Flight Control System of Unmanned Aerial Vehicle

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Abstract: To date unmanned aerial system (UAS) technologies have attracted more and more attention from countries in the world. Unmanned aerial vehicles (UAVs) play an important role in reconnaissance, surveillance, and target tracking within military and civil fields. Here one briefly introduces the development of UAVs, and reviews its various subsystems including autopilot, a ground station, mission planning and management subsystem, navigation system and so on. Furthermore, an overview is provided for advanced design methods of UAVs control system, including the linear feedback control, adaptive and nonlinear control, and intelligent control techniques. Finally, the future of UAVs flight control techniques is forecasted.

Key words: unmanned aerial vehicle (UAV); flight control; optimal control; adaptive control; intelligent control

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0 Introduction

Unmanned aerial vehicle (UAV) is also commonly referred to as aerial robot and unmanned aerial system (UAS) adopted by the US Department of Defense and the Civil Aviation Authority of the UK. The design and application of UAVs begin to skyrocket around the world nowadays since UAVs play an important role in military missions, such as reconnaissance, attack, surveillance, fire fighting, and target tracking. In civilian applications, UAVs also have been used for insecticide spray, patrolling railway, transmission line inspection, goods transportation, and so on.

Ref. [1] summarized the main characteristics of micro and mini fixed-wing, rotary-wing, and multi-rotor UAS according to a weight-based categorization, i. e., ″micro″, which refers to UAS less than 5 kg, ″mini″ (less than 30 kg), and ″tactical″ (less than 150 kg). A large number of world-wide UASs, categorized by size, weight, operating range as well as certification potential are provided in Ref. [2]. The command, control and communication technologies for UAVs are overviewed in Ref. [3]. A review of available open-source hardware and software for UAS can be found in Ref. [4].

UAVs can be remotely controlled by a ground control station, or can be fly autonomously based on many kinds of automatic flight control systems (FCSs) and flight management systems. Authors recapitulate the UAS for the system constituted by a UAV, a ground control station (GCS) and a communication data link for the flight commands and control from the GCS. Furthermore, other UAV components are considered critical, such as autopilots, navigation sensors, vision sensors, mechanical servos, and wireless systems.

1 Unmanned Aerial System

Autonomous flight of UAV depends on the following capabilities: localization, path planning, and control, where localization is defined as

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the positioning for UAV in surrounding space, path planning chooses the feasible route and gives guidance for control, and control is to guarantee the flight performance of UAV. Therefore, high levels of integrity and reliability are required for a UAV system.

1.1 Unmanned aerial vehicle

Since the first UAV was manufactured by the Americans Lawrence and Sperry in 1916, the U. S. has owned the highest techniques for designing UAVs in the world and has developed many typical UAVs. Among them, Northrop Grumman RQ-4 Global Hawk, a UAV for surveillance, is initially designed by Ryan Aeronautical which provides a systematic surveillance and broad overview by high resolution synthetic aperture radar (SAR) and long-range electro-optical/infrared sensors with long loiter times over target areas. Predator, designed by General Atomics Aeronautical Systems, is a UAV for surveillance and reconnaissance. It has been configured with air-to-air or air-to-ground weapons, and joined the military actions in Balkans, Southwest Asia, and Middle East. X-47, designed by Northrop Grumman, is an unmanned combat vehicle which has been successfully recovered from the aircraft carrier in recent years. X-43 is an unmanned hypersonic aircraft as a part of the X-plane series, specifically of Hyper-X program of NASA, which is the fastest aircraft on record at approximately 11 000 km/h. Boeing X-37 known as orbital test vehicle (OTV) is an reusable unmanned spacecraft. Boeing X-51 is an unmanned scramjet demonstration aircraft for hypersonic flight. Furthermore, there are many other kinds of UAVs designed by USA and other countries, such as MQ-8B Fire Scout (USA), RQ-5A Hunter (USA), Spektre (UK), Kestrel (France), Kleinfluggerat Zielortung (Germany), Pioneer (State of Israel), and so on.

The UAV techniques in China have been rapidly developed these years. The development of UAVs in China is mainly undertaken by aerospace scientific research institutions. Especially, Nanjing University of Aeronautics and Astronautics, Northwestern Polytechnical University and Beihang University are the three major institutions. Every two years, the China International Aviation & Aerospace Industries is exhibited in Zhuhai of Guangdong Province of China. UAS China Conference & Exhibition has been held for the fifth time, and in the fifth meeting Nanjing University of Aeronautics and Astronautics displays a spy drone for trade and business, a short range spy drone, a long-endurance reconnaissance UAV, and a small integrated reconnaissance and strike UAV. In the second Aviation Industry Corporation of China (AVIC) Cup-International UAV Innovation Grand Prix held in Beijing 2013, Nanjing University of Aeronautics and Astronautics won several awards in competitions. In the above meetings and activities, new kinds of UAVs impressed most visitors.

Compared with the manned aircrafts, UAVs have many particular characteristics. For instance, the autonomous flight capability is one of the characteristics, which means the system autonomously generates the optimized control strategy and completes a variety of missions without human intervention via online environment perception and information processing. Realization of the autonomous control of UAVs and improvement of intelligence degree are two important development trends of UAVs. Since there are no cockpit and environmental control lifesaving equipments, UAV is lightweight and thereby restrictions on its design conditions can be losssened. Normally, the economic cost of UAV is much lower than that of a manned aircraft. Thanks to flexible operation, UAV can replace the manned aircraft in various dangerous and hazardous tasks.

1.2 Subsystems of UAV

One of the main UAV components is the autopilot system. It can monitor and control many of the aircraft subsystems, provide artificial stability and improve the flying qualities of a UAV. Initially, the autopilot systems were primarily conceived to stabilize the aircraft once disturbed from equilibrium of flight attitude. Modern autopilot systems are much more complex and essential to flight paramedic in flight control, navigation and guidance, flight management, stability augmentation, as well as take-off and landing operations. A survey of UAS autopilots can be found in Ref. [5] and a comprehensive compilation of the main brands of UAS autopilots is provided in UAV MarketSpace[6]. An autopilot system for a small flying wing UAV is described, which only consists of a single axis rate gyro, a pressure sensor, and a GPS receiver[7]. In the research being done in Cal Poly Pomona using a Piccolo II autopilot on autonomous UAV, a dynamics model was then used in the hardware-in-the-loop (HIL) simulation environment for the determination of feedback gains required for the autonomous flight. Finally, the autopilot is integrated into UAV for autonomous flying[8]. The topic of this paper is the development and integration of the autopilot and avionics package in the UAV platform. We describe the selection process and configuration for an autopilot and avionics package, and then integrate them into a hobby remote control aircraft being configured for autonomous flight[9]. Ref. [10] designed a longitudinal autopilot for the entire flight envelope of a Jindivik UAV, and used a linear parameter-varying method based on H1 gain-scheduling control to guarantee the stability, robustness and performance of the aircraft[10].

All UAVs have a ground station where they are given commands, and video or aerial images are relayed. The pilots can fly the UAVs through it. GCSs are transportable hardware and software devices being stationary on ground or mobile platform to monitor the UAVs for mission and safety requirements. GCS is vital in applications, especially when the UAS integrates with air traffic control (ATC) in non-segregated airspace[2]. The data of UAV states and the image data obtained by the cameras can be transmitted to the GCSs. The commands and control parameters are sent back to UAVs through data links, which enables UAV to interface with human intelligence. In Ref. [11] a universal and interoperable ground station simulator for UAVs was presented, which considered the compliance with NATO Combined/Joint Services Operational Environment (STANAG 4586) and assigned the UAV a certain degree of autonomy. It is known that multimodal technologies may improve operator performance in GCS, and information through sensory channels is also the benefit of addressing high information loads. Ref. [12] explored different techniques that can be applied to the development of GCS equipped with a multimodal interface. The interface was comprised of three screens and managed by a single operator. The system integrated visual, aural and tactile modalities, and multiple experiments showed that the use of those modalities had improved the performance of the system[12].

An important component of UAS for geodata acquisition is the mission planning and flight management subsystem, which is the key for competitive exploitation of UAS for remote sensing and photogrammetry[2]. Path planning guides the UAV to find a feasible path which is safe and meets kinematic and optimization constrains. Many approaches had been used in path planning algorithms, mainly including three sorts: the first sort is the algorithms based on grid, the second is the optimization algorithms based on intelligent algorithm, and the last is the algorithms based on curves. Besides, UAV path planning is divided into static and dynamic ones. The static path planning constructs a route once from the initial position to the final position, whereas dynamic path planning requires online path replanning. For interception of a moving target, dynamic path planning must be implemented along the movement of the target. Several dynamic path planning approaches were presented by researchers. For instance, Zhen proposed rapidly-exploring random tree (RRT) algorithm to solve the problem of cooperative path replanning for multiple UAVs under timing constraints[13].

Navigation system is also a critical component for UAS. The autopilot repeatedly reads the aircraft's position, velocity and attitude from the system and uses it in the FCS. A UAS is usually automatically piloted by an autopilot based on two main navigation technologies, global navigation satellite systems (GNSS) (such as GPS) and inertial navigation systems (INS), which can also be fused in certain navigation structures[14].

2 Flight Control Approach

Autonomous flight control technology is the key to complete tasks for UAVs. According to Ref. [15], autonomous control can be divided into three types: adaptive autonomy that adapts UAV for all kinds of uncertainty, such as the uncertainties of aircraft, environment and tasks; cooperative autonomy that makes UAV collaborate with other agents as an independent agent; and learning autonomy that has the ability of learning to correct and optimize.

Design of FCS depends on the development of control theory. In recent years, various control methods have been utilized for the design and analysis of UAV control systems, such as linear feedback control, optimal control, adaptive/robust control, nonlinear control, and intelligent control.

2.1 Linear feedback control

Proportion integration differentiation (PID) control is still the most popular method for UAV control engineering due to its simplicity and reliablity. The development in processing capabilities enables the feasible use of new costly computational control methods like the model predictive control (MPC) on real-time applications. An MPC implemented on an internal loop capacitates PID autopilot to add new capabilities into the internal loop through little corrections on its control demands[16].

Vanek presented a dynamic control allocation architecture for the design of reconfigurable and fault-tolerant control systems in UAV, which was based on linear parameter-varying (LPV) control methods. The design was demonstrated on the lateral axis motion of the NASA AirSTAR Flight Test Vehicle simulation model[17].

Optimal control is a modern control used in FCSs[18]. Zhen proposed an information fusion based optimal control (IFBOC) algorithms and applied them to the attitude control and trajectory tracking control of UAVs. The IFBOC method fuses the information of system model, performance index function and desired future state or output trajectory to estimate an optimal control input[19-20].

2.2 Adaptive and nonlinear control

For the nonlinear system dynamics and physical limitations such as actuator saturation and state constraints, the common linear controllers generally are difficult to provide good tracking performance.

The back-stepping control technique applies a recursive procedure to the dynamic system model for stabilization, which needs to be compatible with a strict-feedback form. Based on Lyapunov method, an input profile is defined to guide the system to a desired stable state. Back-stepping can be used in combination with adaptive techniques that is adaptive back-stepping. It expands the application in non-affine systems in presence of modeling errors, external perturbations or even dramatic modifications of its dynamic equations. There is an increasing interest in adaptive and nonlinear control for aircrafts, especially UAVs. In Ref. [21], a modeling process which involves the estimation of aerodynamic and propulsion system structure and parameters is carried out, and the back-stepping control is applied to nonlinear flight controller design. Finally, the convergence of the system relative to a reference and the robustness in terms of modeling errors is ensured by this method. Ref. [22] presented a mini-UAV attitude controller using a back-stepping control method.

Sliding mode control (SMC) exhibits robust performance against the strong uncertainties in system dynamics. The feedback structure is altered when the system state crosses each discontinuity surface. The system possesses high robustness against uncertainties of various kinds while on the sliding mode, so it is attractive for controlling the uncertain systems. Ref. [23] presented a tracking algorithm based on sliding mode control that enabled a fixed-wing UAV to keep tracking an uncooperative moving target. It is ensured that the UAV could maintain a persistent circular motion with respect to the moving target if the target was not far away from the UAV. Asymptotic stability was achieved for the tracking algorithm. SMC theory has also been applied to decentralized controller design for consensus and formation control of UAVs swarms, which enables a connected and leaderless UAVs swarm to reach a unification in altitude and heading angle autonomously[24]. Babaei et al. developed an efficient flight control strategy combined a classic controller as a basic autopilot and a multi-objective genetic algorithm-based fuzzy output SMC, which was robust to parametric uncertainties, un-modeled nonlinear terms, and external disturbances[25].

A nonlinear control law based on the input-output linearization technique for a pan-tilt camera to be installed on-board a fixed wing UAV was proposed in Ref. [26]. The aim of camera gimbals control was to automatically track a moving target on ground. After introducing a nonlinear dynamics model of a UAV, an adaptive controller based on feedback linearization and using Lyapunov stabilized method was proposed to perform perfect path tracking maneuvers[27]. A combination of linear model predictive control (LMPC) and feedback linearization (FL) was implemented on an autonomous team of UAVs to accomplish dynamic encirclement[28].

In model reference adaptive control (MRAC), the modeling uncertainty is often assumed to be parameterized with unknown ideal time-invariant parameters. The convergence of parameters of the adaptive element to these ideal parameters is beneficial, as it guarantees exponential stability and makes an online learned model of the system available. Most MRAC methods, however, require persistent excitation of the states to guarantee that the adaptive parameters converge to the ideal values. Ref. [29] investigated an MRAC adaptive control method that leveraged the increasing ability to online record and process data by neural networks used as adaptive elements, which was verified by the flight test of a UAV.

Yang et al. presented an adaptive nonlinear model predictive control (NMPC) for the path-following control of a UAV, which guaranteed accurate tracking performance, by varying the control horizon according to the path curvature profile for tight tracking[30].

2.3 Intelligent control

Recently, the artificial intelligence-based technique has represented an alternative design method for various control systems. An intelligent control scheme based on recurrent wavelet neural networks (RWNN) for trajectory tracking of a UAV was investigated in Ref. [31]. RWNN was suitable for dynamic system approximation and used to mimic an ideal controller. Moreover, the adaptive tuning laws were designed by sliding-mode approach. The control performance of UAV was examined under the condition of control effort deterioration and crosswind disturbance[31]. Several fuzzy logic PID controllers and fuzzy logic-based sliding mode adaptive controller were designed for stable autopilot system of UAV[32].

Pu and Zhen presented a novel intelligent control strategy based on a brain emotional learning (BEL) algorithm, which was investigated in the application of attitude control of a UAV. BEL was used to regulate the control gains of traditional flight controllers on-line. Obviously, a BEL intelligent control system is self-learning and self-adaptive, which is important for UAVs when flight conditions change, while traditional FCSs remain unchanged after design[33].

Swarm optimization algorithms or evolutionary algorithm is one of bionic optimization techniques which is intelligent, random and heuristic.

Genetic algorithm (GA) as an evolutionary algorithm can be used to optimize the gains for a variety of control approaches for UAVs[34]. An improved particle swarm optimization (PSO) algorithm[35] and an improved frog shuffled leaping algorithm (SFLA)[36] are presented to determine the UAV flight controller parameters, which provide an automatic searching method for controller gains.

3 Conclusions

In future, flying capability will open new opportunities in UAV applications, such as search and rescue, surveillance navigations and mapping operations. To keep the UAV flying steadily, and even to complete special missions, all important parts of UAV system should be perfectly matched. Therefore, flight control is a meaningful and hot research topic, not to mention the complexity of UAVs and the difficulty of flight control problems. Control methods have developed from the earliest classic PID control for the linear systems to the modern control methods (such as sliding mode control, back-stepping control, feedback linearization control, adaptive control, intelligent control and so on) for the nonlinear systems, making simulation model closer to the actual system and achieving ideal performance in the study.

Development of the autonomous ability of UAVs can improve the perception on battlefield, the speed and precision of localization, and the flexibility of missions. However, it still has a long way to go[37]. For prospect, several points can be summarized for the future of UAVs as follows:

(1) New UAVs with novel configurations will be developed for invisibility, super-maneuvering, and hypersonic, which enhances the role of UAVs in combat.

(2) Small UAVs with fixed-wing or rotor wing will be widely developed for commercial applications in agriculture, public safety, networking fields, and so on.

(3) Along with the development of materials, sensors, chips, communication, and computer technologies, the autonomous level will be upgraded.

(4) Flight control will still be a key technique for the autonomous flight of UAVs. Therefore, advanced control methods that are adaptive, intelligent, and robust will be preferred in applications.

(5) Formation/cooperative control of multiple UAVs become more and more popular for achieving a higher level of autonomy and intelligence.

(6) UAVs with hypersonic flight, super-maneuvering, invisibility and elastic wing deformation are gradually coming into public view.

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