Front. Electr. Electron. Eng. China 2010, 5(1): 1–14
DOI 10.1007/s11460-009-0065-3

REVIEW ARTICLE

Guowei CAI, Ben M. CHEN, Tong H. LEE

An overview on development of miniature unmanned rotorcraft systems

Abstract In this article, we attempt to document a technical overview on modern miniature unmanned rotorcraft systems. We first give a brief review on the historical development of the rotorcraft unmanned aerial vehicles (UAVs), and then move on to present a fairly detailed and general overview on the hardware configuration, software integration, aerodynamic modeling and automatic flight control system involved in constructing the unmanned system. The applications of the emerging technology in the military and civilian domains are also highlighted.

Keywords unmanned aerial vehicle (UAV), rotorcraft, aerodynamic modeling, avionic systems, flight control systems

1 Introduction

In recent years, the research and development of unmanned vehicles have gained much attention in the academic and military communities worldwide. Objects like unmanned aircraft, underwater exploiters, satellites and intelligent robotics are widely investigated as they have potential applications in the military and civil domains. They are developed to be capable of working autonomously without a human pilot. The challenge is that they need to deal with various situations that arise in much complicated and uncertain environments, such as unexpected obstacles, enemies attacking and device failures. Besides, they are required to communicate with technical personnel in the ground station. Consideration on a wide range of factors needs to be taken. Control systems for the unmanned vehicles are required to integrate not only basic input-output control laws, but also high-level functionalities for decision making and task scheduling. Software systems for unmanned vehicles are required to perform tasks from hardware driving to the management of device operation, and from traditional input-output control law implementation to task scheduling and event disposal.

An unmanned aerial vehicle (UAV) is an aircraft that is equipped with necessary data processing units, sensors, automatic control and communications systems, and is capable of performing autonomously flight missions without a human pilot. Miniature (or mini) UAVs refer to those ranging from micro aerial vehicles (MAVs) with less than 15 cm wingspan or rotorspan, to vehicles with a payload of a few tens of kilograms. Characterized by unique features such as relatively low cost, small size and great agility and maneuverability, mini UAVs have gained strong interest and made huge progress during the last couple of decades, with numerous applications in the military and civil domains. Examples include the utilization of mini UAVs to destroy anti-air facilities in the battlefield, and to search and rescue victims in dangerous environments. Driven by rapid advances in related areas such as sensor, manufacturing and communication technologies, mini UAVs are growing faster and smarter than ever, and have gradually become an indispensable assistant to human beings.

Based on their shapes and geometric structures, mini UAVs can roughly be characterized into the following four categories:

1) fixed-wing flying vehicles (see, for example, Aladin UAV System[1)] and WASP III UAV System[2)]);

Received July 9, 2009; accepted July 30, 2009

Guowei CAI, Ben M. CHEN (✉), Tong H. LEE
Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576, Singapore
E-mail: bmchen@nus.edu.sg

1) Aladin UAV System. http://www.emt-penzberg.de/index.php?13
2) WASP III UAV System. http://www.avinc.com/uas/small_uas/wasp/

2) rotorcraft (see, for example, Fancopter UAV System[1) and Ref. [1]);

3) flapping-wing models (see, for example, Delfly MAVs[2) and Ref. [2]);

4) other unconventional designs (see, for example, KillerBee Blended-Wing UAV System[3) and Ref. [3]).

Among them, the first two types are currently the most popular choices for practical missions and scientific research, whereas the third category, i.e., the flapping-wing type, has been attracting great attention in the academic circle during the last decade. Some preliminary progresses have been made along the line of research for the flapping-wing UAVs, although it is still too early to talk about their applications in the real environments. Finally, the last type of mini UAVs remains in its initial and conceptual development stage for the time being.

Because the area related to the research and development of the unmanned aerial systems is huge and diversified, we would thus focus our attention on a particular class of UAVs, i.e., the rotorcraft, which happen to be in line with our work at the National University of Singapore (NUS). Shown in Fig. 1 is HeLion, a UAV helicopter built by the research team at NUS, which is performing an autonomous flight test [4,5]. Mini rotorcraft UAVs are commonly upgraded from radio-controlled (RC) single/multiple-rotor vehicles by equipping appropriate avionic systems for automatic control and the execution of specific airborne missions. Besides all the features of mini UAVs mentioned earlier, the rotorcraft has the unique hovering capability, which makes it the best choice for applications within confined areas.

Fig. 1 HeLion

In this paper, we present an overview on the development of the mini rotorcraft UAVs, covering their past, present and future. It is our wish that this work can depict a fairly complete picture of the mini rotorcraft UAVs. The outline of this work is as follows: We highlight in Sect. 2 the historical development of the miniature rotorcraft UAVs. In Sect. 3, we review from a technical point of view four essential components involved in constructing a mini rotorcraft UAV, i.e., the hardware construction, software integration, aerodynamic modeling, and flight control law design. Sect. 4 presents some application examples of the mini rotorcraft UAVs in the military and civilian domains. Finally, we draw some concluding remarks and highlight some possible future directions in the research and development of the related areas in Sect. 5.

2 Brief history of unmanned rotorcraft systems

Although the mini rotorcraft UAV has become popular in the last few decades, its ancestors, Chinese bamboo dragon and Da Vinci's rotorcraft, for example, can be traced to many hundreds or even thousands of years back in history [6]. The technology boost starting from the 1970s has accelerated the birth of the modern UAV and has further brought a huge progress in its development. In what follows, we review the brief history of the modern unmanned rotorcraft systems.

Since the construction of the first full-scale helicopter by Igor Sikorsky in 1941, many attempts have been made to reduce its size and to realize fully autonomous flight. The first hobby-based helicopter with sufficient controllability was built by Dieter Schluter of West Germany in 1968. The flight performance was further enhanced by Kavan Inc., by combining both the Bell and Hiller concepts[4) for the rotor design in 1974 and installing a yaw rate gyro in 1978, respectively. Such a configuration was quickly adopted as a standard by most aero-model manufacturers for mass production. In the early 1980s, the mature model helicopters had become available in hobby shops all over the world. Advances in the embedded system technology and micro electronic mechanical system (MEMS) technology in the 1980s have made it possible to build a light yet powerful avionic system, which integrates all necessary data processing units, sensors and wireless communication devices, to be installed on a hobby helicopter. It eventually led to the birth of modern rotorcraft UAVs.

Since the 1990s, the development of sophisticated and reliable rotorcraft UAVs has rapidly become an attractive research topic in the academic circle worldwide. In 1991, the first international aerial robotics competition was held at Georgia Institute of Technology. The competition started as a university-based event, but soon has grown into a

1) Fancopter UAV System. http://www.emt-penzberg.de/index.php?10
2) Delfly MAVs. http://www.delfly.nl/
3) KillerBee Blended-Wing UAV System. http://www.raytheon.com/
4) Understanding Flybar Mixing. http://www.rchelimag.com/pages/howto.php?howto = 22&page = 1

major international arena for unmanned aerial systems. The successive years of the competition has seen the aerial robots growing in their capabilities from vehicles that can barely maintain themselves in the air, to those that are capable of self-stabilizing, self-navigating, and interacting with surroundings, especially with objects on the ground[1]. Many research works have been carried out to build more advanced hardware platforms, software systems, aerodynamic models, and automatic flight control systems. In 1992, the idea of using very small microphones in military operations was discussed in a workshop conducted by the Defense Advanced Research Projects Agency (DARPA) of the United States[2]. A multi-year, 35-million-US-dollar development program was eventually launched by DARPA in 1997, directly aiming to develop micro-air-vehicles whose largest dimension (wing span or rotor span) is no more than 15 cm. The initial study of the DARPA project ended in 2001. Unfortunately, the results were somewhat negative, showing that a 15 cm UAV is simply too small to be useful or even workable, at least over the short run[2]. Attention has then been shifted to the development of larger miniature UAVs, and their practical applications (see, for example, Ref. [7]).

As mentioned earlier, the development of unmanned aerial systems has recently gained more and more attention in the academic and military communities worldwide. There are many groups that are actively conducting research on the related areas. We list in the following some active groups along with their representative products, i.e., unmanned systems developed, whose information is readily available in the open literature. We should note that the list is far from complete.

1) Baykar Machine Inc. — Malazgirt Mini Unmanned Helicopters;

2) Beihang University — FH Series UAV Helicopters;

3) Carnegie Mellon University — Yamaha-R50-Based UAV Helicopters;

4) Chiba University — Sky Surveyor;

5) Codarra Advanced Systems — AVATAR;

6) Draganfly Innovations Inc. — Draganflyer Series Multiple Rotor UAVs;

7) Epson Tokyo R&D — Micro Flying Robot;

8) ETH Zurich — AkroHeli, PIXHAWK and muFly;

9) Georgia Institute of Technology — Gtmax;

10) High Eye Aerial Service — He and X2F Series UAV Helicopters;

11) Honeywell — Duct-Fan-Based UAV iSTAR;

12) Israel Aerospace Industries — Naval Rotary UAV;

13) Linkoping University — WITAS Helicopters;

14) Massachusetts Institute of Technology — Draganflyer-Based Quadrotor UAV;

15) Nanjing University of Aeronautics and Astronautics — Yujingling Quadrotor UAV;

16) NASA Ames Research Center — Yamaha-Rmax-Based UAV Helicopters;

17) National University of Singapore — HeLion, SheLion, BabyLion;

18) Neural Robotics Inc. — Guncopter;

19) SAAB Aerosystems — Skeldar V-150 VTOL UAV;

20) Shanghai Jiao Tong University — Sky-Explorer;

21) Schiebel — Schiebel UAV Helicopters;

22) Sikorsky Aircraft Inc. — Cypher and Cypher II;

23) Technische Universität Berlin — Marvin Series UAV;

24) University of California at Berkeley — Ursa Major and Ursa Maxima;

25) University of New South Wales — MAVstar;

26) University of Southern California — AVATAR;

27) University of Waterloo — Custom Ducted fan UAV;

28) US Naval Research Laboratories — Dragon Warrior;

29) Yamaha Inc. — R50 and Rmax UAV Helicopters.

3 Technical overview of miniature rotorcraft unmanned vehicles

We highlight in this section a technical overview on some basic and key components in constructing a fully functional miniature rotorcraft UAV, which include the hardware platform construction, software system design and integration, aerodynamics modeling, and flight control law design and implementation. We also include various examples for illustration purposes.

3.1 Hardware construction

Hardware platform construction is the core in building a UAV system. Although mini rotorcraft UAVs are diversified in size, shape, payload and application purpose, all of them, however, share a similar system configuration as depicted in Fig. 2. More specifically, a complete mini rotorcraft UAV system consists of the following four parts:

1) an RC rotorcraft;

2) an avionic system for collecting inflight data, executing automatic control laws, and communicating with the ground station;

3) a manual control system consisting of an experienced pilot and a wireless joystick;

4) a ground system for monitoring the flight states of the UAV and communicating with the avionic system.

3.1.1 RC rotorcraft

The RC rotorcraft has experienced a rapid development during the last three decades. Its maturity clearly appears in the existence of hundreds of professional hobby-purpose

1) International Aerial Robotics Competition. http://en.wikipedia.org/wiki/International_Aerial_Robotics_Competition
2) Miniature UAVs. http://en.wikipedia.org/wiki/Miniature_UAVs

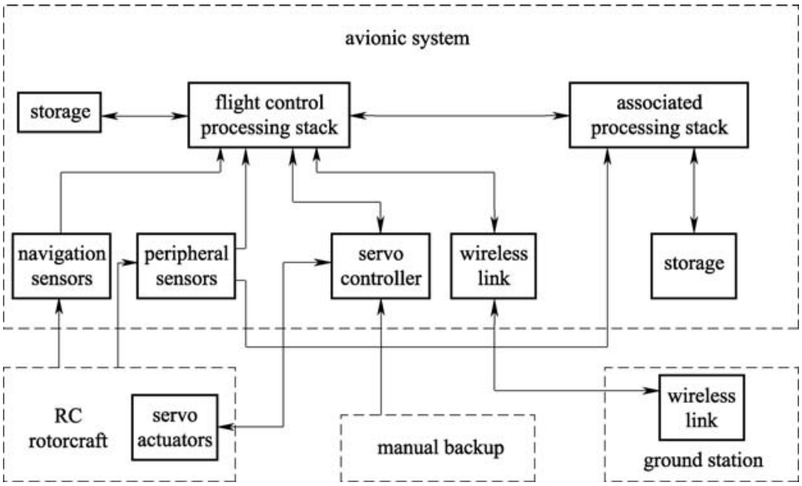

Fig. 2 System configuration of a mini rotorcraft UAV

helicopter products and millions of aeromodeling fans. Despite the increasing popularity of multiple-rotor RC flying vehicles, single-rotor RC helicopters are still dominating in the market and in the research circle. The single-rotor RC helicopters commonly have higher thrust-to-weight ratio, reduced drag, stiffer rotors, and more aggressive head mixing. As such, they can generally achieve greater agility and is able to complete many acrobatic flight motions such as inverted hovering and flapping motion. Interested readers are referred to more acrobatic flight demonstrations on the RC-hobby-related websites (see, for example, Flight Video Gallery[1–3]).

The operation of the single-rotor RC helicopter is generally similar to that of its full-sized counterpart. Small-sized digital or analog servo actuators from well-known vendors, such as Futaba[4] and JR-Propo[5], are equipped to drive the helicopter mechanically. The standard configuration adopted in the RC circle involves five servo actuators as shown in Fig. 3:

1) The aileron and elevator servos are in charge of tilting the swash plate to realize the rolling motion, pitching motion and translational movement.

2) The collective pitch servo is utilized to change the collective pitch angle of the main rotor, which further generates the heave motion. However, there is no such freedom for a small group of low-end fixed-pitch RC helicopters (see, for example, Electric RC Helicopters Community[6]).

3) The throttle servo, cooperating with an engine governor, controls the engine power, which is the second source of heave motion change.

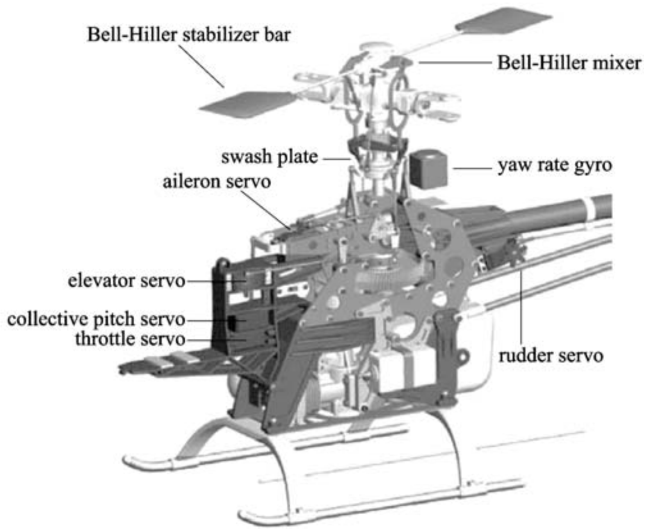

Fig. 3 Typical hardware configuration of single-rotor RC helicopter

4) The rudder servo, generally possessing higher speed and precision, is employed to realize yaw motion control. It is commonly equipped with an additional piezo-electronic yaw rate gyro to facilitate the servo to overcome the over-sensitive dynamics in the bare yaw channel. The configuration for a typical yaw channel is shown in Fig. 4.

We note that a Bell-Hiller stabilizer bar[7], which is the most distinguished feature of the RC helicopter (also shown in Fig. 3), is very often employed for ease to achieve desired stabilization. From the practical point of

1) Flight Video Gallery. http://www.model-helicopters.com/main2_f.php
2) Flight Video Gallery. http://www.rcgroups.com/rc-video-gallery-271/
3) Flight Video Gallery. http://runryder.com/helicopter/galleries/
4) Futaba Servo Actuators. http://www.futaba-rc.com/servos/index.html
5) JR Servo Actuators. http://www.jrradios.com/Products/Servos-Air.aspx
6) Electric RC Helicopters Community. http://www.electric-rc-helicopter.com/
7) Understanding Flybar Mixing. http://www.rchelimag.com/pages/howto.php?howto = 22&page = 1

view, the RC rotorcraft can be further categorized into three types based on its size and characteristics.

1) Type I includes the monsters of the RC rotorcraft. It is generally and relatively large in size and rotorspan. As summarized in Table 1, it has top-level engine power, flight endurance and payload. This type of RC rotorcraft includes Rmax[1] from Yamaha, ZALA 421-02[2] from ZALA Aero, Schiebel S-100[3] from Schiebel, and Dragon Warrior[4] from the US Naval Research Lab (see Fig. 5). Because it is large in size, its aerodynamics is relatively more stable and some of its members adopt a configuration without the stabilizer bar. Compared with the other two types below, Type I rotorcraft is more suitable for long-endurance flight missions.

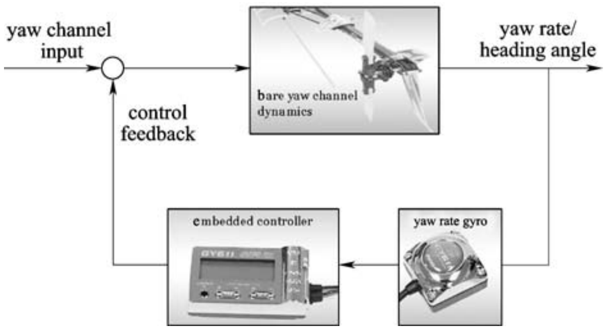

Fig. 4 Configuration of yaw channel in single-rotor RC helicopter

2) Type II covers the main stream of the RC rotorcraft, and it is specially designed for the RC-hobby purpose. Over 100 brands of Type II rotorcraft are currently available in the market. Shown in Fig. 6 are Raptor 90 SE[5] of Thunder Tiger, Dauphin[6] of Hirobo, Maxi-Joker 2[7] of Joker-USA, and Observer-Twin[8] of Bergen, to name a few. As summarized in Table 1, its specifications are far below those of Type I rotorcraft. Although it is not an ideal platform for long-endurance flight tasks, it is a popular choice in the academic research community (see, for

Table 1 Specifications of Type I, II, and III RC rotorcraft

category	type I	type II	type III
fuselage length/m	2.5–4	1–1.5	< 1
fuselage material	aluminum, stainless steel	plastic, carbon fiber	plastic
rotor span/m	3–4	1.5–2	< 0.7
blade number	2/3	2	2
flight duration/min	60–360	15–60	< 10
payload/kg	> 20	2.5–10	< 0.5
power supply/hp	20–50	1.5–4.5	by batteries

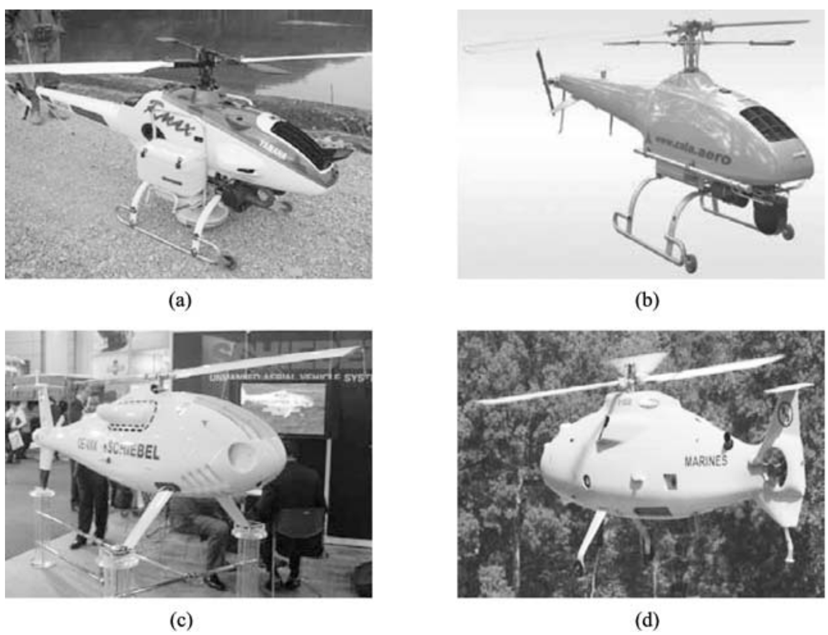

Fig. 5 Type I RC rotorcraft. (a) Rmax; (b) ZALA 421-02; (c) Schiebel S-100; (d) Dragon Warrior

1) Yamaha Rmax Unmanned Helicopter. http://www.yamaha-motor.co.jp/global/news/2002/02/06/sky.html
2) ZALA 421-02 Unmanned Helicopter. http://zala.aero/en/uav/1205400770.htm
3) Schiebel Camcopter. http://www.schiebel.net/
4) Dragon Warrior Unmanned Helicopter. http://cs.itd.nrl.navy.mil/work/dragon_warrior/index.php
5) Raptor 90 SE Helicopter. http://www.tiger.com.tw/product/4891.html
6) Dauphin Helicopter. http://model.hirobo.co.jp/english/
7) Maxi-Joker 2 Helicopter. http://www.joker-usa.com/maxi-joker2.htm
8) Bergen Observer-Twin Helicopter. http://www.bergenrc.com/

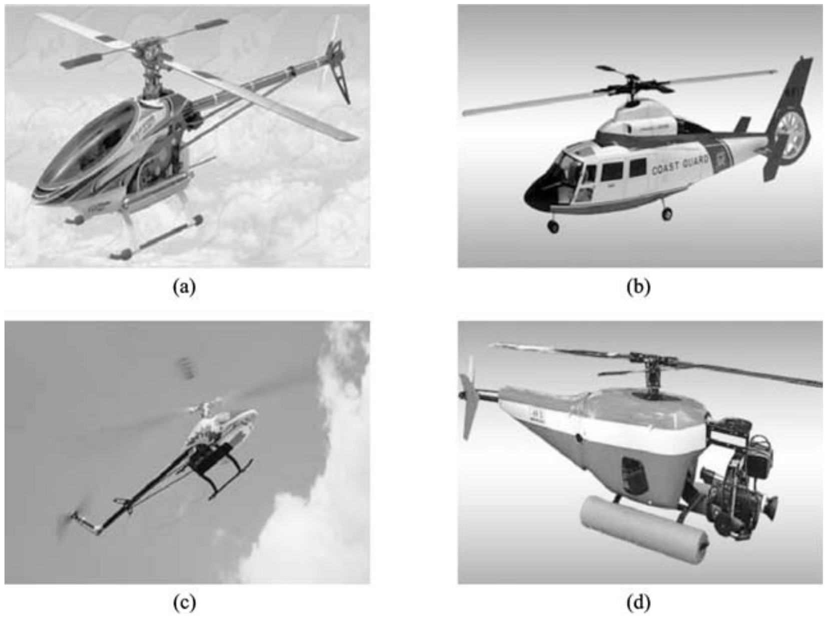

Fig. 6 Type II RC rotorcraft. (a) Raptor 90 SE; (b) Dauphin; (c) Maxi-Joker 2; (d) Observer-Twin

example, Refs. [5,7–9]). Their validity on short-endurance aerial photography has recently been explored by a number of commercial companies (see, for example, AutoCopter Express UAV[1)] and Flying-Cam[2)]).

3) Type III forms the smallest group of the RC rotorcraft. Besides small single-rotor helicopters such as Trex-450[3)] of Align, multiple-rotor helicopters such as coaxial Lama-V4[4)] of ESky, PD-100 Black Hornet[5)] of Proxdynamics, quadrotor Draganflyer[6)] of Draganfly Innovations, are named brands in this category (see Fig. 7). Because it is tiny in size, ultra light in weight and has very limited payload, constructing the avionic system for this type of rotorcraft is extremely difficult. Special care needs to be taken into consideration on the selection of its power supply, layout of the avionic system, choice of its processing and sensing units, and vibration isolation.

The key features of these three types of the RC rotorcraft platforms are intentionally summarized together in Table 1 for easy comparison and reference. It is worth pointing out that the first two types are absolutely dominated by single-rotor.

3.1.2 Avionic processing stack

The functions of the avionic processing stack include analyzing inflight information, executing automatic control laws, communicating with the ground station and logging necessary inflight data. For Type I and Type II mini rotorcraft UAVs, the avionic processing stack is dominated with PC/104(-plus)-based embedded single board computers (SBCs). PC/104(-plus) is an embedded computer standard, which is defined by the PC/104 Consortium[7)] for embedded applications in industries. The standard size of PC/104(-plus) modules is about 90 mm×96 mm with the height of around 10 to 15 mm and with the average weight around 100 g. The PC/104(-plus) standard adopts pin-socket connection, which is initially intended for specialized embedded computing environments where applications depend on reliable data acquisition in the face of strong disturbances and vibrations[8)]. This is what is required for a UAV system working airborne with persistent vibrations generated by its engine and rotors. The pin-socket connection of the PC/104(-plus) SBCs provides greater compatibility for integrating additional modules, such as serial extension boards, analog-to-digital (A/D) conversion boards, power regulator boards and frame grabber boards (for image and video converting), into the system without reconfiguration. It is worth noting that some strong interests have recently been aroused in implementing palm-size or even finger-size SBCs that are ultra small in size with sufficient processing speed (40 to 600 MHz) and low power consumption (commonly less

1) AutoCopter Express UAV. http://autocopter.net/
2) Flying-Cam Helicopter. http://www.flying-cam.com/products.php
3) Trex-450 Helicopter. http://www.align.com.tw/html/en/c_rindexe.htm
4) Lama-V4 Coaxial Helicopter. http://www.twf-sz.com/english/products.asp?prodid = 0194
5) PD-100 Black Hornet Helicopter. http://www.proxdynamics.com/products/pd_100_black_hornet/
6) Draganflyer Quadrotor Helicopter. http://www.rctoys.com/rc-products/DF-VTI.html
7) PC/104 Embedded Consortium. http://www.pc104.org/
8) PC/104 Standard. http://en.wikipedia.org/wiki/PC104

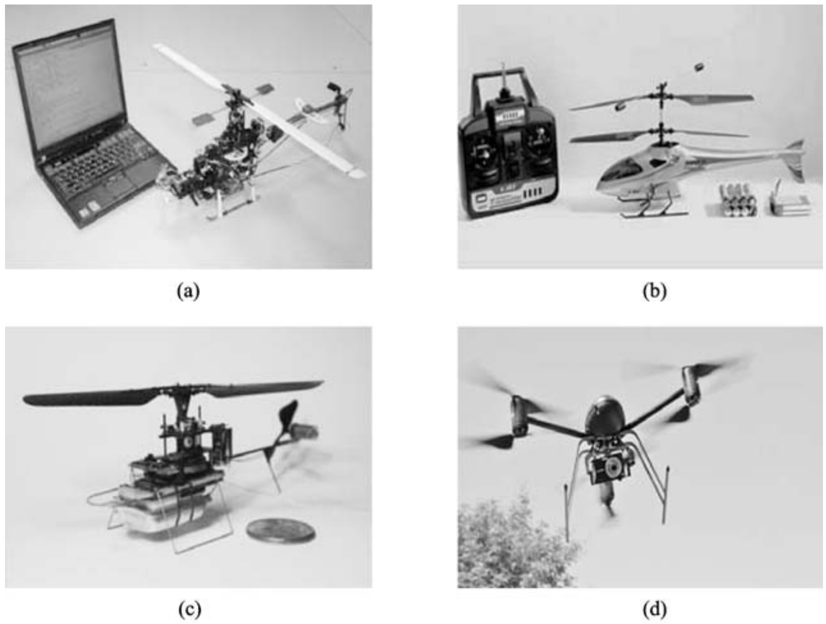

Fig. 7 Type III RC rotorcraft. (a) Trex-450; (b) Lama-V4; (c) PD-100 Black Hornet; (d) Draganflyer

than 2 W). However, such a new trend is still at its very initial stage (see, for example, Vicacopter[1)] and Refs. [10,11]).

3.1.3 Navigation and peripheral sensors

Navigation sensors form the heart of the avionic system, providing all necessary inflight measurement data for automatic flight control. For the majority of outdoor applications, the navigation sensors include an inertial measurement unit (IMU), a global positioning system (GPS), a magnetic compass, and sophisticated estimation algorithms.

IMU refers to a sensor cluster box containing three accelerometers and three gyroscopes. The accelerometers are to measure inertial accelerations and are precisely placed such that their measuring axes are strictly orthogonal to each other[2)]. The gyroscopes are also placed along the same orthogonal pattern and axes measuring rotational rates. Based on its anti-bias/drift capacity, typically, an IMU can be classified as either one of the following categories: the space grade, the navigation grade, the tactical grade, or the low-cost grade. Most of IMUs adopted in mini rotorcraft UAVs belong to the last two categories. Compared with the low-cost IMU, the tactical-grade one usually integrates with a higher precision fiber optic gyro and has more advanced anti-drifting capacity. It can work independently up to one or several hours without external correction from GPS or compass. The low-cost IMUs (most of them are MEMS-based), however, are also capable of providing reasonably good performance with effective calibration and correction from GPS and magnetic compass, as well as with well-designed estimation algorithms.

GPS provides position and velocity signals, which are useful for navigation and anti-drifting correction to the IMU measurement. Currently, most UAV systems adopt the L1-band GPS receivers, which provide sufficient accuracy for positioning (with a probable circular error less than 3 m [12]) and velocity estimation (with an error less than 0.5 m/s) with 1 to 10 Hz updating rate, based on the raw signals modulated onto solo L1 band (1.57542 GHz). The accuracy of position determination can be further improved to m- or even cm-level by employing advanced positioning methodologies such as differential GPS (DGPS) and real time kinematic (RTK) navigation methods. However, a stationary GPS base station is required in order to achieve high accuracy measurement. Other techniques such as shortening the cold/hot starting time and sensing super weak raw signals[3)] can also be adopted to enhance the reliability and performance of the GPS system.

The magnetic compass is a navigational instrument for determining direction relative to the magnetic poles of the earth[4)]. In mini rotorcraft UAV systems, the magnetic compass provides effective initial references and

1) Vicacopter. http://vicacopter.com/
2) Inertial Measurement Unit. http://en.wikipedia.org/wiki/Inertial_measurement_unit
3) Super Sense Indoor GPS. http://www.u-blox.com/en/supersense.html
4) Compass. http://en.wikipedia.org/wiki/Compass

corrections to the heading angle, with a resolution around 0.1° and a relatively low updating rate (less than 10 Hz).

Finally, we note that almost all the commercial navigation sensing systems have integrated some estimation algorithms to enhance their measurement accuracy and to overcome problems such as the immeasurability of Euler angles, insufficient sampling rate of GPS-based positions, and measurement drifting. The well-known extended Kalman filtering (EKF) technique is the most popular choice adopted in the commercial products. The estimation algorithm is executed either on an independent digital signal processor (DSP) or directly on the flight control processing unit. With a carefully designed estimation algorithm, the IMU, GPS and compass form the complete navigation system, which is commonly termed as inertial navigation system calibrated by GPS (INS/GPS), to provide necessary and reliable measurement for the navigation and autonomous flight control of the UAV systems.

3.1.4 Servo controller and wireless link

The servo controller drives the servo actuators and realizes smooth switching between the manual control mode and automatic control mode of the UAV system. The wireless link provides real-time communications and data exchanges between the onboard system and the ground station. The basic configuration for wireless communications is to use a single pair of wireless modules equipped on the avionic system and the ground station, respectively, for inflight data downlink and command/trajectory uplink. In some projects such as those reported in Refs. [13,14], extra set(s) of wireless modules are utilized for special requirements like transmitting GPS calibration signals.

3.1.5 Manual backup

In principle, a manual backup is not necessary for a fully functional UAV. However, for safety, a great majority of existing unmanned systems still retain such a backup, which in fact is commonly assigned with higher control authority than the automatic flight control system. The manual control is commonly realized through either by an RC joystick or directly through ground station manipulation. For most of the mini rotorcraft UAV systems, the manual control signal is generally modulated onto 29 to 72 MHz based on pulse phase modulation (PPM) or more robust pulse width modulation (PWM) techniques. We should also note that the 2.4 GHz frequency hopping modulation technology is a new trend developed within the last five years in the RC flying circle.

3.1.6 Ground station

The last essential part of the overall unmanned system is the ground station. Its main responsibility is to realize effective communications between the avionic system and the ground users and pilots. To fulfill this aim, the ground station is generally required to have capabilities, such as

1) displaying and monitoring the inflight status;
2) displaying images captured by the onboard system;
3) generating and updating flight trajectories;
4) sending control commands to the avionic system;
5) facilitating the ground piloted control or automatic control, especially in unexpected occasions such as emergency landing and cruise;
6) logging inflight data, to name a few.

Some other features such as displaying the reconstruction of the actual flight status in a 3D virtual environment can be very helpful to the ground users when the UAV is flying out of sight (see, for example, Ref. [15]).

3.2 Software integration

A sophisticated software system is required to ensure all of the hardware components for a UAV system work properly and effectively, and to ensure good communication and coordination between the onboard system and the ground station. It can naturally be divided into two parts, one for the avionic system onboard and one for the ground station.

3.2.1 Avionic real-time software system

The avionic software system coordinates all the hardware components onboard in an appropriate sequence. For most of the UAV systems, the essential tasks onboard include navigation data collection, flight control algorithm execution, and servo actuation driving, which are required to be executed strictly and precisely in every execution cycle. As such, the development of avionic software system is dominantly carried out in a real-time operating system (RTOS) environment, which can effectively guarantee the final system executed in a deterministic behavior, based on certain scheduling, intertask communications, resource sharing, interrupt handling, and memory allocation algorithms[1)]. Currently, three most popular real-time operating systems adopted in the UAV development are the QNX Neutrino[2)], VxWorks[3)], and RTLinux[4)]. Shown in Fig. 8 is a general framework of the avionic system adopted in Ref. [16], which employs a multi-thread structure and consists of several blocks with each of them being designed for a specific device and task. More specially,

1) Real-time Operating System. http://en.wikipedia.org/wiki/Real-time_operating_system
2) QNX Neutrino RTOS. http://www.qnx.com/
3) VxWorks RTOS. http://www.windriver.com/products/vxworks/
4) RTLinux RTOS. http://www.rtlinuxfree.com/

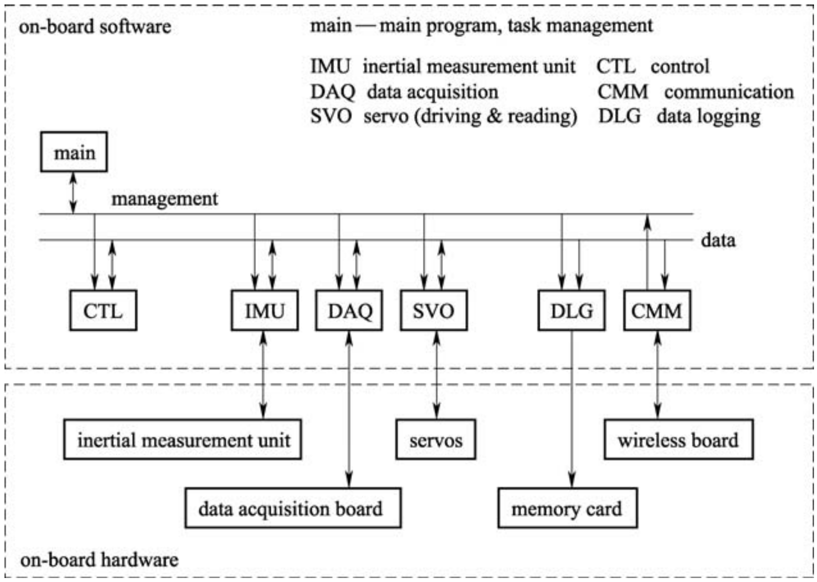

Fig. 8 Framework of an avionic software system

1) IMU is a block interacting with the navigation sensors and collecting necessary measurement data;
2) DAQ is to read additional information from the peripheral sensors;
3) CTL is to implement the automatic flight control laws;
4) SVO is to drive the servo actuators;
5) CMM is to communicate between the avionic system and the ground station through the wireless links;
6) DLG is for data logging, which is usually designed as a background task saving all necessary inflight data;
7) Finally, the main block is to manage all tasks.

3.2.2 Ground station software system

Compared with its avionic counterpart, the real-time feature for the ground station software system is preferable but not strictly compulsory. As such, many ground station software systems, particularly for the scientific research and commercial purposes, are not developed under an RTOS environment. Instead, other powerful programming environments with rich interface capacities, such as Windows-based Visual C++[1)] are commonly adopted. Shown in Fig. 9 is a framework of the ground station software system employed in Ref. [16]. Generally, the ground station software system consists of two layers, i.e., the background and foreground layers. Data transferring usually runs in the background layer, through the wireless channel with the avionic system (i.e., the CMM task thread), receiving data from and sending commands to the avionic system. In the dual-layer configuration, two separate threads are required for receiving and sending data. The receiver thread keeps reading the port connected to the wireless device, whereas the sender thread keeps waiting for commands issued by the ground users and writing it to the port once a command is captured. The foreground interface is capable of displaying windows for showing inflight data and for entering flight commands.

3.3 Dynamic modeling and system identification

It is crucial to obtain a fairly comprehensive model of a UAV if one wishes to design an advanced automatic flight control system by incorporating multivariable control techniques such as linear-quadratic regulator (LQR) and H_∞ control, and nonlinear control. Modeling of a mini rotorcraft UAV, especially for its full flight envelope dynamics, is an extremely challenging task. Because of the nature and physical structure of the rotorcraft UAV, dynamic modeling with inflight data and with parameter identification approach has been proven to be an ideal choice to derive a fairly accurate model of the flying vehicle.

3.3.1 First-principles approach

The first-principles modeling approach is well developed for obtaining dynamical models for full-scale manned and unmanned rotorcrafts. As reported in Ref. [17,18], such a modeling approach is generally labor intensive and requires the estimation or measurement of the aerodynamic, inertial, and structural properties of the rotorcraft. The models adopted are commonly of high-order with complicated structures, and need to be iteratively tuned based on flight-test data and existing databases. For this

1) Visual C++ Developer Center. http://msdn.microsoft.com/en-us/visualc/default.aspx

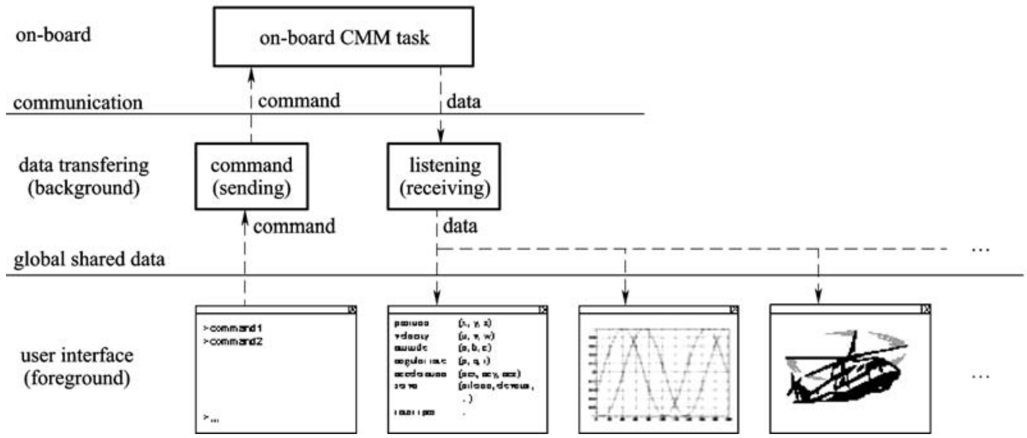

Fig. 9 Framework of ground station software system

reason, such an approach is only recommended for those who are interested in deriving a full nonlinear dynamic model for mini UAV systems.

Aerodynamic modeling associated with the full flight envelope for the mini rotorcraft UAVs has become one of the key research focuses in the last five to ten years. The comprehensive nonlinear model covering the full flight envelope of the UAV is greatly instrumental both for the flight control system design and for implementing a sophisticated and meaningful hardware-in-the-loop simulation system (see, for example, Ref. [19]). It is particularly useful for certain flight conditions, in which flight motions are so aggressive and dangerous that conducting actual flight tests for model identification is extremely difficult or even impractical. In Ref. [20], a 17th order nonlinear model is derived for an X-Cell 60 mini rotorcraft UAV. However, the accuracy of the partial measured/estimated key aerodynamic parameters cannot be guaranteed because the parameter-validation method suggested is hard to be implemented. In Ref. [21], a novel first-principles modeling approach, named MOSCA, is proposed for offlight simulation and linearized-model generation. The parameter identification procedure, the key for deriving a reliable nonlinear model, is not sufficiently utilized. Its parameter tuning is actually adopted for improving a linearized model instead of the full nonlinear one. It is our belief that there are many issues associated with the first-principles modeling of mini rotorcraft UAV systems, including proper structure determination, parameter identification, and model validation, which are yet to be resolved.

3.3.2 System and parameter identification

System and parameter identification is an effective approach commonly adopted for modeling of flight systems. It is suitable for obtaining a linearized model and can be conducted in either the time domain or the frequency domain or both.

For the time-domain identification, the dynamic model is identified by matching predicted time histories against measured ones [18]. For the inherently unstable platform like single-rotor UAVs, the time-domain identification approach is not the best choice because 1) the equations of motion must be numerically integrated in time for each iterative update in the parameters [18], which causes great difficulty in identifying the parameters related to unstable and weakly stable modes, and 2) the large amount of historical data involved in the iteration generates a heavy computational burden. As such, the time-domain approach generally does not guarantee to produce an accurate model. For example, the prediction error method is used in Ref. [22] for identifying a six-degree-of-freedom (6-DOF) model of a mini rotorcraft UAV at the hovering flight condition. The bandwidth limitation, caused by the inability of processing long data records, decreases the accuracy of the identified model. A similar problem has happened in Ref. [14], especially for the situation in identifying parameters related to two phugoid modes.

The frequency-domain identification method is based on frequency responses generated from flight test data, in which the dynamic model is identified by minimizing the error between the predicted frequency histories and measured frequency responses. Compared with its time-domain counterpart, the frequency-domain approach is more suitable for identifying systems with inherent instability, and has unique features such as efficient noise elimination, direct and accurate time-delay identification, and less computation involved. A comprehensive comparison between the frequency-domain and time-domain methods for rotorcraft systems can be found in Ref. [18]. Some persuasive examples of the utilization of the frequency-domain approach for rotorcraft have been reported in the literature. For instance, in Ref. [23], a frequency-response-based identification software package, named Comprehensive Identification from FrEquency Responses (or CIFER in short), is implemented on a

Yamaha R50 based UAV helicopter, and a reliable 11th-order state-space model for the hovering flight condition is successfully identified. This software package has also been implemented in Refs. [24,25] to identify extended higher-order dynamic models with more clear physical meanings, for hovering and forward flight conditions.

Lastly, we would like to conclude this section by noting that a fairly comprehensive and accurate nonlinear model has been obtained in Ref. [26] for HeLion, a Raptor 90 based UAV helicopter, through the combination of both the first-principles approach and the system and parameter identification method. The result has been successfully used in designing an advanced flight control system.

3.4 Automatic flight control system

The automatic flight control system is essential for a UAV to carry out flight missions with minimal or even without interference from human pilots. The classical single-input/single-output (SISO) feedback control method (i.e., PD or PID control) is one of the most common choices because of its simplicity in structure with less requirements on the accuracy on the dynamical model of the UAV. Examples include the CMU-R50 UAV helicopter [27], in which a SISO PD control law is adopted and further optimized using CONDUIT for both hovering and forward flight, and the Ursa Major 3 UAV helicopter [14], in which a SISO PID control is implemented for automatic hovering. To improve flight control performance, many researchers have devoted to the study of implementing more advanced control techniques on mini rotorcraft UAVs. For example, a flight control system using a multiple-input/multiple-output (MIMO) H_∞ control approach has been designed and implemented for mini rotorcraft UAVs in Ref. [28]. It is reported that the resulting system clearly outperforms the classical method. Other cases reported in the literature include systems designed by using: decentralized decoupled model predictive approach [29], neural network method (AutoCopter Express UAV[1]) and Refs. [30,31]), adaptive control technique [32], fuzzy logic approach [33], μ-synthesis [34], approximate linearization method [35], nonlinear feed-forward method [36], differential geometry technique [37], H_∞ static output-feedback control [38], learning control technique [39], and intelligent control methods [40], to name a few. Although there are many works that have been done along the line, many of them are still in the simulation stage. They are far from being ready for actual implementation onto a real platform.

Recently, Ref. [41] have proposed a flight control scheme, which is shown in Fig. 10 and consists of three parts, namely, the inner-loop control law, outer-loop, and flight scheduling. The function of the inner-loop control law is to guarantee the asymptotic stability of the aircraft motion with respect to the surrounding air. The role of the outer-loop is to produce flight commands or references to the inner-loop control layer, and finally the task of the flight scheduling part is to generate the flight references for pre-scheduled flight missions. Since the time scale associated with each part of the overall flight control system is hierarchical in nature, the flight control law can be designed in a decentralized fashion. A newly developed nonlinear control technique, namely, the composite non-linear feedback (CNF) control method [42,43], which has successfully been applied to solve many real-life problems, is employed to design the inner-loop control law based on the identified linear model of the UAV helicopter using inflight data. The dynamic inversion, capable of dealing with nonlinearities completely in affine systems, is adopted to design the outer-loop controller based on the kinematical models of the UAV. Lastly, the flight scheduling is described in a discrete event system that drives the helicopter to fly in some pre-determined flight conditions. The overall design has been successfully implemented and tested on HeLion, a UAV helicopter built at the National University of Singapore.

4 Application examples

Although it is still a long way for the unmanned systems to overtake many missions that are currently carried out by manned systems, some current technologies developed in the unmanned systems are, however, mature enough to be integrated to some real-life applications in both the military and civilian domains. We list in the following some examples, which show a good illustration of the applications of the technologies developed in the unmanned systems.

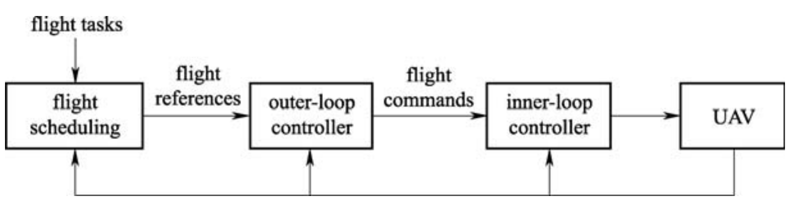

Fig. 10 Structure of overall autonomous flight control

1) AutoCopter Express UAV. http://autocopter.net/

4.1 Battlefield

To some extent, warfare applications can be regarded as a crucial reason for the birth of the unmanned systems including unmanned aerial vehicles and unmanned ground vehicles. The unmanned rotorcraft systems are mostly utilized for combat gunfire support, and surveillance and reconnaissance, on the battlefield.

1) Combat gunfire support

The current miniature unmanned combat aerial vehicles are dominated by fixed wing UAVs due to their superior agility, and longer endurance. The mini rotorcraft UAVs, however, are capable of providing unique combat support battles in confined areas such as streets. Shown in Fig. 11 are some good application examples of the rotorcraft UAV for combat gunfire support. More specifically, they are respectively the AutoCopter Gunship[1] equipped with upto two AA-12 guns for air shooting and the Schiebel S-100 equipped with LMM missiles.

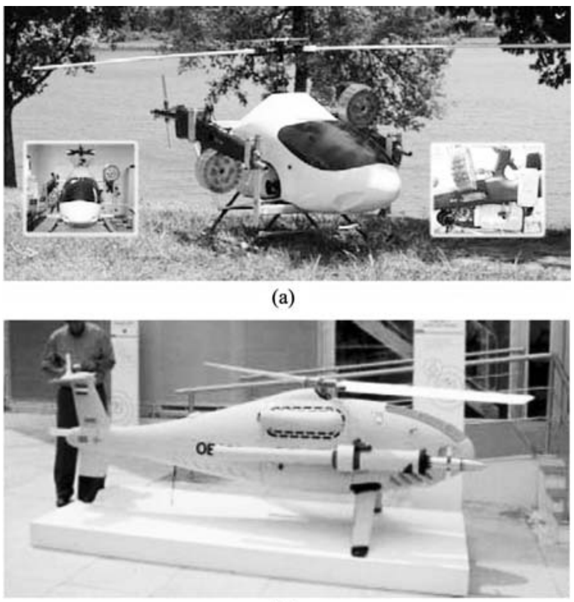

Fig. 11 Mini rotorcraft UAVs for combat gunfire support. (a) AutoCopter Gunship; (b) Schiebel S-100

2) Surveillance and reconnaissance

The unique features of the rotorcraft UAV for being able to hover and to operate at a low attitude make it an ideal platform for surveillance and reconnaissance in some crucial tasks such as range safety monitoring, arms transfer monitoring, and mine detecting. Shown in Fig. 12 is a famous battlefield application of a Honeywell duct fan UAV, which has successfully been deployed in Iraq for explosive detection.

Fig. 12 Honeywell duct fan in explosive detection

The rotorcraft UAVs can be of great assistance in civil defense and law enforcement as well (see, for example, the case reported in Flightglobal[2]).

4.2 Scientific exploration

Equipped with advanced sensors, a mini rotorcraft UAV can serve as an excellent platform for scientific exploration. An impressive example is the implementation of an R50 UAV helicopter at Carnegie Mellon University. In a project called Haughton Crater Mission, the R50 UAV helicopter has demonstrated its validity in geological survey, helping the researchers gain a deeper understanding of the environment on Mars by studying the similarity between the Haughton Crater and Mars [44].

4.3 Agriculture and forestry

One successful application of the rotorcraft UAVs in the civil domain is the pesticide spraying in agriculture and forestry. The most representative examples are the R50 and Rmax helicopters developed by Yamaha. Their birth can be traced back to a request in 1983 from the Japanese Ministry of Agriculture, Forestry and Fisheries for unmanned helicopters for crop dusting that could help reducing labor and costs in the labor-intensive rice farming industry. As a result, the R50 and Rmax series have eventually emerged as the dominating force in the pesticide spraying service nowadays.

4.4 Sports broadcasting and movie making

The audience is filled with wonder at the sight of a bird's-eye view of splendid stadiums or the special effects in functional movies. However, the audience seldom realizes that many of the spectacular sights are aerially photographed by mini rotorcraft UAVs (see Fig. 13 for

1) AutoCopter Express UAV. http://autocopter.net/

2) Miami Police Plans Urban Test of Honeywell's Micro-UAV. http://www.flightglobal.com/articles/2008/02/20/221686/video-miami-police-plans-urban-test-of-honeywells-micro-uav.html

Fig. 13 Sports and entertainment broadcasting

illustrations). Interested readers are referred to Flying-Cam[1)] for more information on aerial photography.

4.5 Engineering and construction

With the help of high resolution cameras or video recorders, rotorcraft UAVs can be utilized to assist workers and engineers to solve their problems in engineering and construction, which are difficult to be resolved through conventional approaches. For instance, the Automatic Lab of Chiba University has successfully developed a rotorcraft UAV, called Sky Surveyor[2)] equipped with a vibration-free PTZ camera (see Fig. 14) to help Chugoku Electric Power conduct inspection on power transmission lines between each conjuncted high-voltage towers.

Fig. 14 Sky Surveyor inspecting power transmission line

5 Conclusion

We have presented in this article a technical overview on mini unmanned rotorcraft vehicles. More specifically, we have reviewed the techniques and key components involved in constructing a fully functional and autonomous rotorcraft unmanned system, which includes the hardware platform construction, software system integration, aerodynamic modeling and automatic flight control design and implementation. Some real-life applications of the rotorcraft unmanned systems in the military and civil domains have also been highlighted. We believe that there are great potentials and practical applications for the unmanned systems. Research focus in the field has also been extended to the development of vision-based unmanned aerial vehicles, which are capable of flying in an environment without GPS, and micro aerial vehicles, which are light in weight and tiny in size, and are capable of performing flight missions indoors.

References

1. Johnson E N, Schrage D P. The Georgia tech unmanned aerial research vehicle: GTMax. In: Proceedings of AIAA Guidance, Navigation, and Control Conference. Austin, 2003
2. Wood R J. The first takeoff of a biologically-inspired at-scale robotic insect. IEEE Transactions on Robotics, 2008, 24(2): 341–347
3. Nickol C, Guynn M, Kohout L, Ozoroski T. High altitude long endurance air vehicle analysis of alternatives and technology requirements development. In: Proceeding of the 45th AIAA Aerospace Sciences Meeting and Exhibit. Reno, 2007
4. Cai G, Chen B M, Peng K, Dong M, Lee T H. Modeling and control system design for a UAV helicopter. In: Proceedings of the 14th Mediterranean Conference on Control and Automation. Ancona, 2006, 600–606
5. Cai G, Peng K, Chen B M, Lee T H. Design and assembling of a UAV helicopter system. In: Proceedings of the 5th International Conference on Control and Automation. Budapest, 2005, 697–702
6. Johnson W. Helicopter Theory. New York: Dover Publications, 1994
7. Gavrilets V, Frazzoli E, Mettler B, Piedmonte M, Feron E. Aggressive maneuvering of small autonomous helicopters: a human-centered approach. International Journal of Robotics Research, 2001, 20(10): 795–807
8. Conway A R. Autonomous control of an unstable model helicopter using carrier phase GPS only. Dissertation for the Doctoral Degree. Stanford, CA: Stanford University, 1995
9. Musial M, Brandenburg U W, Hommel G. Inexpensive system design: the flying robot MARVIN. In: Proceedings of the 16th International UAVs Conference on Unmanned Air Vehicle Systems. Bristol, 2001, 23.1–23.12
10. Cai G, Cai A K, Chen B M, Lee T H. Construction, modeling and control of a mini autonomous UAV helicopter. In: Proceedings of the IEEE International Conference on Automation and Logistics. Qingdao, 2008, 449–454
11. Wang T. Development of a micro unmanned vertical take-off and landing rotorcraft. Dissertation for the Bachelor Degree. National University of Singapore, 2009
12. Circular Error Probable (CEP). Technical paper 6. Air Force Operational Test and Evaluation Center, 1987
13. Mejias L, Saripalli S, Campoy P, Sukhatme G S. Visual servoing of an autonomous helicopter in urban areas using feature tracking.

1) Flying-Cam Helicopter. http://www.flying-cam.com/products.php
2) Sky Surveyor UAV Helicopters. http://mec2.tm.chiba-u.jp/uav/main/

Journal of Field Robotics, 2006, 23(3–4): 185–199
14. Shim D H, Kim H J, Sastry S. Control system design for rotorcraft-based unmanned aerial vehicle using time-domain system identification. In: Proceedings of the 2000 IEEE Conference on Control Applications. Anchorage, 2000, 808–813
15. Dong M, Chen B M, Cheng C. Development of 3D monitoring for an unmanned aerial vehicle. In: Proceedings of the 1st International Conference on Computer Science and Education. Xiamen, 2006, 135–140
16. Dong M, Chen B M, Cai G, Peng K. Development of a real-time onboard and ground station software system for a UAV helicopter. Journal of Aerospace Computing, Information, and Communication, 2007, 4(8): 933–955
17. Stevens B L, Lewis F L. Aircraft Control and Simulation. 2nd ed. New Jersey: John Wiley, 2003
18. Tischler M B, Remple R K. Aircraft and Rotorcraft System Identification: Engineering Methods With Flight Test Examples. AIAA Educational Series. Reston: AIAA, 2006
19. Cai G, Chen B M, Lee T H, Dong M. Design and implementation of a hardware-in-the-loop simulation system for small-scale UAV helicopters. In: Proceedings of the 2008 IEEE International Conference on Automation and Logistics. 2008, 29–34
20. Gavrilets V, Mettler B, Feron E. Nonlinear model for a small-size acrobatic helicopter. In: Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit. Montreal, 2001
21. Civita M L, Messner W, Kanade T. Modeling of small-scale helicopters with integrated first-principles and system-identification techniques. In: Proceedings of the 58th Forum of the American Helicopter Society. Montreal, 2002, 2505–2516
22. Morris J C, van Nieuwstadt M, Bendotti P. Identification and control of a model helicopter in hover. In: Proceedings of the American Control Conference. Baltimore, 1994, 2: 1238–1242
23. Mettler B, Tischler M B, Kanade T. System identification of small-size unmanned helicopter dynamics. In: Proceedings of the American Helicopter Society 55th Forum. Montreal, 1999
24. Cheng R P, Tischler M B, Schulein G J. RMAX helicopter state-space model identification for hover and forward-flight. Journal of the American Helicopter Society, 2006, 51(2): 202–210
25. Mettler B M, Tischler M B, Kanade T. System identification modeling of a small-scale unmanned rotorcraft for control design. Journal of the American Helicopter Society, 2002, 47(1): 50–63
26. Cai G, Chen B M, Lee T H, Lum K Y. Comprehensive nonlinear modeling of an unmanned-aerial-vehicle helicopter. In: Proceedings of the 2008 AIAA Guidance, Navigation and Control Conference. Honolulu, 2008, 2008-7414
27. Mettler B. Identification, Modeling and Characteristics of Miniature Rotorcraft. Boston: Kluver Academic Publishers, 2002
28. Weilenmann M W, Geering H P. A test bench for the rotorcraft hover control. In: Proceedings of AIAA Guidance Navigation and Control Conference. Monterey, 1993, 1371–1382
29. Shim D H, Kim H J, Sastry S. Decentralized nonlinear model predictive control of multiple flying robots. In: Proceedings of the 42nd IEEE Conference on Decision and Control. Maui, 2003, 4: 3621–3626
30. Enns R, Si J. Helicopter flight control design using a learning control approach. In: Proceedings of the 39th IEEE Conference on Decision and Control. Sydney, 2000, 2: 1754–1759
31. Wan E A, Bogdanov A A. Model predictive neural control with applications to a 6 DOF helicopter model. In: Proceedings of the 2001 American Control Conference. Arlington, 2001, 1: 488–493
32. Corban J E, Calise A J, Prasad J V R. Implementation of adaptive nonlinear control for flight test on an unmanned helicopter. In: Proceedings of the 37th IEEE Conference on Decision and Control. Tampa, 1998, 4: 3641–3646
33. Kadmiry B. Fuzzy control for an autonomous helicopter. Thesis No. 938 for the Degree of Licenciate of Engineering. Linkoping, 2002
34. Weilenmann M F, Christen U, Geering H P. Robust helicopter position control at hover. In: Proceedings of American Control Conference. Baltimore, 1994, 3: 2491–2495
35. Koo T J, Sastry S. Output tracking control design of a helicopter model based on approximate linearization. In: Proceedings of the 37th IEEE Conference on Decision and Control. Tampa, 1998, 4: 3635–3640
36. Bogdanov A, Wan E. SDRE control with nonlinear feed forward compensation for a small unmanned helicopter. In: Proceedings of the 2nd AIAA Unmanned Unlimited Systems, Technologies, and Operations Conference. San Diego, 2003, 2003-6512
37. Isidori A, Marconi L, Serrani A. Robust nonlinear motion control of a helicopter. IEEE Transactions on Automatic Control, 2003, 48(3): 413–426
38. Gadewadikar J, Lewis F L, Subbarao K, Peng K, Chen B M. H-infinity static output-feedback control for rotorcraft. Journal of Intelligent and Robotic Systems, 2009, 54(4): 629–646
39. Enns R, Si J. Helicopter trimming and tracking control using direct neural dynamic programming. IEEE Transactions on Neural Networks, 2003, 14(4): 929–939
40. Sugeno M, Hirano I, Nakamura S, Kotsu S. Development of an intelligent unmanned helicopter. In: Proceedings of 1995 IEEE International Conference on Fuzzy Systems. Yokohama, 1995, 5: 33–34
41. Peng K, Dong M, Chen B M, Cai G, Lum K Y, Lee T H. Design and implementation of a fully autonomous flight control system for a UAV helicopter. In: Proceedings of the 26th Chinese Control Conference. Zhangjiajie, 2007, 662–667
42. Chen B M, Lee T H, Peng K, Venkataramanan V. Composite nonlinear feedback control for linear systems with input saturation: theory and an application. IEEE Transactions on Automatic Control, 2003, 48(3): 427–439
43. He Y, Chen B M, Wu C. Composite nonlinear control with state and measurement feedback for general multivariable systems with input saturation. Systems & Control Letters, 2005, 54(5): 455–469
44. Charles J. CMU's autonomous helicopter explores new territory. IEEE Intelligent Systems and Their Applications, 1998, 13(5): 85–87