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Autopilots for Small Fixed-Wing Unmanned Air Vehicles: A Survey

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***Abstract*— This paper presents a survey of the autopilot systems for small fixed-wing unmanned air vehicles (UAVs). The UAV flight control basics are introduced first. The radio control system and autopilot control system are then explained from both hardware and software viewpoints. Several typical commercial off-the-shelf autopilot packages are compared in detail. In addition, some research autopilot systems are introduced. Finally, conclusions are made with a summary of the current autopilot market and a remark on the future development.This paper presents a survey of the autopilot systems for small fixed-wing unmanned air vehicles (UAVs). The UAV flight control basics are introduced first. The radio control system and autopilot control system are then explained from both hardware and software viewpoints. Several typical commercial off-the-shelf autopilot packages are compared in detail. In addition, some research autopilot systems are introduced. Finally, conclusions are made with a summary of the current autopilot market and a remark on the future development.**

Index Terms*—Autopilot systems, autonomous navigation, unmanned air vehicle (UAV), remotely piloted vehicle (RPV), unmanned aircraft system (UAS), flight control.

I. INTRODUCTION

In the past few years, there has been a rapidly increasing interest in using unmanned air vehicles (UAVs) for military and civilian applications including remote sensing, mapping, traffic monitoring, search and rescue. With the emerging of high power density batteries, long range and low power micro radio devices, cheap airframes, and powerful micro-processors and motors, UAV technology has become applicable in civilian circumstances, especially for small UAVs because they are expendable, easy to build and operate. Small UAVs have a relatively short wingspan and light weight. They can be operated by only one to two people [1] [2] [3]. Many can even be hand-carried and hand-launched. In fact, small UAVs are designed to fly at low altitude (normally less than 1000 feet) to provide a close observation of the ground objects. This low flight altitude may make the UAVs easy to crash. A robust and accurate autopilot system is indispensable for small UAVs to successfully perform the task.

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 [4]. A minimal autopilot system include attitude sensors and onboard processor. Due to the high nonlinearities of the air plane dynamics, a lot of intelligent control techniques have been used in autopilot systems to guarantee a smooth desirable trajectory navigation, such as PID control, neural network (NN), fuzzy logic (FL), sliding mode control, and H_∞ control. Nowadays, technological advances in wireless networks and micro electromechanical systems (MEMS) make it possible to use the inexpensive micro autopilots on small UAVs.

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

The paper is organized as follows. Sec. II introduces the UAV basics including the history and categorization. The UAV dynamics is briefly explained in Sec. III. Sec. IV and V focus on radio control (RC) of UAVs and autopilot control of UAVs, respectively. Several typical commercial autopilot systems are surveyed in detail in Sec. VI. Research level autopilot systems are introduced later in Sec. VII. Comparison among these autopilots and concluding remarks are presented in Sec. VIII.

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II. UAV BASICS

In this paper, the acronym UAV (Unmanned Air 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, almost all the UAVs have remote control abilities to avoid some severe failures that may cause crashes.

The first UAV was Q-2 made by Ryan Aeronautical flown in the 1950's for military reconnaissance [4]. The US military uses many UAVs nowadays to spare human pilots from operating dull, dirty or dangerous jobs [1]. Lots of UAVs currently serving in the military weigh hundreds or even thousands of pounds and can fly more than 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 under 1,000 feet.

As mentioned, 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). One typical fixed-wing small UAV frame, Zagi, is shown in Fig. 1. Table I lists the major specifications.

Fig. 1. Zagi 60 Airframe (Delta-wing) [6].

III. UAV DYNAMICS

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

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TABLE I

ZAGI 60 SPECIFICATIONS [6]

Wing Span:	60”
Wing Area:	3.6sq ft
Speed:	50 mph
Wing Loading:	9.44 oz sq ft
Radio Channel:	3-channel w/Mixer
Material:	Expanded Polypropylene Foam

angular control: roll (ϕ), pitch (θ) and yaw (ψ). The axes of motion of airplanes are shown in Fig. 2.

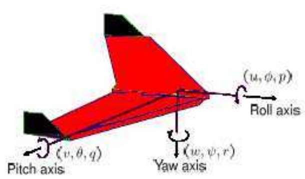


Fig. 2. Definition of UAV Axes.

The main control surfaces or control inputs for a fixed-wing air vehicle may include some or all of the following [7]:

- 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 Zagi airframe only has 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 the UAV include

- p_n: the inertial (north) position.
- p_e: the inertial (east) position.
- h: the altitude or the height.
- u: the body frame velocity measured along body x axis.
- v: the body frame velocity measured along body y axis.
- w: the body frame velocity measured along body z axis.
- ϕ: the roll angle.
- θ: the pitch angle.
- ψ: the yaw angle.
- p: the roll rate measured along body x axis.
- q: the pitch rate measured along body y axis.
- r: the yaw rate measured along body z axis.

Actually, small fixed-wing UAVs are highly dynamical and nonlinear systems because of strong uncertainties caused by speed, altitude, weights, winds and other turbulence [8]. 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 can have two types of control modes: remote control (RC) and autopilot control. Remote control requires human pilots to control the UAV through radio signals. Remote control is also called “radio control”. On the other hand, autopilot can automatically keeps the airplane on the desired state. There are also mixed control modes in small UAV applications, such as 3400 Autopilot from UNAV company [9]. It has semi-autonomous mode where the autopilot controls the altitude and the human operator controls the flight path.

IV. RADIO CONTROL

Small UAVs with only radio controller are also called RC planes. They are normally controlled by an experienced RC hobbyist through a handheld 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 airplane in United States is 72 MHz band. The frequency is normally fixed for RC transmitter/receiver and up to eight channels of PPM signals can be transmitted each period. After the receiver decodes the signals from the transmitter, it will generate pulse width modulation (PWM) signals for servo control.

For example, Zagi RC planes have only three control surfaces including the throttle, so only three PPM channels are needed: CH1 for right elevon, CH2 for left elevon and CH3 for throttle. The fast breaking of MEMS, battery and wireless technology combined with more and more RC hobbyists make UAVs applicable for research and civilian applications.

Although RC planes can also work in some surveillance tasks, the full concentration of an experienced RC human operator is required and they can not fly out of the human eyesight range (about 300 meters). Therefore, autopilot systems are introduced to enhance the navigation accuracy and the autonomous ability of UAVs.

V. AUTOPILOT CONTROL

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

The flight control system of a UAV is shown in Fig. 3. 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.

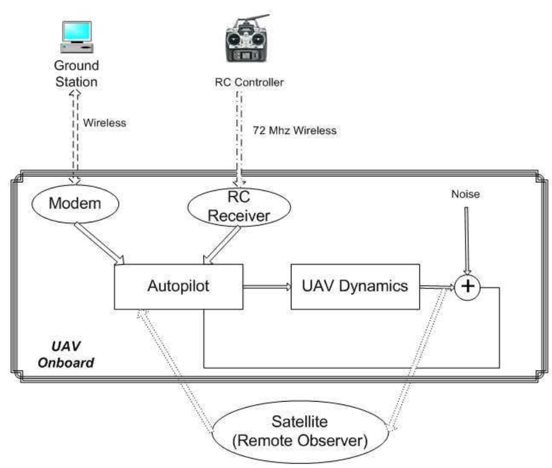


Fig. 3. UAV Flight Control System.

A UAV autopilot is a close-loop control system, which comprises of two parts: the state observer and the controller. The most common state observer is 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 GPS information can be passed to a filter to generate the desired 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 autopilot.

A typical off-the-shelf UAV autopilot comprises of GPS receiver, micro inertial guidance system and onboard processor (state estimator and flight controller) as illustrated in Fig. 4. The autopilot of UAV has two basic functions: state estimation and control inputs generation based on the reference path and current states.

A. Autopilot Hardware

A minimal autopilot includes sensor packages for state determination and onboard processors for estimation and control uses. Due to the

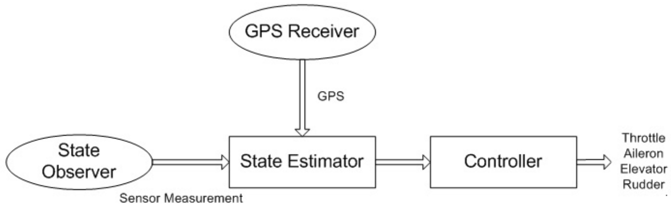


Fig. 4. Functional Structure of UAV Autopilot System.

physical limitation of small UAVs, the autopilot hardware needs to be small, light and consume low power. The accurate flight control of UAV demands an precise observation of the UAV attitude in the sky. Moreover, the sensor packages should also guarantee a good performance especially in a mobile and temperature varying environment.

1) Micro Inertial Guidance System + GPS: The inertial guidance system is widely used in big airplanes. A straightforward sensor solution for small UAVs is to use the micro inertial guidance system, which can provide a complete set of sensor readings like:

1) GPS receiver: to measure the absolute position of UAV.
2) Magnetic: to measure roll ϕ, pitch θ, yaw ψ.
3) Rate: to measure p, q, r.
4) Acceleration: to measure the acceleration information.
5) Pressure: to measure body velocity and the altitude.
6) Ultrasonic sensor or SONAR: to measure the relative altitude to the ground.

The advantage of GPS based IGS is that it can always reset its position errors through GPS updating. The disadvantages include inherited system errors, low update frequency and vulnerability to weather factors.

MNAV from Crossbow company is this kind of micro inertial system with a update rate up to 100 Hz for inertial sensors. MNAV has three-axis magnetic, gyro and acceleration sensors [10]. 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 on pitch and yaw respectively [11].

2) Infrared Sensor as Attitude Estimator: 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 developed this kind of infrared sensors as their primary attitude sensor [12] [13].

The above 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. 5 [14].

(a) Infrared sensor [12] (b) FMA Copilot [14]

Fig. 5. Infrared attitude estimation

3) Vision Sensor as Attitude Estimator: All the above sensor packages use the GPS to reset the system errors from integrating inertial sensors over time. However, there are possibilities that GPS signal is not available or with a slow update rate. Vision based autopilots can perform better in this kind of GPS challenging environments. In addition, vision based navigation demonstrates advantages on task oriented and feature based applications. Experiments on vision only based navigation and obstacle avoidance has been achieved on small rotary wing UAVs [15]. Vision based navigation is more challenging for fixed wing UAVs because rotary wing UAVs can fly slower and even hover around interested area, which means less requirements for high speed image processing. The pseudo roll and pitch can be decided from the onboard video or image streams [16]. Vision sensor can also be combined with the inertial measurement unit to determine the attitude of fixed wing UAVs [17]. Vision based navigation for small fixed wing UAVs is still an undergoing topic and a lot of work are still needed for a mature vision based autopilot.

B. Autopilot Software

All the inertial measurements from sensors will be sent to the onboard processor for further filter and control processing. A lot of UAVs use single board computer onboard for fast onboard processing like PC104, Stargate.

1) State Estimation: Given all these different sensor inputs with different updating rates, Kalman filter can be used to make an optimal estimation (H_2) of the current states including the UAV location, velocity and acceleration. However, the user needs to define a noise estimate matrix, which represents how far the estimate can be trusted for each sensor reading. Kalman filtering needs matrix manipulation, which adds more computational burden to the onboard processor and it needs to be simplified based on each application.

2) Control Strategies: 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 UAVs flight control: altitude controller, velocity and heading controller. Altitude controller is to drive the UAVs fly in a desired altitude including the landing and take-off stages. The heading and velocity controller is to guide the UAV to fly through some waypoints.

To achieve the above control requirements, different control strategies can be used including PID, Adaptive Neural Network and Fuzzy logic. 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.

VI. Typical Off-The-Shelf UAV Autopilot Systems

In this section, several available off-the-shelf autopilots are introduced and compared in detail.

A. Crossbow MNAV+Stargate Autopilot

The MNAV+Stargate autopilot package, shown in Fig. 6, is developed by Crossbow company for small UAV applications. MNAV is a micro inertial system with GPS receiver, servo drivers and 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 [10]. 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 [18]. The autopilot controller uses a three layer PID controller to achieve the waypoint navigation within a certain altitude as illustrated in Fig. 7. The outer layer tracks the x-y positions of 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 pith and roll [19].

(a) MNAV (b) Xbow Autopilot

Fig. 6. Crossbow MNAV [10]

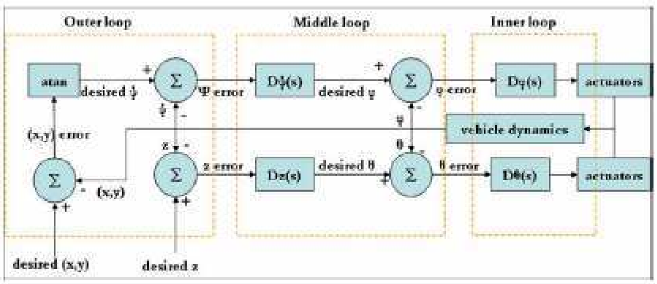


Fig. 7. PID-based Autopilot System by Crossbow [19].

The physical properties of MNAV+Stargate autopilot are provided in Table II. 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, the Stargate is a powerful processor and the IO ports of both MNAV and Stargate offer the users with lots of flexibilities in user-specific development.

B. Procerus Kestrel Autopilot

Procerus Kestrel Autopilot has a much smaller size and weight which is suitable for small UAVs shown in Fig. 8. Again, the specifications are shown in Table II. For the hardware, it has a 29MHz Rabbit 3000 on board processor. It also has all the inertial sensors similar to MNAV, and the difference is that the sensor board is integrated with the processor board except the GPS receiver [20].

Fig. 8. Procerus Kestrel Autopilot [20].

The Kestrel autopilot has the built-in ability to autonomous take-off, landing and waypoint navigation. The preflight sensor checking and failsafe protections are also integrated to the autopilot software package. 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 [21].

C. MicroPilot MP Series

MicroPilot is a world leading company in small UAV autopilots. It has a series of MP autopilots for fixed wing UAVs with price ranging from $1700 to $4000. One typical autopilot for small fixed wing UAVs, MP2028xp, is shown in Fig. 9. The specifications and features are provided in Table II and later section.

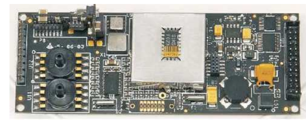


Fig. 9. MP2028xp autopilot [22].

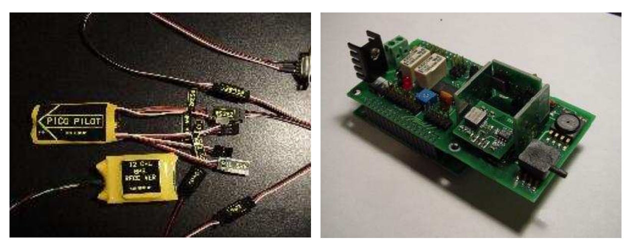
D. Cloud Cap Piccolo

Cloud Cap Company is also a leading company in UAV technologies. Piccolo family of UAV autopilots provide several packages for different applications. PiccoloPlus is a full featured autopilot for fixed wing applications. 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. 10. It includes inertial and air data sensors, GPS, processing, RF data link, and flight termination, all in a shielded enclosure [23]. Piccolo LT has a 40M Hz MPC555 onboard microcontroller. The sensor package includes three gyros and accelerometers, one dynamic pressure sensor and one barometric pressure sensor. Piccolo autopilot supports one groundstation controlling multiple autopilots and it also has a hardware in the loop simulation.

Fig. 10. PICOLLO LT autopilot [23].

E. UNAV 3400

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. This autopilot is especially optimized for ruder controlled small UAVs because the rudder can provide more stability. Unav company also has 3400 autopilots with a more complete sensor set as illustrated in Fig. 11 [9].



(a) Picopilot SP (b) Unav 3400 Autopilot

Fig. 11. Unav Autopilots [9]

F. 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 power consumption issues are shown in Table II. The sensors information is shown in Table III. Both the Crossbow MNAV and Procerus Kestrel have a bias compensation to correct the inertial sensor measurement under different temperatures.

TABLE II

COMPARISON OF PHYSICAL SPECIFICATIONS OF 3 AUTOPILOTS

	Size (cm)	Weight (g) w/o radio	Power Consumption	Price (k USD)
MNAV	5.7*4.5*1.1	33	<0.8W(5V)	1.5
Stargate	9.53*6.33*2.81	80.47	<500mA	0.9
Kestrel 2.2	5.08*3.5*1.2	16.7	500mA (3.3 or 5V)	5
MP Series	10*4*1.5	28	N/A	1.7-6
Piccolo LT	11.94*5.72*1.78	45	N/A	N/A
Uuav 3400	10.16*5.08*4.06	84	180mA (5.5-7.5V)	5

TABLE III

COMPARISON OF SENSOR RANGES

	MNAV	Kestrel	MP series
Operating Temperature(°C)	-5∼+45	-40∼85	NA
Angular Rate(Deg/s)	±200	±300	±150
Acceleration Range(g)	±2	±10	±2
Magnetometer Range(G)	±0.75	±1	NA
Altitude(m)	0∼5000	-13.7∼3414	0∼12000
Air Speed(mile/hour)	0∼180	0∼130	0∼311

The functional specifications of these three typical autopilot are listed in detail as follows:

Xbow Stargate+MNAV

1) GPS based waypoint tracking.
2) Altitude maintenance.

Kestrel Autopilot 2.2

1) GPS based waypoint tracking.
2) Change waypoint and velocity during the flight.
3) Autonomous take off and landing.
4) Joystick control with altitude stabilization.
5) Loiter mode and rally mode for specific area monitoring.
6) Failsafe mode: loss of communication, GPS lock, low battery, flight termination.

MicroPilot MP Series

1) GPS waypoint navigation with predefined altitude and airspeed.
2) Change altitude/airspeed during flight.
3) Change waypoints in flight.
4) Autonomous take-off, bungee launch, hand launch and landing. (Except MP1028g)

CloudCap Piccolo

1) Autonomous, manual and stick mode operation.
2) Single 44-pin EMI filtered interface connector and shielded case.

G. *Other Commercial Autopilot Systems*

There are also several other commercial off-the-shelf autopilots similar to the above ones like AP50 Autopilot from UAV Flight Systems, 3400 Autopilot from UNAV, Microbot Autopilot from Microbotics INC. [24].

VII. AUTOPILOT SYSTEMS DEVELOPED FOR RESEARCH

All the above commercial autopilots are traditional PID controllers. They are easy to understand and implement on the small UAV platforms. But PID controller has its limitations in optimality and robustness. Sometimes it is also difficult to tune the parameters. Research on autopilots for small UAVs is also quite active with a lot of modern control strategies used.

A. *Fuzzy Based Autopilot*

Fuzzy logic control systems can be used in a lot of applications including flight control [25]. There are totally three fuzzy controllers, 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 the FLC autopilot includes one PC 104 single board computer and similar sensor packages. This autopilot can guarantee waypoint navigation.

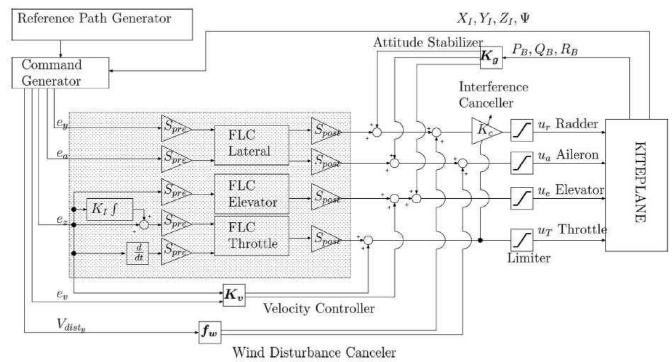


Fig. 12. FL-based Autopilot System for Kite UAV [25]

B. *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 [26], it can also be applied in fixed wing UAVs like GT-wing test bed in Georgia Institute of Technology.

C. *Robust Autopilot: LQG/LTR & H_∞*

Both PID and NN controllers 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 [27]. H_∞ loop shaping techniques can also be used on small fixed wing UAVs for improvements in noisy or even payload changing circumstances [28].

VIII. COMPARISON & CONCLUSION

The topic of small UAVs is quite hot in the past few years. A lot of small fixed-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 first issues the autopilot must deal with. 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 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. But that is definitely not enough for UAVs. So what kind of functions must the autopilot have? To answer this question, we must think about what we use the small UAVs for first.

A. *Why Flying Small Fixed-Wing UAVs?*

Clearly, the answer is not "just for fun". RC hobbyists pursue for the hard aerial acrobatics motions instead of autopilot control 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 monitoring, 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 waypoint based navigation.

B. 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 of it.
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 [29].
2) Stability: the nominal operating point of PID control may be unstable in specific cases like 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 attempted with improved performance.

C. 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 waypoint 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.
4) Cooperative properties added to the autopilot system. Tasks like mapping or sensing of a large area require more than one UAV. So, the autopilot needs to have the cooperative control function to support this.

D. Conclusion

In this paper, both commercial and research autopilot systems for small fixed-wing UAVs are reviewed and discussed in detail. 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 are predicted.

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