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Autopilots for Small Unmanned Aerial Vehicles: A Survey

HaiYang Chao, YongCan Cao, and YangQuan Chen

Abstract: This paper presents a survey of the autopilot systems for small or micro unmanned aerial vehicles (UAVs). The objective is to provide a summary of the current commercial, open source and research autopilot systems for convenience of potential small UAV users. The UAV flight control basics are introduced first. The radio control system and autopilot control system are then explained from both the hardware and software viewpoints. Several typical off-the-shelf autopilot packages are compared in terms of sensor packages, observation approaches and controller strengths. Afterwards some open source autopilot systems are introduced. Conclusion is made with a summary of the current autopilot market and a remark on the future development.

Keywords: Autopilot systems, autonomous navigation, flight control, remotely piloted vehicle (RPV), unmanned aircraft system (UAS), unmanned aerial vehicle (UAV).

1. INTRODUCTION

Recently, there has been a rapidly increasing interest in small unmanned aerial vehicles (UAVs). With the emergence of high power density batteries, long range and low-power micro radio devices, cheap airframes, and powerful micro-processors and motors, small/micro UAVs have become applicable in civilian circumstances like remote sensing, mapping, traffic monitoring, search and rescue, etc. Small UAVs have a relatively short wingspan and light weight. They are expendable, easy to be built and operated. Most of them can be operated by one to two people, or even be hand-carried and hand-launched [1,2]. In fact, small UAVs are designed to fly at low altitude (normally less than 1000 meters) to provide a close observation of the ground objects. This low altitude flight makes the UAVs easy to crash. A robust and accurate autopilot system is indispensable for small UAVs to successfully perform tasks like low-altitude surveillance.

Autopilots are systems to guide the UAVs in flight with no assistance from human operators. Autopilots were firstly developed for missiles and later extended to aircrafts and ships since 1910s [3]. A minimal autopilot system includes attitude sensors and onboard processor. Due to the high nonlinearities of the air plane dynamics, a lot of advanced control techniques, such as PID control, neural network (NN), fuzzy logic (FL), sliding mode control, and H_∞ control, have been used in autopilot systems to guarantee a smooth desirable trajectory navigation. Nowadays, technological advances in wireless networks and micro electromechanical systems (MEMS) make it possible to use inexpensive micro autopilots on small UAVs.

The small UAVs can provide researchers a different view of the environment and a much easier way for remote sensing, especially in cases like environment characterization and natural habitats monitoring [4]. This paper attempts to provide a summary of the current commercial and research autopilot systems so that researchers can either purchase or build the UAVs and autopilots based on their specific application requirements.

The paper is organized as follows: Section 2 introduces the UAV basics including the history and categorization. The UAV flight control basics are explained in Section 3 briefly. Sections 4-5 focus on, respectively, radio control (RC) of UAVs and autopilot control of UAVs. Several typical commercial autopilots are compared in Section 6. Open source autopilot systems are introduced later in Section 7. Concluding remarks are presented in Section 8.

2. UAV BASICS

In this paper, the acronym UAV (Unmanned Aerial Vehicle) is used to represent a power-driven, reusable airplane operated without a human pilot on board. So the unmanned missile or bomb is not within this category because they are designed for one time use only. UAVs can also be called "unmanned aircraft systems" (UAS) [5]. With this definition, remote controlled aircrafts also fall into this category. Actually, most UAVs have remote control abilities to avoid some severe failures that may cause crashes.

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HaiYang Chao, YongCan Cao, and YangQuan Chen are with Center for Self-Organizing and Intelligent Systems (CSOIS), Department of Electrical and Computer Engineering, 4160 Old Main Hill, Utah State University, Logan, UT 84322-4160, USA (e-mails: {haiyang.chao, yongcan.cao}@aggiemail.usu.edu, yqchen @ieee.org).

The first UAV was the Q-2 made by Ryan Aeronautical flown in the 1950's for military reconnaissance [3]. The US military uses many UAVs nowadays to spare human pilots from operating dull, dirty or dangerous jobs [1]. Many UAVs serving in the military weigh hundreds or even thousands of pounds and can fly as high as 6000 feet. The military also uses small or micro UAVs like Dragon Eye, FPASS, Pointer and Raven [5]. These small UAVs use electric batteries for power, weigh less than 10 pounds and fly usually as 1,000 feet or lower.

As mentioned above, most early UAVs were developed for military applications. They are expensive to develop and maintain, which makes it hard for civilian uses. Since 1990s, the emergence of high power density batteries (Lithium-Ion and Lithium-Polymer), miniaturized equipments, and wireless network devices makes the small UAVs affordable to researchers and even hobbyists. Based on wing shapes and body structures, UAVs can be categorized into fixed-wing UAVs and rotary-wing UAVs (e.g., helicopters).

3. UAV FLIGHT CONTROL BASICS

An airplane can rotate around three axes (x, y, z) from the plane's center of gravity. The position control of UAV is usually converted to the angular control: roll (ϕ), pitch (θ) and yaw (ψ), as defined later. The axes of motion of airplanes are shown in Fig. 1.

The main control surfaces or control inputs for a fixed-wing UAV may include some or all of the following:

- Ailerons: to control the roll angle.
- Elevator: to control the pitch angle (up and down).
- Throttle: to control the motor speed.
- Rudder: to control the yaw angle (left and right).

Small UAVs, however, may not have all these control surfaces. For example, the Unicorn airframe only has one throttle and two control surfaces: left and right ailerons, and the ailerons can be mixed to work as an elevator. The ailerons of this type of airframe are also called elevons.

The state variables of a UAV include

- p_n, p_e, and h: the inertial (north, east) position and the altitude or the height, e.g., latitude longitude and height (LLH) or universal transverse mercator (UTM) coordinates.
- v_n, v_e, and v_d: the speeds with respect to the ground coordinate frame.
- u, v, and w: the velocities measured along body x, y, and z axes.
- a_x, a_y, and a_z: the accelerations measured along body x, y, and z axes.
- ϕ, θ, and ψ: the roll, pitch, and yaw angles.
- p, q, and r: the angular rates measured along body x, y, and z axes.
- v, α and β: the air speed, the angle of attack, and the sideslip angle.

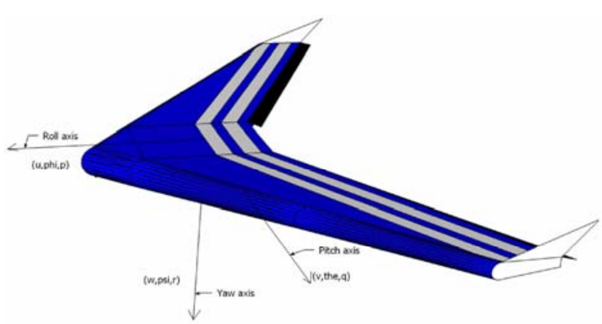


Fig. 1. Definition of UAV axes.

Actually, small fixed-wing UAVs are highly dynamical and nonlinear systems because of uncertainties caused by speed, altitude, weights, winds and turbulences [7]. Therefore, it is hard to get an accurate and complete nonlinear model. But some linear models can be used to approximate the UAV dynamics.

Small UAVs normally have two control modes: remote control (RC) mode and autopilot control mode. Remote control mode, or radio control mode, requires human pilots to control the UAV through radio signals, while autopilot control mode can automatically keep the airplane at the desired state. There are also mixed control modes in some small UAV applications, such as 3400 Autopilot from UNAV company. A semi-autonomous control mode is provided in [8] where the onboard autopilot controls the altitude and the human operator controls the flight path.

4. RADIO CONTROL

Radio controlled small UAVs are also called RC planes, which are normally controlled by an experienced RC hobbyist through a hand-held RC transmitter with a RC receiver onboard. The signals transmitted can be pulse position modulation (PPM) signals, or pulse code modulation (PCM) signals. PPM also falls into the category of frequency modulation (FM). The operating frequency for RC airplanes in United States is 72 MHz or 2.4 GHz band. The frequency is normally fixed for RC transmitter/receiver and up to eight channels of PPM signals can be transmitted each time. After the receiver decodes the signals from the transmitter, pulse width modulation (PWM) signals will be generated for servo control.

For example, Unicorn RC planes have only three control surfaces including the throttle. Therefore, only three PPM channels are required: CH1 for right elevon, CH2 for left elevon, and CH3 for throttle. The fast breaking of MEMS, batteries, and wireless technologies combined with more and more RC hobbyists make UAVs applicable for many research and civilian applications.

Although RC planes can be applied in some surveillance situations, the full concentration of an experienced RC human operator is required all the time. Therefore, autopilot systems are necessary to free human operators from tedious and repeatable jobs. In addition, they can also improve the navigation accuracy and the autonomy of UAVs.

5. AUTOPILOT CONTROL

An autopilot is a MEMS system used to guide the UAV without assistance from human operators, consisting of both hardware and its supporting software. The first aircraft autopilot was developed by Sperry Corporation in 1912 [6] and demonstrated in a hands-free flight two years later. Autopilot systems are now widely used in modern aircrafts and ships. The objective of UAV autopilot systems is to consistently guide UAVs to follow reference paths, or navigate through some waypoints. A powerful UAV autopilot system can guide UAVs in all stages including take-off, ascent, descent, trajectory following, and landing.

Note that the autopilot is a part of the UAV flight control system as shown in Fig. 2. The autopilot needs to communicate with ground station for control mode switch, receive broadcast from GPS satellite for position updates and send out control inputs to the servo motors on UAVs.

A UAV autopilot system is a close-loop control system, which comprises of two parts: the state observer and the controller. The most common state observer is the micro inertial guidance system including gyro, acceleration, and magnetic sensors. There are also other attitude determination devices available like infrared or vision based ones. The sensor readings combined with the GPS information can be passed to a filter to generate the estimates of the current states for later control uses. Based on different control strategies, the UAV autopilots can be categorized to PID based autopilots, fuzzy based autopilots, NN based autopilots and other robust autopilots.

A typical off-the-shelf UAV autopilot system comprises of the GPS receiver, the micro inertial guidance system and the onboard processor (state estimator and flight controller) as illustrated in Fig. 3. The UAV autopilot system has two fundamental functions: state estimation and control inputs generation based on the reference paths and the current states.

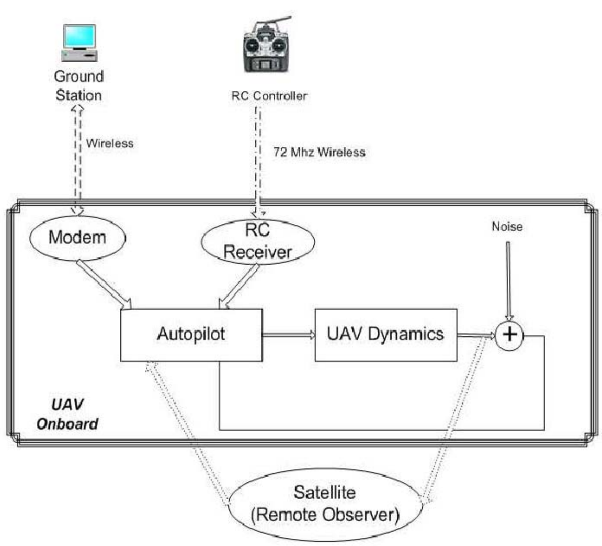


Fig. 2. UAV flight control system.

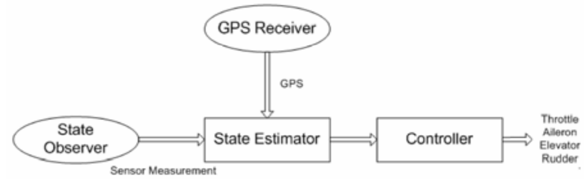


Fig. 3. Functional structure of the UAV autopilot.

5.1. Autopilot hardware

A minimal autopilot system includes sensor packages for state determination and onboard processors for estimation & control uses, and peripheral circuits for servo & modem communications. Due to the physical limitations of small UAVs, the autopilot hardware needs to be of small sizes, light weights and low power consumptions. The accurate flight control of UAVs demands a precise observation of the UAV attitude in the air. Moreover, the sensor packages should also guarantee a good performance, especially in a mobile and temperature-varying environment.

5.1.1 MEMS inertial sensors

Inertial sensors are used to measure the 3-D position and attitude information in the inertial frame. The current MEMS technology makes it possible to use tiny and light sensors on small or micro UAVs. Available MEMS inertial sensors include:

(1) GPS receiver: to measure the absolute positions (p_n, p_e, h) and ground velocities (v_n, v_e, v_d).
(2) Rate or gyro: to measure the angular rates (p, q, r).
(3) Acceleration: to measure the accelerations (a_x, a_y, a_z).
(4) Magnetic: to measure the magnetic field, which could be used for the heading correction (ψ).
(5) Pressure: to measure the air speed (the relative pressure) and the altitude (h).
(6) Ultrasonic sensor or SONAR: to measure the relative height above the ground.
(7) Infrared sensor: to measure the attitude angles (ϕ, θ).
(8) RGB camera or other image sensors: to replace one or several of the above sensors.

GPS plays an indispensable role in the autonomous control of UAVs because it provides an absolute position measurement. A known bounded error between GPS measurement and the real position can be guaranteed as long as there is a valid 3-D lock. For instance, u-blox 5 GPS receiver could achieve a three meter 3-D accuracy (PACC) in the best case for civilian applications in the United States. There are also differential GPS units which could achieve centimeter level accuracy. The disadvantage of GPS is its vulnerability to weather factors and its relatively low updating frequency (commonly 4Hz), which may not be enough for flight control applications.

5.1.2 Possible sensor configurations

Given all the above inertial sensors, several sensor combinations could be chosen for different types of UAVs to achieve the basic autonomous waypoints navigation task. Most current outdoor UAVs have GPS receivers onboard to provide the absolute position feedback. The main difference is the attitude measurement solution, which could be inertial measurement unit (IMU), infrared sensor or image sensor etc.

Micro Inertial Guidance System (IGS): A typical IGS or IMU includes 3-axis gyro rate and acceleration sensors, which could be filtered to generate an estimation of the attitude (ϕ, θ, ψ). The IGS is widely used in big airplanes. A straightforward sensor solution for small UAVs is to use the micro IGS, which can provide a complete set of sensor readings. MNAV from Crossbow company is this kind of micro IGS with an update rate up to 100 Hz for inertial sensors. MNAV has 3-axis magnetic, gyro and acceleration sensors [16]. There are also simpler off-the-shelf sensor packages available like ET 301 from Sparkfun company, which only has two gyros and a dual axis accelerometer, respectively, on pitch and yaw [9].

Infrared Sensor: Another solution for attitude sensing is using infrared thermopiles. The basic idea of infrared attitude sensor is to measure the heat difference between two sensors on one axis to determine the angle of the UAV because the Earth emits more IR than the sky. Paparazzi Open Source Autopilot group used this kind of infrared sensors as their primary attitude sensor [10] [11]. The infrared sensors can be used for UAV stabilization and RC plane training since it can work as a leveler. One similar commercial package called Copilot is shown in Fig. 4 [12].

Vision Sensor: Vision sensor could also be used to estimate the attitude by itself or combined with other inertial measurements [15]. The pseudo roll and pitch can be decided from the onboard video or image streams [14]. Experiments on vision only based navigation and obstacle avoidance have been achieved on small rotary wing UAVs [13]. In addition, vision based navigation has potentials to replace the GPS in providing position measurements especially in task oriented and feature based applications. Vision based navigation for small fixed wing UAVs is still an undergoing topic and a lot of work are still needed for mature commercial autopilots.

5.2. Autopilot software

All the inertial measurements from sensors will be sent to the onboard processor for further filter and control processing. Autopilot could subscribe services from the available sensors based on different control objectives.

(a) Infrared Sensor [10] (b) FMA Copilot [12]

Fig. 4. Infrared attitude estimation.

5.2.1 State observation

The autopilot processor needs to collect all the sensor readings in real time. Then all these state observations are passed on for further processing.

5.2.2 Autopilot control objectives

Most UAVs can be treated as mobile platforms for all kinds of sensors. The basic UAV waypoints tracking task could be decomposed into several subtasks including:

(1) Pitch attitude hold.
(2) Altitude hold.
(3) Speed hold.
(4) Automatic take-off and landing.
(5) Roll-Angle hold.
(6) Turn coordination.
(7) Heading hold.

5.2.3 State estimation

To achieve the above control objectives, different system states are needed with relatively high frequency (typically above 20Hz for small UAVs). However, sensors like GPS can only provide a noisy measurement in 4Hz. Kalman filter can be used here to make an optimal estimation (H_2) of the current states including the UAV location, velocity and acceleration. The users need to define a noise estimation matrix, which represents how far the estimate can be trusted from the true states. Kalman filtering needs lots of matrix manipulations, which adds more computational burden to the onboard processor. Therefore, it is necessary to simplify the existing Kalman filtering techniques based on different applications. Besides, several other issues like gyro drifting and high frequency sensor noise also need to be canceled out through filtering techniques.

5.2.4 Controller design for autopilots

Most current commercial and research autopilots focus on GPS based waypoints navigation. The path-following control of the UAV can be separated to different layers:

(1) Inner loop on roll and pitch for attitude.
(2) Outer loop on heading and altitude for trajectory or waypoints tracking.
(3) Waypoint navigation.

There are two basic controllers for the UAV flight control: altitude controller, velocity and heading controller. Altitude controller is to drive the UAV to fly at a desired altitude including the landing and take-off stages. The heading and velocity controller is to guide the UAV to fly through the desired waypoints. To achieve the above control requirements, different control strategies can be used including PID, Adaptive Neural Network, Fuzzy Logic and Fractional Order Control [24], etc.

PID Approach: Most commercial autopilots use PID controllers. Given the reference waypoint coordinates and the current UAV state estimates, the controller parameters of different layers can be tuned off-line first and re-tuned during the flight. Most commercial autopilots use traditional PID controllers because they are easy to be implemented on the small UAV platforms. But the PID controllers have limitations in optimality and robustness. Besides, it is also difficult to tune the parameters under some circumstances.

Fuzzy Based Autopilot: Research on autopilots for small UAVs is also quite active with other modern control strategies. Fuzzy logic control systems can be used in a lot of applications including flight control. There are totally three fuzzy controllers in [20], one for lateral control and two for longitudinal control. A speed controller and a wind disturbance attenuation block are added for robustness. The hardware of this autopilot includes one PC 104 single board computer as the processor and a micro IGS as the sensing unit. This autopilot can guarantee waypoint navigation.

NN Based Autopilot: Adaptive neural network controller does not require an accurate mathematical model and is suitable for multi-variable flight control. Although the NN based autopilot is originally developed for unmanned helicopter control [21], it can also be applied in fixed wing UAVs like GT-wing test bed in Georgia Institute of Technology.

LQG/LTR & H_∞ Based Autopilot: Both PID and NN autopilots are non-model based and the optimality and robustness of the controller can not be guaranteed. As most small UAVs are highly nonlinear systems and hard to get an accurate nonlinear model, a linear model can be used to approximate the UAV dynamics. A combination of Linear Quadratic Gaussian controller and kalman filter can be used to achieve better altitude control performance [22]. H_∞ loop shaping techniques can also be used on small fixed wing UAVs for improvements in noisy or even payload changing circumstances [23].

6. TYPICAL OFF-THE-SHELF AUTOPILOTS

In this section, several available off-the-shelf autopilots are introduced and compared in terms of sensor configurations, state estimations and controller strengths. Most commercial UAV autopilots have sensors, processors and peripheral circuits integrated into one single board to account for size and weight constraints. Due to commercial reasons, it is sometimes impossible to make a complete comparison on the software implementation details.

6.1. Procerus Kestrel autopilot

Procerus Kestrel autopilot is specially designed for small or micro UAVs weighing only 16.7 grams (modem and GPS receiver not included), shown in Fig. 5. The specifications are shown in Table 1. Kestrel 2.2 includes a complete inertial sensor set including: 3-axis accelerometers, 3-axis angular rate sensors, 2-axis magnetometers, one static pressure sensor (altitude) and one dynamic pressure sensor (airspeed). With the special temperature compensations for sensors, it can estimate the UAV attitude (ϕ and θ) and the wind speed pretty accurately [17].

Kestrel has a 29MHz Rabbit 3000 onboard processor with 512K RAM for onboard data logging. It has the built-in ability to autonomous take-off and landing, waypoint navigation, speed and altitude hold. The flight control algorithm is based on the traditional PID control. The autopilot has elevator controller, throttle controller and aileron controller separately. Elevator control is used for longitude and airspeed stability of the UAV. Throttle control is for controlling airspeed during level flight. Aileron control is used for lateral stability of the UAV [17]. Procerus provides in-flight PID gain tuning with real-time performance graph.

Fig. 5. Procerus Kestrel autopilot [17].

The preflight sensor checking and failsafe protections are also integrated to the autopilot software package. Multiple UAV flights are also supported by Kestrel.

6.2. MicroPilot MP series

MicroPilot offers a series of autopilots for small rotary-wing or fixed-wing UAVs with the price ranging from \$2000 to \$8000. To make a fair comparison, MP 2028^g is chosen based on the price, shown in Fig. 6. The specifications and features are provided in Table 1 and later section. MP 2028^g has a similar sensor package as Kestrel except that it doesn’t have magnetometer. The GPS receiver is integrated into one single board for MP 2028^g, which makes the autopilot smaller in size. But the electromagnetic interference (EMI) from other circuits may cause slightly bigger GPS position errors. The GPS data is updated at 1Hz by default.

The MP 2028^g autopilot supports altitude hold, airspeed hold and waypoint navigation. It also supports different kinds of autonomous take-off and landing including hand launch, bungee launch, run-way takeoff, deep stall landing, etc. The inner PID control rate is 30 Hz and the servo can update as fast as 50 Hz. MP 2028^g also supports user definable PID feedback loops and table lookup functions, which could be used for camera stabilization.

6.3. Cloud Cap Piccolo

Piccolo family of UAV autopilots from Cloud Cap Company provide several packages for different applications. PiccoloPlus is a full featured autopilot for

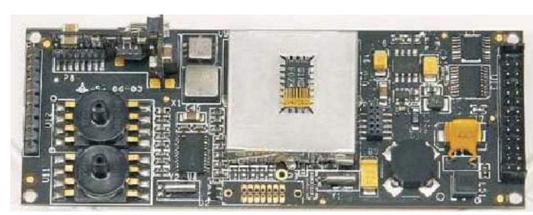


Fig. 6. MP2028xp autopilot [18].

Fig. 7. PICCOLO LT autopilot [19].

fixed-wing UAVs. Piccolo *II* is an autopilot with user payload interface added. Piccolo LT is a size optimized one for small electric UAVs as shown in Fig. 7. It includes inertial and air data sensors, GPS, processing, RF data link, and flight termination, all in a shielded enclosure [19]. The sensor package includes three gyros and accelerometers, one dynamic pressure sensor and one barometric pressure sensor. Piccolo has special sensor configuration sections to correct errors like IMU to GPS antenna offset, avionics orientation with respect to the UAV body frame.

Piccolo LT has a 40M Hz MPC555 onboard microcontroller. Piccolo provides a universal controller with different user configurations including legacy fixed wing controller, neutral net helicopter controller, fixed wing generation 2 controller, and PID helicopter controller. Fixed wing generation 2 controller is the most commonly used flight controller for conventional fixed wing UAVs. It includes support for altitude, bank, flaps, heading & vertical rate hold, and auto take-off and landing. Piccolo autopilot supports one ground station controlling multiple autopilots and it also has a hardware-in-the-loop simulation.

6.4. UNAV 3500

The autopilots from Unav company have special types of cheap autopilots for UAV beginners. Picopilot-SP costs only $400 and provides the basic autonomous navigation function with self programming mode. That is, the UAV can copy the same waypoints after it is manually flied in record mode. Unav company also has 3500 autopilot with a more complete sensor set including 3 axis rate gyros, 2 axis accelerometers, baro and pitot pressure sensors. Unav 3500 communicates with the external GPS receiver through the serial port by NMEA 0183 protocol. Unav uses electronic gyros, which could prevent the gyro drift during a sustained bank as claimed.

One advantage of Unav 3500 autopilot is its truly autonomous ability, which means that it doesn't require constant communication with ground station in autonomous mode. It supports GPS waypoints navigation, altitude and speed hold mode with the possible gain and rate setup for roll, pitch, rudder, and power loops respectively. Unav 3500 has two versions: 3500FW for the fixed wing UAVs and 3500HL for the helicopter UAVs.

6.5. Specification comparisons

The physical specifications of the autopilots are important since small UAVs demand as fewer space, payload and power as possible. The size, weight, and

Table 1. Comparison of physical specifications of autopilots.

	Size (cm)	Weight (g) w/o radio	Power Consumption	Price (k USD)	DC In (V)	CPU	Memory (K)
Kestrel 2.2	5.08*3.5*1.2	16.7	500mA(3.3 or 5V)	5	6-16.5	29MHz	512
MP 2028^g	10*4*1.5	28	140mA@6.5V	5.5	4.2-26	3MIPS	-
Piccolo LT(w.modem)	13*5.9*1.9	45	4W	-	4.8-24	40MHz	448
Unav 3500	10.16*5.08*2.03	42.45	100mA@6V	3/5(FW/HL)	5-7	40MIPS	256

Table 2. Comparison of sensor ranges.

	Kestrel	MP 2028^g	Piccolo LT	Unav 3500
Operating Temperature(^{o}C)	-40 ~ +85	-	-40 ~ +80	0 ~ +60
Max Angular Rate(Deg/s)	± 300	± 150	-	± 150
Max Acceleration(g)	± 10	± 2	-	± 2
Max Magnetometer(G)	± 1	-	-	-
Altitude(m)	-13.7 ~ 3414	0 ~ 12000	-	0 ~ 4876.8
Air Speed(mile/hour)	0 ~ 130	0 ~ 311	-	-

Table 3. Comparison of autopilot functions.

	Kestrel	MP 2028^g	Piccolo LT	Unav 3500
Waypints Navigation	Y	Y	Y	Y
Auto-takeoff & landing	Y	Y	Y	N
Altitude Hold	Y	Y	Y	Y
Air Speed Hold	Y	Y	Y	Y
Multi-UAV Support	Y	N	Y	N
Attitude Control Loop	-	30Hz	-	50 Hz
Servo Control Rate	-	50Hz	-	50 Hz
Telemetry Rate	-	5Hz	25Hz or faster	1 Hz
Onboard Log Rate	<100Hz	5Hz	-	1 Hz

power consumption issues are shown in Table 1. The sensors information is shown in Table 2. Both the Crossbow MNAV and Procerus Kestrel have a bias compensation to correct the inertial sensor measurement under different temperatures. The functional specifications of these four typical autopilot are listed in detail in Table 3.

7. OPEN SOURCE AUTOPILOTS

With the lowering price of MEMS inertial sensors and RC air frames, several open source UAV autopilot projects received a lot of interests from researchers around the world. The advantage of the open source autopilots is its flexibility in both hardware and software. Researcher can easily modify the autopilot based on their own special requirements.

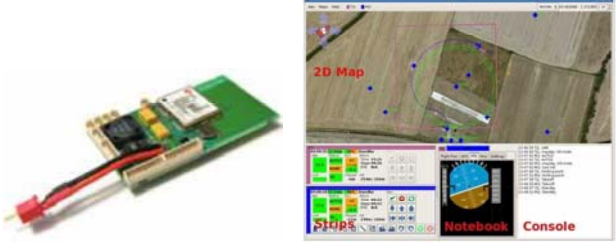
7.1. Paparazzi autopilot

Paprazzi autopilot is a very popular project first developed by researchers from ENAC university, France. Infrared sensors combined with GPS are used as the default sensing unit. Although Infrared sensor can only provide a rough estimation of the attitude, it is enough for a steady flight control once tuned well. Tiny 13 is the autopilot hardware with the GPS receiver integrated, shown in Fig. 8. Paparazzi also has Tiny Twog autopilot with two open serial ports, which could be used to connect with IMU and modem. One Kalman filter is running on the autopilot to provide a faster position estimation based on GPS updates.

Paparazzi uses LPC 2148 ARM7 chip as the central processor. For the software, it could achieve waypoints tracking, auto-takeoff & landing, and altitude hold. The flight controller could also be configured if gyro rate is used for roll and pitch tracking control especially for micro UAVs. However, paparazzi doesn't have a good speed hold and changing function currently since no air speed sensor reading is considered in the controller part. Paparazzi is also a truly autonomous autopilot without any rely on the ground control station (GCS). It also has a lot of safety considerations in conditions like RC signal lost, out of predefined range, GPS lost, etc.

7.2. Crossbow MNAV+Stargate autopilot

The MNAV+Stargate autopilot package, shown in Fig. 9, is developed by Crossbow company for small UAV



(a) Tiny 13. (b) Paparazzi GCS.

Fig. 8. Paparazzi autopilot system [10].

(a) MNAV. (b) Xbow autopilot.

Fig. 9. Crossbow MNAV [16].

applications. MNAV is a micro inertial system with the GPS receiver, servo drivers and the PPM interface. The MNAV100CA includes the following sensors: 3-axis accelerometers, 3-axis angular rate sensors, 3-axis magnetometers, one static pressure sensor (altitude) and one dynamic pressure sensor (airspeed). Stargate is a powerful single board computer with a 400 MHz PXA255 processor and 64M SDRAM. The powerful computation ability guarantees realtime processing of extended Kalman filter and autopilot control [16]. This package also provide several spare interfaces like general IO, serial ports, USB, PCMCIA, and compact flash, so that researchers can easily add their specific sensors.

In the software, a waypoint autonomous navigation algorithm is developed and the source code is accessible by the users [16]. The autopilot controller uses a three-layer PID controller to achieve the waypoint navigation within a certain altitude. The outer layer tracks the x - y positions of the UAV and converts the reference positions into the heading ψ. The middle layer stabilizes the heading and the altitude. The inner layer is the attitude stabilization layer to control pitch and roll [16].

MNAV+Stargate autopilot is mid-size and not so light to carry on for small UAVs. However, the beneficial side is that the source code is open in Linux. Moreover, Stargate is a powerful processor and the IO ports of both MNAV and Stargate offer the users with lots of flexibilities in the user-specific development.

8. COMPARISON & CONCLUSION

The topic of small UAVs is quite active in the past few years. A lot of small fixed-wing or rotary-wing UAVs are flying in the air under the guidance from the autopilot systems. Due to the limited size and payload of the UAVs, the physical features like size, weight and power consumption are the primary issues that the autopilot must take into consideration. A good autopilot should be small, light and have a long endurance life. It is not so hard to design the hardware to fulfill the autopilot requirements. The current bottleneck for autopilot systems lies more in the software side. The autopilot for manned aircraft is to help the human pilots to move either human beings or cargos from one city to another. However, that is definitely not enough for the UAVs. So what kind of functions must the autopilot have? To answer this question, the first thing we must think about is what we use the small UAVs for first.

8.1. Why flying small UAVs?

RC hobbyists pursue for the aerial acrobatics instead of autopilot control possibly beyond operator's eyesight range. But the acrobatics may not be the first priority for autopilot development by researchers. Typical tasks for small UAVs include remote sensing with camera(s), traffic monitoring, border/fire monitor-ing, search and rescue, etc.

Although most current autopilot systems for UAVs have the ability to autonomously navigate through waypoints, it is actually not enough for some emerging small UAV applications. For example, we may wish to dynamically characterize how the forest fire is developing. Therefore, another layer of dynamic data driven navigation needs to be built on top of the waypoints based navigation.

8.2. Controller design for the autopilot

Many current commercial off-the-shelf autopilot systems use PID control algorithms. The advantages of PID based autopilot control include:

(1) Simple and easy to design and understand.
(2) Higher level control strategies can be built on top.
(3) Small memory and processing resources required.

However, PID based autopilot controls also have some disadvantages:

(1) Robustness: the PID parameters need to be re-tuned if the payload is changed [25].
(2) Stability: the nominal operating point of PID control may be unstable in specific cases e.g., in the presence of wind disturbances.
(3) Hard in parameter tuning, especially for beginners.

With more research in the modeling of the small fixed-wing UAVs, more complex control strategies can also be attemped with improved performance.

8.3. Future direction of autopilot systems for small UAVs

(1) Robustness analysis. Most current autopilots for small UAVs do not need an accurate dynamical model and they are hard to test with disturbance from wind or mechanics.
(2) More friendly Human-UAV interface. Fully autonomous UAV autopilot may not be a good choice for surveillance uses because the end user of the data may have specific requirements to the data like video size or accuracy.
(3) Dynamic data driven autopilot controller design. The current autopilots mainly focus on waypoints navigation. But the ultimate goal to fly the small UAVs is to get the sensor data of areas of interests. How to incorporate the sensor data as the input for the autopilot is quite important for sensing tasks. Other researchers have done some work in this field [26], but more efforts are needed to get this question answered in real UAV applications.
(4) Cooperative properties added to the autopilot system. Tasks like mapping or sensing of a large area require multiple UAVs. So, the autopilot needs to have the cooperative control function to support this. Although several researchers have done quite some experiments in this topic [28,29,27], few commercial autopilot systems have true multiple functions built in like formation flight or cooperative vision tracking.

8.4. Conclusion

In this paper, both commercial and research autopilot systems for small UAVs are reviewed and discussed in detail with an emphasize on hardware. The whole autopilot system includes several parts like state observer, state estimator, and flight controller. Finally, the different autopilot systems are compared and the future directions for the autopilot systems are predicted.

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HaiYang Chao received the B.S. and M.S. degrees in Electrical Engineering both from Zhejiang University, China, in 2001 and 2005, respectively. He is currently a Ph.D. candidate in the Department of Electrical and Computer Engineering, Utah State University. His research interests include cooperative control, cooperative remote sensing, distributed control, mobile sensor networks and flight control of unmanned aerial vehicles.

YongCan Cao received the B.S. degree from Nanjing University of Aeronautics and Astronautics, China, in 2003 and the M.S. degree from Shanghai Jiaotong University, China, in 2006. He is currently a Ph.D. student in the Department of Electrical and Computer Engineering, Utah State University. His research interests include cooperative control, robotics and unmanned aerial vehicles.

YangQuan Chen is currently an associate professor of electrical engineering at Utah State University, Logan, and the Director of the Center for Self-Organizing and Intelligent Systems. In addition to 13 granted and two pending U.S. patents, he has published over 100 refereed journal papers, over 20 refereed book chapter papers, over 200 refereed conference papers, and more than 50 industrial technical reports. He has coauthored three research monographs (Springer 1999, 2007, 2009) and six textbooks (Tsinghua University Press 2002, 2004, 2007, 2008; SIAM Press 2007; CRC Press, 2008). His current areas of research interests include: applied fractional calculus, distributed measurement and distributed control of distributed parameter systems using mobile actuator and sensor networks, mechatronics and controls (intelligent, optimal, robust, nonlinear and adaptive), UAV multi-spectral cooperative remote sensing and real-time water management and irrigation control.