF	3 to 30 MHz
VHF	30 to 3 MHz
UHF	0.3 to 1 GHz
L	1 to 2 GHz
S	2 to 4 GHz
C	4 to 8 GHz
X	8 to 12 GHz
K_u	12 to 18 GHz
K	18 to 26 GHz
K_a	26 to 40 GHz
V	40 to 75 GHz
W	75 to 111 GHz

The advances of communication modules are mainly reflected by the following three aspects:

- Signal modulation: The recent wide utilization of frequency hopping spread spectrum (FHSS) has significantly decreased the chance of lose communication between UAVs and GCS due to signal interference. Such technique spreads the signal across the frequency spectrum and repeats the frequencies witching to minimize the effectiveness of unauthorized interception or jamming [7].
- Device miniaturization: With the rapid evolvement of manufacturing technologies, the footprint of modern communication modules have been significantly reduced to less than 50 cm^2. For instance, as shown in Fig. 5, the 900 MHz, military-level AC4490 module, developed by AeroComm and featuring FHSS and 500 mW transmission power, has a footprint of 4 cm × 4 cm. In another example, the XBee series, which is extremely popular in civil small-scale UAV development due to low cost but qualified performance, has a smaller size of 2.7 cm × 2.4 cm.

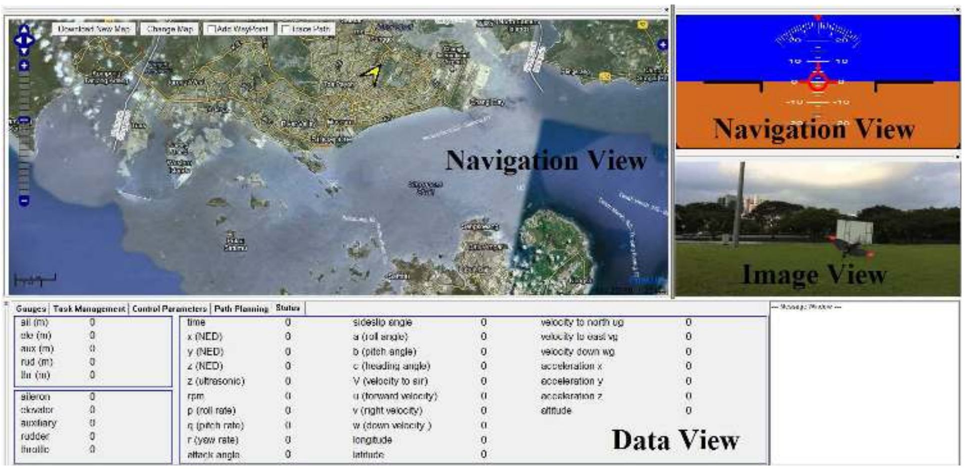
Fig. 5. Size illustration of two representative communication modules.

- Variety: Despite the dominance of a number of leading RF device manufacturers (e.g., Freewave, Microhard, and AeroComm) in military small-scale UAV market, countless modules have recently emerged for civil- and research-based small-scale UAV development.

3.5. *Ground control station*

A GCS for small-scale UAVs is commonly man-portable. A rugged laptop is normally used as the baseline, extended by connecting communication base and antenna. Its main responsibilities include:

- Displaying and monitoring real-time in-flight status data numerically (GUI configuration as shown in Fig. 6),
- Displaying navigation view (GUI configuration as shown in Fig. 6),
- Displaying images received from the video receiver (GUI configuration as shown in Fig. 6),
- Intervene with UAV decision making, mission planning, and specific operation if required,



ail (m) 0
ele (m) 0
aux (m) 0
rud (m) 0
thr (m) 0

aileron 0
elevator 0
auxiliary 0
rudder 0
throttle 0

time 0
x (NED) 0
y (NED) 0
z (NED) 0
z (ultrasonic) 0
rpm 0
p (roll rate) 0
q (pitch rate) 0
r (yaw rate) 0
attack angle 0

sideslip angle 0
a (roll angle) 0
b (pitch angle) 0
c (heading angle) 0
V (velocity to air) 0
u (forward velocity) 0
v (right velocity) 0
w (down velocity) 0
longitude 0
latitude 0

velocity to north ug 0
velocity to east vg 0
velocity down wg 0
acceleration x 0
acceleration y 0
acceleration z 0
altitude 0

Fig. 6. Representative GUI configuration of a GCS (developed by NUS UAV Research Team).

- Sending real-time commands to the avionic system,
- Facilitating the ground users and pilots in automatic control, especially in unexpected occasions such as emergency landing, and
- Logging in-flight data as a backup of the onboard data recording.

The most obvious advance of GCS development in small-scale UAV field is the increasing prevalence of the open-source GCS software toolkits. Two most successful cases are Mission Planner [80] and Q Ground Control [84]. Both are linked to the civil- or research-based UAV products developed by 3D Robotics Inc., featuring robust performance, user-friendly graphical user interface (GUI), and custom defined MAVLink date transmission protocol [79]. The latter toolkit is even fully open-source for experienced end-user customization.

4. Advances in Small-Scale UAV Research

Small-scale UAV's entrance to the academic community has posed challenges in a variety of research fields such as aerodynamics and flight dynamics modeling, flight control, computer vision, and so on. In the meantime, it also brings an excellent opportunity of developing design methodologies and further evaluating their practical performances. The rapidly grown popularity on small-scale UAV research can be clearly observed from the following three aspects:

- Enthusiasm on small-scale UAV research has been widely spread to many institutions worldwide. Table 6 is a primary result of our survey, which indicates that to date there have been 36 world-leading groups that are devoted to the exploration in this promising field.
- A number of competitions and contests on small-scale UAVs have been held over the past two decades, and huge enhancements on robustness, autonomy, and intelligence have been witnessed. Among them, the International Aerial Robotics Competition (IARC) [23] is mostly well known and has the longest history of 24 years. A number of other competitions (such as DARPA's UAVForge [22] and International UAV Innovation Grand Prix [24]) have recently emerged and gained strong interest promptly in the academic circle. In Fig. 7, two representative competition scenarios are provided for illustration.
- Many influential research results on small-scale UAVs have been documented in the literature. Taking monograph as an example, to date over 20 monographs have been published in this promising area, ranging from UAV fundamentals [7, 5], to more advanced topics such as dynamics modeling [59, 136], flight control [12, 64, 88], navigation [8, 64], and guidance [3, 126]. Furthermore, in a number of recent monographs [25, 138–141], research papers particularly on UAV-related topics have been summarized systematically, attempting to serve as topic-based UAV handbooks.

In what follows of this section, we intend to present a brief overview on small-scale UAV research over the past three decades. It should be noted that for scientific research purposes, small-scale UAVs are preferably classified in terms of operation principle, that is, rotorcraft, fixed-wing, and flapping-wing. Such categorization will be followed throughout the rest of this section. For ease of understanding, the remaining contents start with an introduction of fundamental background of small-scale UAV research, and further provide the research overview of rotorcraft, fixed-wing, and flapping-wing UAVs sequentially, focusing on three aspects including: (1) platform design and construction, (2) dynamics modeling, and (3) flight control.

4.1. *Background of small-scale UAV research*

The process of developing a fully autonomous small-scale UAV mainly consists of five steps: (1) platform design and construction, (2) dynamics modeling, (3) flight control, (4) navigation algorithms design and implementation, and (5) guidance algorithms design and implementation. Their fundamental background knowledge is addressed below.

4.1.1. *Platform design and construction*

Platform design and construction is the first challenge to overcome in small-scale UAV research. As open-source autopilot systems with reliable performance (e.g., PixHawk and ArduPilot) were not publicly available until 2010, most research groups listed in Table 6 had to start their UAV research work by scratch-building reliable UAV platforms. To rotorcraft and fixed-wing aircraft that are relatively conventional, the work scope can be further narrowed down to onboard FCS development, which is generally a technical work but proven time- and labor-consuming. Referring to Fig. 4, the main concerns involved in this process include:

- Processing power of both flight control and mission-oriented processing units,
- Sensing capabilities of the navigation sensors and mission-oriented sensors,
- Power consumption and range of the communication modules,
- Anti-vibration design,
- Electromagnetic interference (EMI) design, and
- Layout design for optimal weight distribution.

Table 6. Research institutions with their small-scale UAV platforms and research focuses.

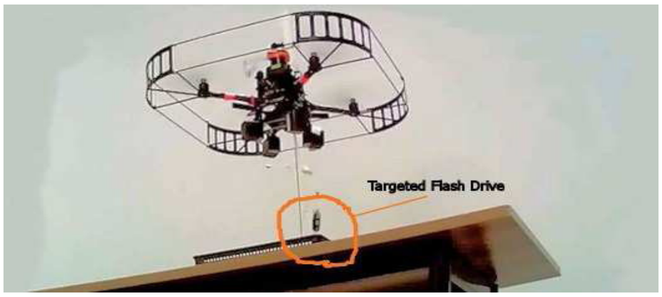
	Small-scale UAV platforms							Recent research focuses				
Institutions (web link)	HB	FW	FX	RC	RD	RM	RS	P	M	C	N	G
Arizona State University [93]						✓	✓			✓	✓	✓
Brigham Young University [85]			✓						✓	✓	✓	✓
Carnegie Mellon University [76]							✓		✓	✓	✓	
Chiba University [113]						✓	✓			✓	✓	
Chiba University [96]		✓						✓	✓			
Delft University of Technology [107]		✓						✓	✓	✓	✓	
EPFL [105]			✓	✓		✓		✓	✓	✓	✓	✓
ETH Zurich [106]							✓		✓	✓		
ETH Zurich [111]						✓		✓	✓	✓	✓	
ETH Zurich [100]						✓			✓	✓	✓	✓
Georgia Institute of Technology [99]	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓
Harvard University [102]		✓						✓	✓	✓	✓	
KAIST [91]			✓			✓	✓		✓	✓	✓	
KAIST [118]	✓		✓		✓	✓	✓	✓	✓	✓	✓	
Khalifa University [104]						✓			✓	✓	✓	
Linkoping University [116]							✓		✓	✓	✓	
Massachusetts Institute of Technology [90]						✓				✓	✓	✓
National University of Singapore [110]	✓					✓	✓		✓	✓	✓	✓
Purdue University [97]		✓						✓	✓	✓		
Queensland University [112]						✓	✓		✓	✓		
ShenYang Institute of Automation [115]							✓	✓	✓	✓	✓	✓
Stanford University [103]						✓			✓	✓		
Technical University of Madrid [98]						✓	✓			✓	✓	✓
University of Arizona [108]			✓						✓	✓		
University of California, Berkeley [95]			✓					✓	✓	✓	✓	✓
University of California, Berkeley [83]		✓						✓	✓	✓	✓	
University of Florida [109]			✓								✓	
University of Maryland [94]		✓				✓	✓	✓	✓	✓	✓	
University of Maryland [78]		✓						✓	✓			
University of Minnesota [117]			✓						✓		✓	
University of New South Wales [74]							✓			✓	✓	
University of Pennsylvania [101]						✓				✓	✓	✓
University of Seville [114]						✓			✓	✓	✓	✓
University of Southern California [75]							✓			✓	✓	
University of Sydney [92]			✓				✓		✓	✓	✓	✓
Wright State University [119]		✓						✓	✓			

4.1.2. *Dynamics modeling*

Dynamics modeling forms the second step in the roadmap. A dynamics model, which can be either linear or nonlinear, represents the relationship between the actuators (i.e., servos or motors) input and the in-flight responses (i.e., acceleration, angular rate, attitude, velocity, and position). The goal of this step is to obtain a mathematics model that is sufficiently accurate to capture aircraft flight dynamics either in certain flight conditions or over a flight envelope. Such a model is the prerequisite of the subsequent FCS design, particularly to model-based control techniques.

Regardless of aircraft types, there are two key elements that directly determine the model's quality: model structure and parameter identification method. For the former, a model can be either simplified to a pure 6-DoF (6-degree-of-freedom) rigid-body dynamics focusing on only one specific flight condition, or complicated to a high-order, highly nonlinear equation set covering a wide flight envelope. In our survey, it is observed that the Newton–Euler equations-based, linear or nonlinear dynamics model structures with significant structural simplification dominate this research area. On the other hand, for parameter identification, assuming the parameterized model is identifiable, there are

NUS's UAV in International UAV Innovation Grand Prix.



Tsinghua University's UAV in IARC competition.

Fig. 7. Research-based UAVs operating in competitions.

basically three methods that have been frequently applied to small-scale UAVs to achieve this aim:

- First-principles modeling: The model is derived based on the established aircraft theories and the results obtained via ground experiments (typically directly measurement and wind-tunnel tests). Although the models derived via this method (typically nonlinear) cover flight dynamics over certain flight envelope, further tuning is generally needed prior to the practical implementation.
- System identification: Flight tests shall be conducted in advance for input–output responses collection. The dynamics model can then be identified by matching the practical response and the counterpart predicted by the model, in either time domain or frequency domain. This method is particularly suitable for linearized model identification.
- Hybrid identification: This technique basically is an integration of the above two methods. Generally, first-principles modeling will be first applied to obtain the estimates of the unknown parameters, and those related to key aerodynamics/flight-dynamics or with high uncertainties will be further tuned via system identification to maximize the model fidelity. This method is applicable to both linear and nonlinear model structures.

4.1.3. *Flight control*

Flight control is used to stabilize the UAV aircraft's attitude and achieve the desired velocity, position, and heading. Over the last three decades, flight control has been extensively studied, and various control techniques have been applied to research-based small-scale UAV platforms, mostly rotorcraft and fixed-wing vehicles. In terms of practical implementation, the classical method that has been widely adopted is the so-called cascaded flight control structure. More specifically, the flight dynamics model obtained in the former step is first decoupled into a number of modes in either the SISO or MIMO format, based on the physical principles and the associated response time. Next, for each mode a proper control technique is selected for designing a controller that can meet certain required performance indices. The entire control system is accomplished via a successive connection of these closed-loop designs. One key issue for such flight control design is that sufficient bandwidth severation must be reserved to ensure the successive-loop-closure design functional properly [8]. According to our review, to date most mainstream control techniques have been studied and applied to small-scale UAVs. As suggested in [49], they can be principally categorized into three groups: (1) model-based linear control, (2) model-based nonlinear control, and (3) model-free control.

Model-based linear control, among these three types, is the most conventional approach. The baseline model is typically linearized with time-invariant parameters, which means the model accuracy can be only held in a specific flight condition or over a narrow envelope. As a result, the control performance can be only guaranteed within the same limited range. Model-based linear control further consists of three sub-groups: (1) PID (proportional-integral-differential) control, (2) optimal control, typically linear-quadratic regulation (LQR) and linear-quadratic-Gaussian (LQG) control [57], and (3) robust control (one most well-known method is H_∞ control [17]).

Model-based nonlinear control is proposed to overcome some limitations of linear approaches, and the controller design is normally based on nonlinear UAV dynamics model [49]. Representative model-based nonlinear control methods include: (1) adaptive control [124], (2) backstepping [51], (3) composite nonlinear feedback (CNF) control [18], (4) feedback linearization [51], (5) gain scheduling [56], and (6) model predictive control (MPC) [31].

Besides the model-based control techniques, some implementations based on model-free control have been documented in the literature. The main characteristic of this control scheme is that the dynamics model is not compulsory, but sufficient manual flight trials should be conducted in advance for system training purpose [49]. Popular techniques belonging to this category include fuzzy logic [9] and learning control [133].

Detailing the background of the aforementioned control technologies is out of the scope of our survey. Instead, for each method addressed, a reference containing the detailed background knowledge has been provided to interested readers.

4.1.4. *Navigation and guidance*

Following the definition given in [49], for small-scale UAVs, navigation can be referred to the process of data acquisition, data analysis, and extraction and inference of information about the vehicle's states and its surrounding environment with the objective of accomplishing assigned missions. Navigation of small-scale UAVs can be conducted in both global and local levels. For the former, qualified flight-state measurement and estimation can be provided by many COTS navigation sensor suits. Therefore, global navigation is currently not a popular research topic in the academic community. On the contrary, research on local navigation has arisen great interest over the last one to two decades: small-scale UAVs commonly operate in a relatively confined space with limited airborne endurance, and researchers worldwide are indeed intending to achieve a reliable navigation solution for small-scale UAVs without involving the vulnerable GNSS signals. Local navigation is mainly achieved by using aforementioned passive or active mission-oriented sensors. In terms of functionality, local navigation can be further categorized into two types:

- State estimation, which refers to the process to estimate various in-flight states of the UAV based on the sensor measurement.
- Perception, which refers to the ability to use inputs from sensors to build a model of the surrounding environment within which the vehicle is operating, and to assign entities, events, and situations perceived in the environment to different classes [49].

Guidance, as indicated in [49], can be defined as the "driver" of a UAV that exercises planning and decision-making functions to achieve assigned missions or goals. Typical functions enabled by the guidance system include: (1) trajectory generation, (2) path planning, (3) mission planning, (4) reasoning, and (5) high-level decision making.

The following review does not detail the recent advances of local navigation and guidance research due to the following three reasons:

- For small-scale fixed-wing UAVs, few research results on navigation and guidance algorithm implementations have been found in the literature. Among the 10 research institutions with small-scale fixed-wing UAVs involved shown in Table 6, only four have proceeded to the navigation research. Furthermore, in terms of the influence, the achieved results are analogous to those based on small-scale rotorcraft UAVs.
- For flapping-wing UAVs, only few results on optical-flow-based pose estimation have been conducted in 2013 based on two flapping-wing UAV prototypes developed at University of California, Berkeley and Delft University of Technology. Furthermore, the practical performances are still preliminary.
- A large amount of work on local navigation and guidance for small-scale rotorcraft UAVs have been documented. In our survey, we found that this research area has been comprehensively reviewed in [49] published in 2012. Therefore, we recommend the interested readers to use this survey as a companion to our work in which the concentrations are particularly on small-scale UAV platform design and construction, dynamics modeling, and flight control.

4.2. ***Research on small-scale rotorcraft UAVs***

Small-scale rotorcraft UAVs are undoubtedly the most prominent platforms among the three types. Many attractive features such as hovering capability, good maneuverability, and acceptable payload, lead to their current prevalence. Research on small-scale rotorcraft UAVs can be traced back to the early 1990s, during which a number of projects (such as [76] at Carnegie Mellon University and [95] at University of California, Berkeley) were launched, aiming for basic autonomy. Such tendency has rapidly grown and spread worldwide. According to our survey, 24 of the 36 research groups listed in Table 6 (70%) have selected small-scale single-rotor, multi-rotor, duct-fan or coaxial rotorcraft UAVs as their experimental platforms. In what follows this section, a brief overview on the research work accomplished in platform design and construction, dynamics modeling, and flight control is presented.

4.2.1. *Small-scale rotorcraft UAV platforms*

Reports on platform design and construction for small-scale rotorcraft UAVs appear frequently in the literature before roughly 2005. Such enthusiasm has recently decreased, as developing a rotorcraft UAV is basically a technical work and thus has low scientific value. Our survey indicates that most institutions have followed similar methodologies in developing their small-scale rotorcraft UAVs. In our opinion, a list of common design features, which is given below, is more helpful to readers in understanding the related work:

- For onboard FCS construction, the elements are generally COTS products. I/O (input/output) compatibility is a primary concern for components selection, and serial communication is widely adopted. The reason for such prevalence is that most researchers sought for a prompt

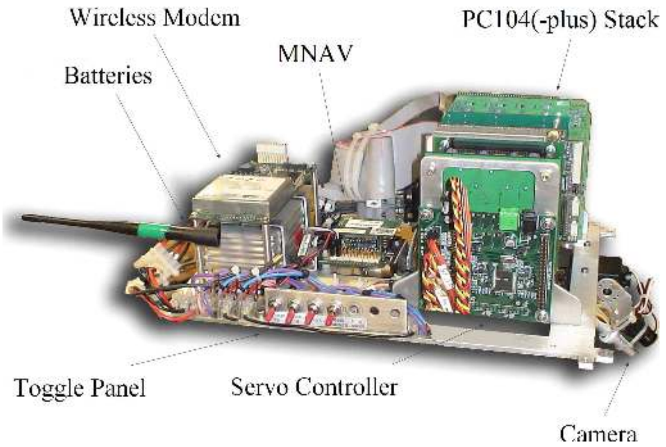


Fig. 8. A FCS design example (developed by NUS UAV Research Team on 2005).

but reliable solution for FCS development. A representative example is shown in Fig. 8.

- Onboard software is generally developed based on real-time operating system (RTOS). Three main options include: QNX [129], RTLinux [130], and VxWorks [131]. In terms of software architecture, hierarchical and modular design was commonly adopted. Key tasks such as data acquisition and flight control execution are programmed as individual modules and assigned with different priorities. A benchmark work is presented in [45], which was developed for Stanford's DragonFly UAVs.
- Aerial platforms developed for RC purposes are widely adopted as the baseline with minimum modification. RC link is commonly retained for crash avoidance.
- For GCS, a rugged laptop is the most typical hardware, whereas the GCS software is commonly developed based on non-RTOS.

Readers can refer to the web pages provided in Table 6 to trace individual development work completed by the listed research groups. Besides, a number of novel designs have been documented recently in the literature and shown cheerful prospects, particularly focusing on: (1) operational principle (e.g., Samara-inspired rotorcraft UAV at University of Maryland [137]), and (2) rotorcraft peripheral design (e.g., Euler spring protection design for coaxial UAV at EPFL [53]).

4.2.2. *Dynamics modeling of small-scale rotorcraft UAVs*

Challenges for dynamics modeling of small-scale rotorcraft UAVs exist in both model structure establishment and parameter identification. The operation principle of rotorcraft leads to the necessity of coupling rotor flapping dynamics with the baseline 6-DoF rigid-body dynamics. The simplification of the complex, nonlinear rotor flapping dynamics is tricky and heavily affects the identifiability of the entire model. On the other hand, the high-order model structure involves more parameters and significantly increases the difficulty of parameter identification. In the literature, work on dynamics modeling have covered all three main rotorcraft types (i.e., single-rotor, coaxial and multi-rotor), despite the dominance of the work on single-rotor UAVs. According to our survey, the following research achievements are representative and highlighted as follows:

The result presented in [61] can be regarded as one of the most influential modeling work for small-scale rotorcraft UAVs. The main contributions are twofold: (1) a minimum-complexity model structure, which adopts 6-DoF rigid-body dynamics as the baseline and integrates simplified rotor flapping dynamics, stabilizer bar dynamics, and factory-installed yaw rate gyro dynamics, is proposed, and (2) CIFER (Comprehensive Identification from FrEquency Responses), a professional frequency-domain identification toolkit developed by NASA Ames Research Center, is first applied to small-scale rotorcraft UAVs to obtain fairly accurate results for both hover and forward flight conditions. Indeed, many subsequent modeling work use this pioneer work as the baseline by either adopting the proposed model structure or CIFER utilization.

Roughly in the same period, hybrid identification has been explored and successfully applied to single-rotor UAV dynamics identification. In [13, 21], suitable nonlinear model structures are proposed, and CIFER is further utilized for parameter fine tuning. The nonlinear models obtained are able to cover fairly wide envelopes, and both can be further linearized for model-based flight control design.

For small-scale multi-rotor UAVs, an advanced research result has been documented in [42]. Particular effort is put in propeller aerodynamics study, and a nonlinear model for a miniature quad-rotor UAV, which is able to cover flight dynamics in acrobatic maneuvering such as stall turn, is developed.

In [1, 2], the dynamics modeling topic is considered through the novel perspective of state-action trajectories. A baseline 6-DoF model structure is adopted and roughly identified first. The parameters are further refined via selected learning techniques (linear regression and apprenticeship learning in the cited work) based on a batch of flight records on certain specified acrobatic flight trajectories. As a result, a nonlinear model, which is capable of capturing the flight dynamics of the specific acrobatic maneuvers, is obtained.

Interested readers can refer to other modeling work for small-scale rotorcraft UAVs via two surveys presented in [41, 49]. A number of books that provide details on CIFER-based system identification [59, 64, 136] are also recommended. Finally, it should be noted that in a few work documented, estimation methods based on neural network, unscented Kalman filter, genetic algorithm, etc., are proposed and implemented for dynamics modeling of small-scale rotorcraft UAVs. However, it is difficult to find sufficient justifications on their superiority over the classical methods such as PEM. Similar situation also applies to the modeling work for small-scale fixed-wing UAVs.

4.2.3. *Flight control of small-scale rotorcraft UAVs*

Over the past three decades, researchers worldwide have actively applied various control techniques to achieve automatic flight control for their small-scale rotorcraft UAV platforms. Such enthusiasm can be clearly seen from Table 6, in which all the 23 research groups with small-scale rotorcraft UAV research involved have conducted research on flight control. According to our survey, results on flight control synthesized with sensor-based navigation have frequently appeared in the literature over the last three years.

Table 7 provides benchmark work in terms of practical implementation of the control techniques addressed in Sec. 4.1.3, together with the automatic flight maneuvers achieved. Interested readers are referred to [49] for other flight control work completed for small-scale rotorcraft UAVs to gain a comprehensive understanding of this research area. The overview on the current accomplishments leads us to two key observations:

- From the perspective of control techniques implementation on small-scale rotorcraft UAVs, it is somewhat difficult to justify the superiority of the advanced model-based

Table 7. Representative flight control work implemented on small-scale rotorcraft UAV.

Control technique	Work	Brief description
PID control	[125]	PID control is applied successively to the decoupled SISO attitude, velocity, and position dynamics, and precise hover with 0.2 m deviation is achieved.
LQR (optimal control)	[43]	LQR control is applied to a quad-rotor UAV prototype for velocity and position control with the assistance of an indoor tracking system.
H_∞ (robust control)	[12]	H_∞ γ-suboptimal controller is designed for the coupled MIMO attitude and heading dynamics, and further evaluated based on the selected handling qualities in CONDUIT [135] design environment. The controller is flight-tested via a predefined maneuver series including cruise, backward, and sideward maneuvers with moderate speed.
Adaptive control	[47]	An adaptive control technique, named pseudo control hedging (PCH), is applied for position control. Pole-placement is utilized for inner- and outer-loop bandwidth separation. The resulting controller features the capability of handling inaccurate flight dynamics and tracking desired position precisely.
Backstepping	[70]	Backstepping control technique is applied to both attitude stabilization and position tracking. Stability of the closed-loop system is proved, and way-point flight test is conducted.
CNF control	[11]	CNF control is applied to the decoupled SISO position and heading dynamics, and autonomy is achieved for a predefined maneuver series including cruise, backward, and sideward maneuvers with moderate speed.
Feedback linearization	[50]	Flight control is designed for a quad-rotor UAV by deriving a mathematical model and transferring the structural properties into successive attitude and translation dynamics. Partial passivation design and inverse dynamics techniques are used to synthesize the controller designed. Flight tests on various modes such as attitude tracking and way-point navigation are conducted [49].
Gain scheduling	[134]	Gain scheduling technique is used to handle the transition of multiple PID controllers designed for different flight conditions. Hover to forward automatic transition is flight-tested.
MPC	[52]	A nonlinear MPC is developed for position control of a single-rotor UAV by minimizing the cost function using a gradient-descent method. Flight test on position tracking has been conducted to validate the design feasibility.
Fuzzy logic	[32]	Fuzzy logic control is applied to decoupled roll, pitch, heading, and heave dynamic modes of a single-rotor UAV. The controllers developed are tested in over 300 flight tests for guaranteeing the reliability.
Apprenticeship learning (learning control)	[2]	Apprenticeship learning approach is incorporated in the flight control design for a single-rotor UAV. Using a 6-DoF baseline model, apprenticeship Learning is adopted to refine partial parameters for a specific acrobatic maneuver, and LQR controller is designed and tested. Such procedure is recursively executed until qualified performance is achieved. A wide range of acrobatic maneuvers are successfully tested.

linear or nonlinear control schemes over the classical, widely used ones such as PID and LQR. For now, various advanced control techniques have been studied and tested on research-based rotorcraft UAVs. However, it is indeed rare to see any significant flight performances enhancement because of their usage. Such awkward situation is partially due to the fact that the majority of flight control work concentrates on the routine flight conditions or envelopes, in which the rotorcraft dynamics holds a good linearity and thus can be properly handled by classical control techniques.

- Achieving autonomous control for aggressive or acrobatic maneuvers did not ignite strong interest, and the accomplished work are all based on learning control techniques. The reasons for such situation are mainly twofold: first, the nonlinear dynamics models generated by first-principles or hybrid modeling approach are commonly not able to accurately cover the highly complex and nonlinear dynamics of the aggressive or acrobatic maneuvers. Furthermore, it is extremely difficult, or even impractical to build up such physically meaningful models via flight experiments. As a consequence, model-based linear or nonlinear control techniques cannot be applied in aggressive or acrobatic maneuver control. Second, from the perspective of practical implementation, most current navigation and guidance work only require flight control in the routine flight envelopes. The necessity of conducting research on aggressive or acrobatic flight control is thus relatively weak.

4.3. *Research on small-scale fixed-wing UAVs*

Small-scale fixed-wing UAVs as research platforms are generally less popular than the rotorcraft counterparts. As shown in Table 6 only 10 of the 36 research groups listed have conducted research based on small-scale fixed-wing UAVs. Such inactivity is partially caused by: (1) the maturity of the small-scale fixed-wing UAVs in both military and civil applications, and (2) theory and algorithm validations based on small-scale fixed-wing UAVs need to be conducted in outdoor environment, which is relatively more complex and time- and labor-consuming.

4.3.1. *Small-scale fixed-wing UAV platforms*

It has been observed that most design and construction work of small-scale fixed-wing and rotorcraft UAVs share the features addressed in Sec. 4.2.1 in common. Readers are thus referred to the aforementioned feature list and the web links provided in Table 6 for individual construction work. Furthermore, the following two observations need to be highlighted: (1) micro UAV platform design and performance optimization, as a promising research topic with representative results documented (e.g., [127]) before 2007, is less studied recently, and (2) a number of work on hybrid UAV design by integrating the features of both fixed-wing aircraft and rotorcraft (e.g., Hybrid UAV developed at NUS [110]) has emerged recently.

4.3.2. *Dynamics modeling of small-scale fixed-wing UAVs*

Two main characteristics can be summarized based on our survey of the current dynamics modeling work for small-scale fixed-wing UAVs. First, the majority of documented work focuses on routine flight conditions, which can be well covered by 6-DoF rigid-body dynamics mode. Second, system identification has been primarily adopted for parameter estimation. In what follows, representative modeling achievements are picked out and briefly introduced.

In [27], CIFER is applied to identify the flight dynamics model a miniature fixed-wing UAV in cruise flight condition. Indeed, this work can be treated as a continuity of the benchmark work described in [61] for single-rotor UAVs. Recently, promising results have been documented, regarding dynamics model identification for non-routine flight conditions or envelopes. Two successful cases can be founded in reports [40, 44], in which system identification is applied to model take-off process (based on ARX/ARMAX/BJ models) and perching (based on decoupled 6-DoF rigid-body dynamics model).

Other successful results of dynamics modeling for small-scale fixed-wing UAVs are summarized in a comprehensive overview [41]. Interested readers are also referred to a textbook [54] for more detailed background knowledge on system identification and its application to fixed-wing aircraft.

4.3.3. *Flight control of small-scale fixed-wing UAVs*

The representative results on flight control implementation in small-scale fixed-wing UAVs have been summarized in Table 8. The current status of this research area can be outlined as follows:

- There is indeed a large amount of documents addressing flight control design (and more broadly, in navigation and guidance research area) using various aforementioned control techniques. However, the majority ceases at the simulation step, partially due to the exponentially increased difficulty in practical implementations.
- Implementation results listed in Table 8 are mainly based on PID and model-based linear control methods. Most model-based nonlinear control techniques have not been flight-tested yet.
- The two key characteristics, which are summarized in Sec. 4.2.3 for the flight control of small-scale rotorcraft UAVs, are also applicable to small-scale fixed-wing UAVs.

Table 8. Representative flight control work implemented on a miniature fixed-wing UAV.

Control technique	Work	Brief description
PID control	[8]	PID control is applied successively to decoupled attitude, velocity, and position dynamics. Way-point flight has been tested to evaluate the practicability of the designed controller.
LQG (optimal control)	[55]	LQG control is applied to decoupled longitudinal and lateral flight dynamics. A fully automatic 44-km cross-sea flight is conducted to demonstrate the reliability of the FCS.
μ-synthesis (robust control)	[46]	μ-synthesis is adopted to attitude control of a miniature fixed-wing UAV for robustness enhancement. Cooperated with the PID-based outer-loop guidance controller, the flight control design is evaluated in way-point automatic flight tests.
Adaptive control	[20]	A Model Reference Adaptive Control (MRAC) architecture is proposed, in which adaptive control design is involved for both attitude loop stabilization and guidance logic augmentation. The complete FCS has been tested in a twin-engine miniature fixed-wing UAV with 25% left-wing missing for fault tolerance.
Feedback linearization	[48]	Dynamic inversion and neural network are incorporated in providing an adaptive control scheme for a miniature fixed-wing UAV. Low speed flight envelopes including stall conditions are covered. The proposed flight control is evaluated in real flight tests on UAV transitions from cruse flight into hover and then back.
Neural network	[48]	As described above.

4.4. *Research on small-scale flapping-wing UAVs*

Research on flapping-wing UAVs is an emerging topic since roughly 2000. Over the past decade, eight research groups out of the 36 listed in Table 6 (i.e., 20%) have carried out research in this promising field. Generally, the academic activities on flapping-wing UAVs are still in its infancy: there is still a large amount of work to be done or significantly improved regarding platform design, dynamics modeling, and flight control, and very few successful results have been reported on flapping-wing UAV control and navigation. In what follows of this section, the representative research achievements achieved to date are reviewed briefly.

4.4.1. *Small-scale flapping-wing UAV platforms*

Platform design of small-scale flapping-wing UAVs is extremely challenging. First, a fundamental contradiction exists between (1) decreased aerodynamic efficiency and power transmission, which is due to the small size and light weight of flapping-wing UAVs, and (2) increased thrust-to-weight ratio requirement to overcome the decreasing aerodynamic efficiency. Second, with the above constrains, researchers are required to develop suitable flight schemes instead of simply adopting a well-developed fixed-wing or rotorcraft baseline. Furthermore, strict limitations are posed in terms of size, weight, and processing power for the processing unit, navigation sensors, and mission-oriented sensors, which makes the difficulty of FCS design increase exponentially.

The following analyses focus on 10 platforms summarized briefly in Table 9. Among them, two belong to miniature category (i.e., bird side), seven (i.e., 70%) fall into micro category with around 15 cm wingspan, and one prototype developed by Harvard Microrobotics Laboratory features insect or nano-size. As stated in [123], current flapping-wing UAV design practice is basically an *ad hoc* approach with multiple design, prototype build, and test cycles. Such diversity can be viewed from the following three aspects [33]:

- Wing configuration: The two primary wing configurations documented in the literature are: (1) two-wing flapping, and (2) four-wing clapping. Although the former is the most nature-inspired method, a considerable number of current prototypes (i.e., 40% in Table 9) adopt the four-wing clapping mechanism because of the enhanced stability via oscillation cancellation and increased lift via clap-and-fling [33]. Other less prevalent but prospective configurations such as flexible wing [62, 68] and quad-wing [89] have been also documented.
- Wing geometry design: One key element affecting lift and thrust forces generation is wing geometry. Explorations on this topics have been recently documented in literatures, such as [38], in which wing geometry is characterized by a motion tracking system and the efficiency is determined via the comparison of experimental record on aerodynamic load, and [36], in which thrust-to-power ratio has been increased by 10% by optimizing the orientation of stiffener.
- Drive mechanism: As reported in [33], four drive mechanisms have been successfully applied to flapping-wing UAVs design, including (1) front mounted double pushrod that adopts simplest mechanical design but suffers asymmetric flapping, (2) front mounted double

Table 9. Featured small-scale flapping-wing UAVs.

Platform	Main features
Bird series (Univ. of Maryland) [78]	Flapping-wing, single crank, rudder tail, DC motor actuator
DelFly series (TU Delft) [107]	Four-wing clapping, front mounted double crank or side mounted crank, T-tail, no actuator
Dragonfly Robot (Techject) [77]	Quad-wing, cam-follower drive train, coil actuators, pseudo dragonfly flying style
Bioinspired MAVs (Chiba Univ.) [96]	Four-wing clapping, front mounted double crank, T-tail, DC motor actuator
Speed MAV (Wright State Univ.) [119]	Four-wing clapping, front mounted double pushrod, T-tail, DC motor actuator
Ornithopter UAV (UC Berkeley) [83]	Four-wing clapping, parallel single cranks, T-tail, DC motor actuator
Trinity UAV (Univ. of Maryland) [82]	Flapping-wing, side mounted crank, rudder tail, DC motor actuator, bird size
RoboBee (Harvard Univ.) [102]	Flapping-wing, tailless design, independent wing directional control, PTZ BiMorph actuator, nano-size
Nano Hummingbird (AeroVironment) [81]	Flapping-wing, double pulley drive, DC motor actuator, pseudo hummingbird flying style, four-million USD defense project over five years development
SmartBird (Festo) [86]	Flapping-wing, parallel single cranks, rudder tail, DC motor actuator, seagull size

crank that is varied from the double pushrod setting but with decreased asymmetry, (3) single pushrod that maintains strict symmetry but sustains higher stress, and (4) side-mounted crank that features the gearing axis parallel to the fuselage starboard and relatively complex design. Their implementations on prototyping small-scale flapping-wing UAVs are summarized in Table 9.

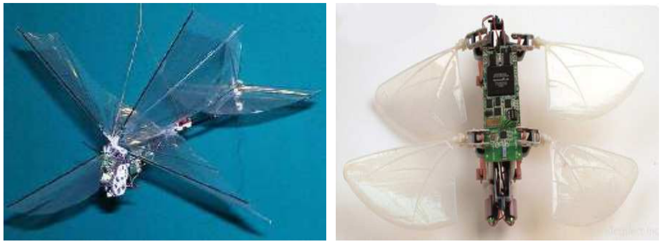
The above three elements are key to the flight capability of small-scale flapping-wing UAVs. Indeed, many other design issues, including (1) directional control scheme [33], (2) actuator type [123], (3) flapping frequency [89], and (4) material [143], also heavily affect the overall flight performance. Table 9 contains a list of latest and representative flapping-wing UAV prototypes together with their design features, with the assistance of Fig. 9 for visual illustration on representative platforms. Interested readers are referred to two comprehensive survey work [33, 123] for more details regarding the platform design and classification of small-scale flapping-wing UAVs.

4.4.2. *Dynamics modeling of small-scale flapping-wing UAVs*

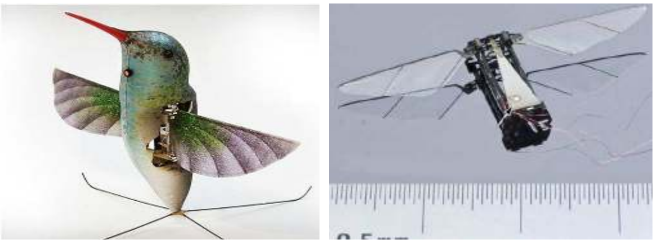
Using the prototypes listed in Table 9 as the baseline, most groups have carried out research on dynamics modeling via either first-principles modeling and system identification.

For the former, our survey has located the following work that represent the start-of-the-art technologies:

SmartBird Trinity



Delfly Dragonfly Robot



Nano Hummingbird RoboBee

Fig. 9. Featured small-scale flapping-wing UAVs.

- Regarding model structure establishment, a nonlinear model is proposed in [26] for an insect-size flapping-wing robot, by integrating 6-DoF Newton–Euler equations, quasi-steady flapping aerodynamics, and linear actuator dynamics. Initial model validation is conducted, and a simulator is built up to assist flight control design. In another representative work documented in [35], a nonlinear model for bird-size flapping-wing prototype has been proposed by integrating Lagrange equations and averaged wing-flapping aerodynamics.
- CFD has been also utilized in this research area initially. For instance, combined flow solver and grid deformation methodology have been applied in [122] to the study of flexible wing kinematics. A CFD model that holds

sufficient accuracy in a narrow flapping frequency range has been obtained.

Furthermore, in a recently published book [128] rigid and flexible flapping-wing aerodynamics has been studied intensively and can be adopted as the baseline of first-principles modeling work. Interested reader can also refer to [4] for a fairly complete review on the recent development of aerodynamics modeling for insect-size flapping-wing robots.

On the other hand, system identification has been applied to flapping-wing UAV dynamics modeling. In [34], a motion tracking system is used to record the cruise flight maneuvers of a bird-size flapping-wing UAV, and a simplified linearized model, featuring accurate pitch and heave dynamics prediction, has been identified. In [14], a micro flapping-wing prototypes is studied, and parameters of a proposed 6-DoF linear dynamics model at near hover condition are identified. As for nano-size flapping-wing UAVs, a representative work has been documented in [29], which implements system identification method to identify partial flight dynamics of a nano-size RoboBee platform with a fixed flapping rate.

Generally, the dynamics modeling research for small-scale flapping-wing UAVs is still in its initial stage. For now research focus is still restricted to the dynamic models expressed in steady-state or quasi-steady format for a number of specific flight conditions such as hover or cruise flight.

4.4.3. *Flight control of small-scale flapping-wing UAVs*

Due to the immaturity of the platform design and dynamics modeling, fewer research activities on flight control for flapping-wing UAVs have been reported. Furthermore, the flight control is generally achieved via classical control (mainly PID), and there is a huge space in terms of autonomy enhancement. The currently documented work can be categorized for micro- and nano-sizes as follows:

- For micro-size level, there are two research groups who have recently achieved initial autonomous flight for their platforms. In [6], researchers at University of California, Berkeley have designed two PID controllers for decoupled 6-DoF longitudinal and lateral dynamics models, and they are executed onboard at 400 Hz to drive 13-gram ornithopter during cruise flight. In [142], DelFly II MAV accomplished autonomous station-keeping in a small wind-tunnel, and similarly two PID controllers are developed for decoupled longitudinal and lateral dynamics control.
- Flight control for nano-size flapping-wing robot is solely pursued by researchers at Harvard Microrobotics Laboratory. Proportional control [28], adaptive control [19], and model-free control techniques [69] have been recently applied to their RoboBee platform to achieve fundamental autonomous flight in second level. It should be noted that to capture the instant flight motion, several markers are attached to the rear side of the RoboBee, which somehow changes the vehicle's dynamics, particularly in terms of inherent stability. Achieving full autonomy for nano-size flapping-wing UAVs is generally still a long run.

5. Future Development Trends

Predicting the future development trends of small-scale UAVs is indeed challenging. Taking the unmanned systems integrated roadmap series as an example, the newest version [121] was released by US Department of Defense in 2013, which has been the seventh edition of this roadmap series. Despite its aim of establishing a vision for the next 25 years and outlines actions and technologies for Department of Defense, industry, universities mainly for UAVs in US, it has been regularly updated every two years since 2005, and significant strategic changes can be observed by comparing two adjacent versions. In this section, we attempt to forecast the development trends of small-scale UAVs in the very near future (2 to 5 years span), for respectively scientific research, civil applications and military applications.

5.1. *UAV research in the near future*

Table 6 lists the currently active academic institutions active in small-scale UAV research, together with their UAV platforms and research focuses. Note that UAV types (i.e., hybrid, flapping-wing, fixed-wing, coaxial, duct-fan, single-rotor, and multi-rotor) are again abbreviated to HB, FW, FX, RC, RD, RM, and RS, and research focuses (i.e., platform design, modeling, control, navigation, and guidance) to P, M, C, N, and G. Based on this summary and more detailed information provided by their research web links, we forecast the research envision on small-scale rotorcraft, fixed-wing, and flapping-wing UAVs as follows.

The activity of the research on small-scale rotorcraft UAVs will continuously soar. A number of specific envisions we have drawn include:

- Multi-rotor UAVs have shown their potential in dominating the rotorcraft UAV research area in both indoor and outdoor environments, mainly because of their low cost, good maneuverability, and various sizes ranging from miniature to micro level.
- Dynamics modeling for rotorcraft UAVs has entered the mature stage.
- Flight control and sensor-based local navigation form the current research mainstream. More experimental results,

particularly conducted in indoor testing environment, will appear in the literature. Advanced sensors such as (1) ranging camera that can provide RGB plus depth information and (2) flash LIDAR with 3D scanning capability, will be gradually incorporated into this research area for performance enhancement of local navigation.
- Future research focuses will gradually shift to guidance algorithm development and implementation, particularly for multi-UAV cooperative control, perception, and mission planning.

As for small-scale fixed-wing UAVs, the following three points can be predicted:

- In terms of platform design and construction, hybrid UAV by incorporating VTOL functions will gain increasing popularity, whereas the effort on micro fixed-wing UAV will continuously decrease.
- Research on dynamics modeling and flight control for fixed-wing UAVs has saturated. As a possible extension, more results will be documented for aggressive or acrobatic flight conditions or envelope.
- Similar to rotorcraft UAV side, navigation and control will be the main research focuses in the near future, while more results will be progressed from simulation to practical implementation.

Lastly, the promising research on small-scale flapping-wing UAVs will gain an increasing popularity. More influential work is expected to be carried out in:

- More advanced platform design, particularly in micro and nano levels,
- Dynamics modeling using the aforementioned three techniques (i.e., first-principles modeling, system identification, and hybrid modeling),
- Application of model-based linear and nonlinear flight control techniques for autonomy and performance enhancement, and
- Vision-based state estimation and perception.

5.2. *Civil applications in the near future*

The ultimate goal of small-scale UAVs for civil applications is a scene like "Small aerial vehicles operate as normally as seeing mail trucks on the road today". The information gathered during our survey drive us envision the future of the civil side from two aspects: aviation regulation and applications.

5.2.1. *Aviation regulation*

A primary factor that limits the expansion of civil small-scale UAVs is their over restricted airspace operation. As stated in [58], almost all the civil applications require access to either a country's specific national air space (NAS) and/or foreign air space at some point in the flight pattern. According to the review provided in [7, 5], neither any national-level authority (e.g., FAA in US and CASA in Australia) nor the international-level authority (International Civil Aviation Organisation) has established a comprehensive aviation regulation for civil applications. Achieving this goal is indeed challenging: the concerns on safety, ethics, and privacy due to civil UAV's large deployment, which are detailed in [30], is kept increasing, whereas the majority of civil UAVs possess insufficient intelligence and thus cannot mitigate the stress. Despite the tough situation, some initial effort has been made recently. For instance, in 2013 US Department of Transportation released the first roadmap of the future integration of civil UAV in the NAS [120]. An optimistic estimate is further given by BBC [63], stating that the NAS is expected to be opened up to civil UAVs in US by 2015 and in Europe by 2016.

5.2.2. *Applications*

The current applications of small-scale civil UAVs can be generally categorized into three groups: (1) aerial sensing, (2) goods or post delivery, and (3) communication relay.

Aerial sensing, in the near future, will still dominate the civil UAV market. Sensing, more specifically consists of photography and monitoring. Representative applications for the former include (1) emergency monitoring, (2) victim search and rescue, (3) aerial filming, and (4) geological survey, whereas the latter mainly contains (1) weather forecast, (2) pollution assessment, (3) fire detection, and (4) radiation monitoring. The common feature of aerial photography and sensing is that the UAV mainly acts as a carrier, carrying remote imager or mission-oriented sensors to accomplish certain predefined mission. Furthermore, lots of the aforementioned missions prefer human pilot to have the higher control authority. The relatively lower requests on UAV autonomy and operational range enable the continuous popularity. The major focus of UAV development for this category will be the payload increasing and the platform robustness enhancement (e.g., more advanced motor and electronic-speed-controller manufacturing technology and airframe design using lighter but higher-strength material).

Goods or Post Delivery is a recently emerging application. The strong interest on this application is ignited by the rapid maturity of hobby-based multi-rotor UAVs over the past five years. A number of pioneer achievements have been conducted in 2013 (e.g., the package delivery test conducted by Amazon's Prime Air Octocopter), aiming to initially examine the feasibility. The challenge posed by this novel application resides in three manifolds: UAV robust performance, intelligence, and flight endurance. Among them,

- The first request is recently not regarded as a formal barrier: in a latest record-breaking demo [87], an S1000 octocopter has successfully conducted a 72-h flight using an external powering system, indicating the maturity of the industry-level UAV manufacturing technology.
- The growing popularity of drones delivery will expedite the UAV intelligence enhancement and further the aviation regulation progress of civil UAV. A stronger liaison and technology transfer from leading UAV research institutions to their industry partners (e.g., PixHawk autopilot system, from ETH's Computer Vision and Geometry Lab to 3D Robotics Inc.) will form an effective solution to this issue.
- The goods or post delivery market will be primarily occupied by multi-rotor civil UAV due to the features like simple physical construction and low cost.

The possibility of utilizing civil UAVs as telecommunication relay or airborne communication router has been addressed in many UAV introductory documents. However, our survey does not find any well-documented record on civil UAVs serving as communication relay. The necessity as well as the prosperity will be still in the infancy stage.

5.3. *Military applications in the near future*

Our prediction on the development of military small-scale UAV is mainly based on two sources: (1) the seven editions of unmanned systems integrated roadmap from 2000 to 2013, and (2) the UAS market analyses conducted by two major UAS market research firms (i.e., Teal Group Corporation and MarketResearch.com). We extract the information related to small-scale UAVs and briefly outline its future for military service as follows:

- Demand of small-scale UAVs will increase annually, and there would be totally over 10,000 sets of small-scale UASs (i.e., each set consists of one or more than one UAV units) serving for US military by the end of 2020s. Despite the model variety, military are still strict to a very limited number of leading UAV manufacturers (such as AeroVironment and Insitu-Boeing).
- Fixed-wing will still take the dominance in military market: the ratio of fixed-wing to rotorcraft is around 97:3.
- Customization and miniaturization of onboard sensors will be reinforced to enhance the efficiency of information collection and better suit various mission environments.
- The effort on weaponry of small-scale UAVs (particularly fixed-wing type) will be further strengthened by extending from delivery or information gathering to carrying explosive for target damage.
- A new deployment scheme, named Manned-Unmanned System Teaming (MUM-T), has been proposed. Small-scale UAVs will be playing an essential role in forming small and agile manned-unmanned systems to mobilize quickly to deter and defeat aggression.
- Training on small-scale UAVs will be further regularized and spread to both officers and enlisted soldiers.

6. Conclusion

We have presented a fairly comprehensive overview on the recent advances of the small-scale UAVs from three key perspectives. A detailed survey has been conducted on 132 small-scale UAV models available worldwide. Based on the collected information, the small-scale UAVs are classified into three categories (i.e., small-tactical, miniature, and micro), and a brief but precise introduction on the advances of current UAV platforms has been presented. Based on the understanding on the overall picture, we narrow down the scope to the UAV element level, and have sequentially reviewed the advances of all key elements of a small-scale UAV, including: onboard processing units, navigation sensors, mission-oriented sensors, communication modules, and GCS. The third part of this paper briefly reviews the advances of small-scale UAVs in the academic communities. A regrouping, based on fixed-wing, rotorcraft, and flapping-wing types, is adopted, and for each category, the benchmark work and current state-of-the-art technologies for three essential aspects (i.e., platform design and construction, dynamics modeling, and control) are analyzed. Finally, we have completed this survey work by providing a forecast of the small-scale UAV's 2- to 5-year future in military utilization, civil utilization, and scientific research.

References

[1] P. Abbeel, A. Coates, M. Quingley and A. Y. Ng, An application of reinforcement learning to aerobatic helicopter flight, in *Proc. Adv. Neural Inf.* (2007).

[2] P. Abbeel, A. Coates and A. Y. Ng, Autonomous helicopter aerobatics through apprenticeship learning, *Int. J. Robot. Res.* **29**(13) (2010) 1–31.

[3] A. Abdessameud and A. Tayebi, *Motion Coordination for VTOL Unmanned Aerial Vehicles: Attitude Synchronisation and Formation Control* (Springer, 2013).

[4] S. Ansari, R. Zbikowski and K. Knowles, Aerodynamic modelling of insect-like flapping flight for micro air vehicles, *Prog. Aerosp. Sci.* **42** (2) (2006) 129–172.

[5] R. Austin, *Unmanned Aircraft Systems: UAVs Design, Development, and Deployment* (Wiley, 2010).

[6] S. Baek, F. Bermudez and R. Fearing, Flight control for target seeking by 13 gram ornithopter, *Intelligent Robots and Systems*, San Francisco, CA (2011), pp. 286–292.

[7] R. K. Barnhart, S. B. Hottman, D. M. Marshall and E. Shappee (eds.), *Introduction to Unmanned Aircraft System* (CRC Press, 2012).

[8] R. W. Beard and T. W. McLain, *Small Unmanned Aircraft: Theory and Practice* (Princeton University Press, 2012).

[9] L. Biacino and G. Gerla, Fuzzy logic, continuity and effectiveness, *Arch. Math. Logic* **41**(7) (2002) 643–667.

[10] D. J. Biezad, *Integrated Navigation and Guidance Systems* (AIAA, 1999).

[11] G. Cai, B. M. Chen, X. Dong and T. H. Lee, Design and implementation of a robust and nonlinear flight control system for an unmanned helicopter, *J. Mechatron.* **21**(5) (2011) 803–820.

[12] G. Cai, B. M. Chen and T. H. Lee, *Unmanned Rotorcraft Systems* (Springer, New York, 2011).

[13] G. Cai, B. M. Chen, T. H. Lee and K.-Y. Lum, Comprehensive nonlinear modeling of a miniature unmanned helicopter, *J Am. Helicopter Soc.* **57**(1) (2012) 1–13.

[14] J. Caetano, J. Verboom, C. Visser, G. Croon, B. Remes, C. Wagter and M. Mulder, Near-hover flapping wing MAV aerodynamic modelling — A linear model approach, *Int. J. Micro Air Vehicles* **5**(4) (2013).

[15] H. Chao, Y. Cao and Y. Chen, Autopilots for small unmanned aerial vehicles: A survey, *Int. J. Control Autom.* **8**(1) (2010) 36–44.

[16] A. B. Chatfield, *Fundamentals of High Accuracy Inertial Navigation* (AIAA, 1997).

[17] B. M. Chen, *Robust and Hinfty Control* (Springer, 2000).

[18] B. M. Chen, T. H. Lee, K. Peng and V. Venkataramanan, Composite nonlinear feedback control for linear systems with input saturation: Theory and an application, *IEEE Trans. Autom. Control* **48**(3) (2003) 427–439.

[19] P. Chirarattananon, K. Ma and R. J. Wood, Adaptive control for takeoff, hovering, and landing of a robotic fly, *Intelligent Robots and Systems*, Tokyo, Japan (2013), pp. 3808–3815.

[20] G. Chowdhary, E. Johnson, M. S. Kimbrell, R. Chandramohan and A. Calise, Flight test results of adaptive controllers in presence of severe structural damage, *AIAA Guidance, Navigation, and Control*, Toronto, Canada (2010).

[21] M. La Civita, W. C. Messner and T. Kanade, Modeling of small-scale helicopters with integrated first-principles and system-identification techniques, *Forum of the American Helicopter Society*, Montreal, Canada (2002), pp. 2505–2516.

[22] Competition link, DARPA UAVForge Competition, Available at www.uavforge.net/.

[23] Competition link, International Aerial Robotics Competition, Available at www.aerialroboticscompetition.org/.

[24] Competition link, International UAV Innovation Grand Prix, Available at www.uavgp.com.cn/Home/Index.

[25] K. Dalamagkidis, K. P. Valavanis and L. A. Piegl (eds.), *On Integrating Unmanned Aircraft Systems into the National Airspace System*, 2nd edn. (Springer, 2012).

[26] X. Deng, L. Schenato, W-C. Wu and S. Sastry, Flapping flight for biomimetic robotic insects: Part I - system modeling, *IEEE Trans. Robot.* **22**(4) (2006) 776–788.

[27] A. Dorobantu, A. M. Murch, B. Mettler and G. J. Balas, System identification for small, low-cost, fixed-wing unmanned aircraft, *J. Aircraft* **50**(4) (2013) 1117–1130.

[28] P. J. Duhamel, N. Perez-Arancibia, G. L. Barrows and R. J. Wood, Altitude feedback control of a flapping-wing microrobot using an on-board biologically inspired optical flow sensor, *Robotics and Automation*, St. Paul, MN (2012), pp. 4228–4235.

[29] B. Finio, N. Perez-Arancibia and R. J. Wood, System identification, modeling, and optimization of an insect-sized flapping-wing micro air vehicle, *Intelligent Robots and Systems*, San Francisco, CA (2011), pp. 1389–1396.

[30] R. L. Finn and D. Wright, Unmanned aircraft systems: surveillance, ethics and privacy in civil applications, *Comput. Law Sec. Rev.* **28**(2) (2012) 184–194.

[31] C. Garcia and P. Morari, Model predictive control: Theory and practice, *J. Automatica* **25**(3) (1989) 335–348.

[32] R. Garcia and K. Valavanis, The implementation of an autonomous helicopter testbed, *J. Intell. Robot. Syst.* **54**(1) (2009) 423–454.

[33] J. W. Gerdes, S. K. Gupta and S. Wilkerson, A review of bird-inspired flapping wing miniature air vehicle designs, *J. Mech. Robot.* **4**(2) (2012) 1–11.

[34] J. A. Grauer, Modeling and system identification of an ornithopter flight dynamics model, Doctoral dissertation, The University of Maryland (2012).

[35] J. Grauer and J. Hubbard, A multibody model of an ornithopter, in *Proc. AIAA Aerospace Sciences Meeting*, Orlando, Florida (2009).

[36] M. Groen, B. Bruggeman, B. Remes, R. Ruijsink, B. W. van Oudheusden and H. Bijl, Improving flight performance of the flapping wing MAV DelFly II, in *Proc. International Micro Air Vehicle*, Braunschweig, Germany (2010).

[37] S. G. Gupta, M. M. Ghonge and P. M. Jawandhiya, Review of unmanned aircraft system (UAS), *Int. J. Adv. Res. Comput. Eng. Technol.* **2**(4) (2013) 1646–1658.

[38] R. Harmon, J. Grauer, J. Hubbard and J. S. Humbert, Experimental determination of ornithopter membrane wing shapes used for simple aerodynamic modeling, *AIAA Atmospheric Flight Mechanics*, Honolulu, Hawaii (2008).

[39] A. M. Hasan, K. Samsudin, A. R. Ramli, R. S. Azmir and S. A. Ismaeel, A review of navigation systems (integration and algorithms), *Aust. J. Basic Appl. Sci.* **3**(2) (2009) 943–959.

[40] W. Hoburg and R. Tedrake, System identification of post stall aerodynamics for UAV perching, *AIAA Infotech @ Aerospace*, Seattle, WA (2009), pp. 1–9.

[41] N. V. Hoffer, C. Coopmans, A. M. Jensen and Y. Chen, A survey and categorization of small low-cost unmanned aerial vehicle system identification, *J. Intell. Robot. Syst.* **74**(1) (2014) 129–145.

[42] G. M. Hoffmann, H. Huang, S. L. Wasl and C. J. Tomlin, Quadrotor helicopter flight dynamics and control: Theory and experiment, *AIAA Guidance, Navigation, and Control*, Hilton Head, CA (2007).

[43] J. How, B. Bethke, A. Frank, D. Dale and J. Vian, Realtime indoor autonomous vehicle test environment, *IEEE Control. Syst. Mag.* **28** (2) (2008) 51–64.

[44] C. Hu, X. Huang, J. Hu and J. Zhu, System identification of a small UAVs speeding up process before take-off, *2004 Asian Control*, Melbourne, Australia (2004), pp. 392–395.

[45] J. S. Jang and C. Tomlin, Design and implementation of a low cost, hierarchical and modular avionics architecture for the DragonFly UAVs, *AIAA Guidance, Navigation, and Control*, Monterey, CA (2002).

[46] F. Jin, T. Hiroshi and S. Shigeru, Development of small unmanned aerial vehicle and flight controller design, *AIAA Atmospheric Flight Mechanics*, Hilton Head, CA (2007).

[47] E. N. Johnson and S. K. Kannan, Adaptive trajectory control for autonomous helicopters, *J. Guid. Control Dynam.* **28**(3) (2005) 524–538.

[48] E. N. Johnson, M. A. Turbe, A. D. Wu, S. K. Kannan and J. C. Neidhoefer, Flight test results of autonomous fixed-wing UAV transitions to and from stationary hover, *AIAA Guidance, Navigation, and Control*, Keystone, CO (2006).

[49] F. Kendoul, Survey of advances in guidance, navigation, and control of unmanned rotorcraft systems, *J. Field Robot.* **29**(2) (2012) 315–378.

[50] F. Kendoul, Z. Yu and K. Nonami, Guidance and nonlinear control system for autonomous flight of mini rotorcraft unmanned aerial vehicles, *J. Field Robot.* **27**(3) (2010) 311–334.

[51] H. S. Khalil, *Nonlinear Systems*, 2nd edn. (Prentice Hall, 2002).

[52] H. Kim, D. Shim and S. Sastry, Nonlinear model predictive tracking control for rotorcraft-based unmanned aerial vehicles, *American Control*, Anchorage, AK (2002), pp. 3576–3581.

[53] A. Klaptocz, A. Briod, L. Daler, J. Zufferey and D. Floreano, Euler spring collision protection for flying robots, in *Proc. Intelligent Robots and Systems*, Tokyo, Japan (2013), pp. 1886–1892.

[54] V. Klein and E. A. Morelli, *Aircraft System Identification: Theory and Practice* (AIAA, 2006).

[55] C. S. Lee, W. L. Chan, S. S. Jan and F. B. Hsiao, A linear-quadratic-Gaussian approach for automatic flight control of fixed-wing unmanned air vehicles, *Aeronautical J.* **115**(1163) (2011) 29–41.

[56] W. E. Leithead, Survey of gain-scheduling analysis & design, *Int. J. Control* **73**(1) (1999) 1001–1025.

[57] F. L. Lewis, D. Vrabie and V. L. Syrmos, *Optimal Control*, 3rd edn. (Wiley, 2012).

[58] G. Limnaios, Current usage of unmanned aircraft systems (UAS) and future challenges: A mission oriented simulator for UAS as a tool for design and performance evaluation, *J. Comput. Model.* **4**(1) (2014) 167–188.

[59] B. Mettler, *Identification Modeling and Characteristics of Miniature Rotorcraft* (Kluwer Academics Publisher, 2003).

[60] B. Mettler, Z. Kong, C. Goerzen and M. Whalley, Benchmarking of obstacle field navigation algorithms for autonomous helicopters, *Annual Forum of the American Helicopter Society*, Phoenix, AZ (2010) pp. 1–18.

[61] B. Mettler, T. Kanade and M. Tischler, System identification modeling of a model-scale helicopter, Carnegie Mellon University, The Robotics Institute Archive (2000), pp. 1–25.

[62] D. Mueller, J. Gerdes and S. K. Gupta, Incorporation of passive wing folding in flapping wing miniature air vehicles, *ASME Mechanism and Robotics*, San Diego, CA (2009).

[63] News weblink, Amazon testing drones for deliveries, Available at http://www.bbc.co.uk/news/technology-25180906.

[64] K. Nonami, F. Kendoul, S. Suzuki, W. Wang and D. Nakazawa, *Autonomous Flying Robots* (Springer, 2010).

[65] A. Ollero and L. Merino, Control and perception techniques for aerial robotics, *Annu. Rev. Control* **28**(2) (2004) 167–178.

[66] Overview of inertial sensors, Available at www.vectornav.com/support/library.

[67] B. W. Parkinson, P. Enge, P. Axelrad and J. J. Spilker Jr., *Global Positioning System: Theory and Applications*, Vol. II (AIAA, 1996).

[68] M. Percin, Y. Hu, B. W. van Oudheusden, B. Remes and F. Scarano, Wing flexibility effects in clap-and-fling, *Int. J. MAV* **3**(4) (2011) 217–227.

[69] N. Perez-Arancibia, P. J. Duhamel, K. Ma and R. J. Wood, Model-free control of a flapping-wing flying microrobot, in *Advanced Robotics* (Montevideo, Uruguay, 2013).

[70] J. M. Pflimlin, P. Soures and T. Hamel, A hierarchical control strategy for the autonomous navigation of a ducted fan flying robot, *Robotics and Automation*, Orlando, FL (2006), pp. 2491–2496.

[71] A. A. Proctor, S. K. Kannan, C. Raabe, H. B. Christophersen and E. N. Johnson, Development of an autonomous aerial reconnaissance system at Georgia Tech, *Association for Unmanned Vehicle Systems International Unmanned Systems*, Baltimore, MA (2003).

[72] Product link, IMU/INS/INU manufacturer list, Available at damien.douxchamps.net/research/imu/.

[73] Product weblink, List of UAV Manufacturers, Available at www.uavglobal.com/.

[74] Project weblink, Autonomous Control Project, University of New South Wales, Available at seit.unsw.adfa.edu.au/staff/sites/hrp/research/UAV/index.html.

[75] Project weblink, Autonomous Flying Vehicle Project, University of Southern California, Available at www-robotics.usc.edu/ãvatar/.

[76] Project weblink, Autonomous Helicopter Project, Carnegie Mellon University, Available at www.cs.cmu.edu/afs/cs/project/chopper/www/.

[77] Project weblink, Dragonfly Robot, Techject Inc., Available at innovations.techject.com/.

[78] Project weblink, Flapping Wing MAV project, University of Maryland, Available at terpconnect.umd.edu/∼skgupta/UMdBird/.

[79] Project link, MAVLink Communication Protocol, Available at qgroundcontrol.org/mavlink/start.

[80] Project link, Mission Planner Ground Control Station Software, Available at planner.ardupilot.com/.

[81] Project weblink, Nano Hummingbird, AeroVironment, Available at www.avinc.com/nano.

[82] Project weblink, Ornithopter Flapping-Wing UAV Project, University of Maryland, Available at www.morpheus.umd.edu/research/flapping-wing-flight/index.html.

[83] Project weblink, Ornithopter MAV Project, University of California, Berkeley, Available at robotics.eecs.berkeley.edu/∼ronf/Biomimetics.html.

[84] Project link, QGroundControl Ground Control Station Software, Available at qgroundcontrol.org/.

[85] Project weblink, Small Unmanned Aircraft Project, Brigham Young University, Available at uavbook.byu.edu/doku.php.

[86] Project weblink, SmartBird flapping-wing prototype, Festo Inc., Available at www.festo.com/cms/en_corp/11369.htm.

[87] Project weblink, S1000 72-hour flight test, Available at www.dji.com/product/spreading-wings-s1000/video.

[88] I. A. Raptis and K. P. Valavanis, *Linear and Nonlinear Control of Small-Scale Unmanned Helicopters* (Springer, 2011).

[89] J. Ratti and G. Vachtsevanos, Inventing a biologically inspired, eEnergy efficient micro aerial vehicle, *J. Intell. Robot. Syst.* **65**(1) (2012) 437–455.

[90] Research group weblink, Aerospace Controls Laboratory, Massachusetts Institute of Technology, Available at www.mit.edu/people/jhow/.

[91] Research group weblink, Aerospace Systems and Control Lab, Korea Advanced Institute of Science & Technology, Available at ascl.kaist.ac.kr/systems_09.

[92] Research group weblink, Australian Centre for Field Robotics, University of Sydney, Available at www.acfr.usyd.edu.au/research/.

[93] Research group weblink, Autonomous System Technologies Research Integration Lab, Arizona State University, Available at robotics.asu.edu/.

[94] Research group weblink, Autonomous Vehicle Laboratory, University of Maryland, Available at www.avl.umd.edu/index.html.

[95] Research group weblink, Berkeley Aerobot Team, University of California, Berkeley, Available at robotics.eecs.berkeley.edu/bear/index.html.

[96] Research group weblink, Biomechanical Engineering Laboratory, Chiba University, Available at www.em.eng.chiba-u.jp/∼lab8/research.html.

[97] Research group weblink, Bio-Robotics Lab, Purdue University, Available at engineering.purdue.edu/xdeng/index.html.

[98] Research group weblink, Centro Automatica y Robotica (C.A.R.), Technical University of Madrid, Available at www.vision4uav.com/.

[99] Research group weblink, Flight Mechanics and Controls Group, Georgia Institute of Technology, Available at controls.ae.gatech.edu/wiki/Main_Page.

[100] Research group weblink, Flying Machine Arena Project, ETH Zurich, Available at www.idsc.ethz.ch/Research_DAndrea/Flying_Machine_Arena.

[101] Research group weblink, GRASP Laboratory, University of Pennsylvania, Available at www.kumarrobotics.org/.

[102] Research group weblink, Harvard Microrobotics Lab, Harvard University, Available at micro.seas.harvard.edu/.

[103] Research group weblink, Hybrid Systems Lab, Stanford University, Available at hybrid.eecs.berkeley.edu/starmac/.

[104] Research group weblink, Khalifa University Robotics Institute, Khalifa Unversity, Available at www.kustar.ac.ae/pages/khalifa-university-robotics-institute-kuri/5206.

[105] Research group weblink, Laboratory of Intelligent Systems, Available at EPFL, lis.epfl.ch/.

[106] Research group weblink, Measurement and Control Laboratory, ETH Zurich, Available at www.uav.ethz.ch/.

[107] Research group weblink, Micro Air Vehicle Laboratory, Delft University of Technology, Available at www.lr.tudelft.nl/en/cooperation/facilities/mav-laboratory.

[108] Research group weblink, Micro Air Vehicles Laboratory, University of Arizona, Available at devame.engr.arizona.edu/sergey-v-shkarayev#res.

[109] Research group weblink, Multidisciplinary Unmanned Aerial Systems Research Group, University of Florida, Available at uav.ifas.ufl.edu/index.shtml.

[110] Research group weblink, NUS UAV Team, National University of Singapore, Available at uav.ece.nus.edu.sg/index.html.

[111] Research group weblink, Pixhawk Project, Computer Vision and Geometry Lab, ETH Zurich, Available at pixhawk.ethz.ch/overview.

[112] Research group weblink, Robotics Design Lab, Queensland University, Available at robotics.itee.uq.edu.au/wiki/pmwiki.php?n=Site.Research.

[113] Research group weblink, Robotics & Systems Control Laboratory, Chiba University, Available at mec2.tm.chiba-u.jp/nonami/index.html.

[114] Research group weblink, Robotics, Vision and Control Group, University of Seville, Available at grvc.us.es/en/.

[115] Research group weblink, ServoHeli Lab, ShenYang Institute of Automation, Available at uav.sia.cn/team.php?id=4.

[116] Research group weblink, UASTech Lab, Linkoping University, Available at www.ida.liu.se/∼patdo/auttek/introdu-ction/index.html.

[117] Research group weblink, UAV Research Group, University of Minnesota, Available at www.uav.aem.umn.edu/.

[118] Research group weblink, Unmanned System Research Group, Korea Advanced Institute of Science & Technology, Available at unmanned.kaist.ac.kr/.

[119] Research group weblink, Wright State Center of Excellence, Wright State University, Available at cecs.wright.edu/mav/research/.

[120] Roadmap, Integration of civil unmanned aircraft systems (UAS) in the national airspace system, US Department of Transportation (2013).

[121] Roadmap, Unmanned systems integrated roadmap 20132038, US Office of the Secretary of Defense (2013).

[122] B. Roget, J. Sitaraman, R. Harmon, J. Grauer, J. Hubbard and S. Humbert, Computational study of flexible wing ornithopter flight, *J. Aircraft* **466** (2009) 2016–2031.

[123] M. Ryan and H. Su, Classification of flapping wing mechanisms for micro air vehicles, *ASME Int. Design Engineering and Computers and Information in Engineering*, Chicago, IL (2012), pp. 105–115.

[124] S. Sastry and M. Bodson, *Adaptive Control: Stability, Convergence, and Robustness* (Prentice-Hall, 1989–1994).

[125] D. H. Shim, H. J. Kim and S. Sastry, Control system design for rotorcraft-based unmanned aerial vehicles using time-domain system identification, *IEEE Control Applications*, Anchorage, AK (2000), pp. 808–813.

[126] T. Shima (ed.), *UAV Cooperative Decision and Control* (Society for Industrial Mathematics, 2008).

[127] S. V. Shkarayev, P. G. Ifju, J. C. Kellogg and T. J. Mueller, *Introduction to the Design of Fixed-Wing Micro Air Vehicles Including Three Case Studies* (AIAA, 2007).

[128] W. Shyy, H. Aono, C.-K. Kang and H. Liu, *An Introduction to Flapping Wing Aerodynamics* (Cambridge University Press, 2013).

[129] Software weblink, QNX Operating System, Available at www.qnx.com/.

[130] Software weblink, RTLinux Operating System, Available at en.wikipedia.org/wiki/RTLinux.

[131] Software weblink, VxWorks Operating System, Available at www.windriver.com/products/vxworks/.

[132] P. B. Sujit, S. Saripalli and J. B. Sousa, Unmanned aerial vehicle path following: A survey and analysis of algorithms for fixed-wing unmanned aerial vehicles, *IEEE Control Syst.* **34**(1) (2014) 42–59.

[133] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction* (MIT Press, 1998).

[134] M. Takahashi, G. Schulein and M. Whalley, Flight control law design and development for an autonomous rotorcraft, *Annual Forum of the American Helicopter Society*, Montreal, Quebec (2008), pp. 1652–1671.

[135] M. B. Tischler, J. D. Colbourne, M. R. Morel *et al.*, CONDUIT — A new multidisciplinary integration environment for flight control development, *AIAA Guidance, Navigation, and Control*, New Orleans, LA (1997).

[136] M. B. Tischler and R. K. Remple, *Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples* (AIAA, 2006).

[137] E. Ulrich, Flight Dynamics and Control of Micro-Scaled Robotic Samara (Winged-Seed) Rotorcraft, Doctoral dissertation, University of Maryland (2013).

[138] K. P. Valavanis (ed.), *Advances in Unmanned Aerial Vehicles* (Springer, 2007).

[139] K. P. Valavanis, R. Beard, P. Oh, A. Ollero, L. Piegl and H. D. Shim (eds.), *Unmanned Aircraft Systems* (Springer, 2010).

[140] K. P. Valavanis, P. Oh and L. A. Piegl (eds.), *Unmanned Aircraft Systems* (Springer, 2009).

[141] K. P. Valavanis and G. J. Vachtsevanos (eds.), *Handbook of Unmanned Aerial Vehicles (UAVs)* (Springer, 2013).

[142] C. Wagter, A. Koopmans, G. Croon, B. Remes and R. Ruijsink, Autonomous wind tunnel free-flight of a flapping wing MAV, in *Advances in Aerospace Guidance, Navigation and Control* (2013), pp. 603–621.

[143] R. J. Wood, S. Avadhanula, M. Menon and R. S. Fearing, Microrobotics using composite materials: The micromechanical flying insect thorax, *Robotics and Automation*, Taipei Taiwan (2003), pp. 1842–1849.

[144] R. Yanushevsky, *Guidance of Unmanned Aerial Vehicles* (CRC Press, 2011).

Guowei Cai is an Assistant Professor of Robotics Institute and Aerospace Engineering at Khalifa University. Guowei Cai received his B.E. degree in Electrical and Electronics Engineering from Tianjin University, Tianjin, China, in 2002, and his Ph.D. degree in Electrical and Computer Engineering from National University of Singapore, Singapore, in 2009. From 2008 to 2009, Guowei Cai was a research fellow in the Department of Electrical and Computer Engineering, National University of Singapore, Singapore. From 2009 to August 2012, Guowei Cai was a research scientist in Temasek Laboratories, National University of Singapore. Since August 2012, Guowei Cai has joined Khalifa University of Science Technology & Research as an Assistant Professor. Guowei Cai's research interest is primarily in flight dynamics modeling, control system design, and multiple-agent cooperation of unmanned aerial vehicles. Guowei Cai is currently a member of AIAA and IEEE. He was a recipient of the Best Application Paper Prize at the *7th Asian Control Conference*, Hong Kong, China (2009).

Jorge Dias has a Ph.D. on Electrical Engineering by the University of Coimbra, Portugal, specialization in Control and Instrumentation. Jorge Dias have been Professor at the Department of Electrical Engineering and Computers (www.deec.uc.pt) and researcher from the Institute of Systems and Robotics (ISR) (www.isr.uc.pt) from the University of Coimbra (UC) (www.uc.pt). Jorge Dias research is in the area of Computer Vision and Robotics and has contributions on the field since 1984. He has several publications in international journals, books, and conferences. Jorge Dias has been teaching several courses on Computer Vision, Robotics, Automation, he has supervised several Ph.D. students in the topic of Computer Vision and Robotics. Jorge Dias was been principal investigator in several research projects. Jorge Dias coordinates the Mobile Robotics Laboratory of Institute of Systems and Robotics from University of Coimbra and the Laboratory of Systems and Automation (http://las.ipn.pt) from the Instituto Pedro Nunes (IPN) (www.ipn.pt) — a technology transfer institute from the University of Coimbra, Portugal. Since July 2011, Jorge Dias is on leave of absence to setup the Robotics Institute and research activities on robotics at Khalifa University (Abu Dhabi-UAE).

Lakmal Seneviratne is a Professor of Mechanical Engineering at Khalifa University (KU), UAE (2010-to date) and Professor of Mechatronics at Kings College London (1987-to date). He is also the Associate Provost for Research and Graduate Studies and the Director of the Robotics Institute at KU. He was the founding Director of the Centre for Robotics Research at KCL. His main research interests are centered on robotics and automation, with particular emphasis on increasing the autonomy of robotic systems interacting with complex dynamic environments. He has published over 300 peer reviewed articles on these topics.