Review Article

Survey on Flight Control Technology for Large-Scale Helicopter

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A literature review of flight control technology is presented for large-scale helicopter. Challenges of large-scale helicopter flight control system (FCS) design are illustrated. Following this, various flight control methodologies are described with respect to their engineering implementation and theoretical developments, whose advantages and disadvantages are also analyzed. Then, the challenging research issues on flight control technology are identified, and future directions are highlighted.

1. Introduction

Large-scale helicopter has its unique characteristics of maneuverability and low speed performance compared to fixed-wing aircraft, which significantly extends its application in both military and civil. The complicated dynamic system of large-scale helicopter brings to the FCS a great deal of design considerations and updates.

Early helicopters were primarily controlled through mechanical linkages, and then, electronic stabilization was implemented via analog systems to provide electronic feedback. As technology developed, digital systems, with advantages in development flexibility, complex function support, and power reduction, started to replace analog systems. The most currently used FCS is digital Fly-By-Wire (FBW) system, designed to improve handling qualities, alleviate failure transients, and reduce maintenance activities [1]. This technique has been adopted by JUH-60A [2], AH-64D [3], CH-47B [4], RAH-66 [5], Bell-205 [6–8], NH-90 [9], and so forth. Besides, Fly-By-Light (FBL) system, which has demonstrated its superiority in saving weights and reducing electromagnetic interference susceptibility problems, was already applied to helicopter in-flight simulators, such as UH-60A [10], EC-135 [11, 12], and BO-105 [13].

With the improvement of helicopter multirole capability, FCS design has become more demanding, requiring large-scale helicopter capable of executing multitasks in adverse flying conditions. The advances of flight control methodologies play a central role in helicopter FCS design on

improving helicopter dynamic performance and handling qualities. Moreover, the application of advanced flight control methodologies directly contributes to the rapid development of helicopter flight simulation technique which paves the way from advanced control theories to practical implementation. Therefore, a highly reliable flight control methodology considerably improves helicopters' performance and stability for implementing their various properties safely and effectively, within the flight envelop.

The rest of this paper is organized as follows. Section 2 illustrates the primary challenges of designing helicopter FCS. Section 3 gives an elaborate survey of flight control methodologies on classical control, modern control, and intelligent control. Core research questions are summarized and future developments of helicopter flight control technology are discussed in Section 4.

2. Challenges of Large-Scale Helicopter FCS Design

Large-scale helicopters are strong nonlinear, highly coupled, time-varying dynamic systems, which makes the FCS design a difficult task due to the following aspects.

(1) *Complicated Dynamic Response.* The nonlinear helicopter system is not affine in control inputs, which causes unwanted controller response if actuator and main-rotor dynamics are considered. Besides, the strong dynamic coupling effect makes the FCS design challenging, since each control input

not only affects the state variables of interest but also produces unintended secondary responses [14].

(2) *Multiple Flight Modes.* According to ADS-33E, military helicopters are capable of activating different flight modes, such as RC (Rate Command), ACAH (Attitude Command Attitude Hold), and TRC (Translational Rate Command) [15]. These advanced flight modes are designed to improve handling qualities in various flight conditions when executing military tasks. However, the complexity of controller design is increased, since quantities of switching logics are involved in flight mode transitions. Moreover, flight mode transitions may result in a few problems, such as unsmooth transition trajectory and actuator saturation.

(3) *System Uncertainties.* Model uncertainties primarily arise from the complicated aerodynamic nature of thrust generation. Unmodeled rotor dynamics (flapping and lagging dynamics) and high frequency dynamics associated with actuators make the controller sensitive to uncertainties. Besides, neglected dynamics, such as ground effect, near-ground wind gust and atmospheric turbulence, tend to reduce the controller efficiency as well.

(4) *Rapid Varying Flight Conditions.* Large-scale helicopters are capable of performing highly flexible maneuvers and producing multiple flight mode transitions within the full flight envelop, in which case flight parameters and dynamic states undergo intensive changes. The conventional linear controller is not able to stabilize the helicopter across various flight regimes.

3. Various Flight Control Methodologies for Large-Scale Helicopter

3.1. *Classical Control.* In general, the current helicopter FCS is designed either using PID-based feedback techniques or with model following architecture. Both of the control methods are elaborately reviewed in Sections 3.1.1 and 3.1.2. The application of gain-scheduling control policy is proposed in Section 3.1.3.

3.1.1. *PID-Based Feedback Control.* The design of primary flight control law is often accomplished using PID-based feedback controllers due to their easiness of realization and application. Without considering helicopter dynamics, the expected dynamic response is achieved by tuning PID parameters manually and by designing decoupling gains empirically. An overview of the PID FCS design for ARH-70 is provided in Figure 1. The helicopter was made to follow angular rate signals in pitch, roll, and yaw axes. The reference signals are provided by input filters and rate gyros are applied to detect angular rate feedback signals. Variables δ_e , δ_a , δ_r , and δ_c correspond to the longitudinal cyclic input, lateral cyclic input, tail rotor collective input, and main-rotor collective input, respectively. The mechanical mixer is designed to remove the inherent pitch/roll helicopter coupling. A limiting block is used to prevent actuator activities from reaching saturation limit.

From the late 1970s, large quantities of researches were conducted to evaluate PID-based feedback controllers with different levels of complexity and to investigate the influence of flight control methods on helicopter handling qualities [16–18]. Besides, the US Army initiated the Advanced Digital Optical Control System (ADOCS) program to investigate modern FCS concepts and conducted four simulations on Vertical Motion Simulator (VMS) from 1981 to 1985 [19, 20]. The partial authority FCS was tested on VMS since 1990s [21], and several simulation studies were conducted on VMS to evaluate the CH-47F Digital Automatic Flight Control System (DAFCS) in degraded visual environment from 2004 to 2005 [22].

In 2011, a novel automatic control system, using lagged-gains and scheduled SCAS (Stability and Control Augmentation System) gains, was tested on OH-58D helicopter to evaluate handling qualities in the good visual environment (GVE) and degraded visual environment (DVE) [23]. During the development of ARH-70, piloted tests of the optimized PID SCAS have been accomplished through ground-based and airborne simulations. Moreover, the development of ARH-70 FCS stands out as an excellent example of how linear modeling, gain optimization, and simulation can deliver the best possible flight control design with a minimal amount of flight testing required for design validation [24].

With the application of multiobjective parametric optimization approach, the performance of PID-based feedback control methods has been enhanced more significantly than before. However, the achievable performance is rather limited when applying classical PID control approach to multivariable, time-varying, highly coupled helicopter dynamics, since high frequency characteristic and disturbance rejection are not considered.

3.1.2. *Explicit Model Following Control.* Explicit model following control performs good command tracking and control decoupling properties, and this control method has been widely adopted in designing helicopter FCS.

From the 1980s to the beginning of 21st century, NASA-Ames and NASA-Army conducted several experiments to evaluate the explicit model following control technology on BO-105 [25] and UH-60A [2, 10]. This control architecture was also applied to the Core Automatic Flight Control System (CAFC) on the RAH-66 Comanche [5]. In 2000, Modernized Control Laws (MCLAWS), designed to satisfy the ADS-33 DVE requirements using the existing limited authority actuators, began to replace the legacy explicit model following control architecture [26–28].

A schematic of the MCLAWS architecture is illustrated in Figure 2. This control architecture uses a model following approach to provide ACAH control mode in pitch and roll axes. ACAH means that the attitude of helicopter is proportional to pilot stick positions. The LVDT block represents Linear Variable Differential Transducers, which measure the pilot's stick positions and provide input signals to the control system. The command model transforms pilot inputs to desired attitudes, and the sensor data of attitudes are provided by vertical gyros. An inverse plant works to cancel

FIGURE 1: Implementation of RC mode into ARH-70's PID control architecture.

FIGURE 2: Implementation of ACAH mode into UH-60's MCLAWS model following control architecture.

the helicopter internal dynamics. Disturbance rejection and plant stabilization are achieved using feedback compensation.

The MCLAWS has a model following type architecture with the following unique characteristics different from the legacy explicit model following concept: (1) instead of just using a commanded attitude, both rate and attitude commands are generated and used; (2) unlike a full authority system, the MCLAWS has to contend with a full authority mechanical system and to achieve desired performance with partial authority AFCS; (3) the current implementation uses a low order inverse plant model. The MCLAWS architecture provides a high level of modularity and enhances its practicability in helicopter FCS design.

In 2003, the MCLAWS was tested on VMS and results indicated that improved handling qualities and reduced pilot workload are achieved in DVE [26]. Besides, piloted simulations also demonstrated that the MCLAWS performs better than the UH-60A legacy control laws when operating in wind and turbulence. Several upgrades were accomplished to enhance the performance of the standard MCLAWS in the following years. An improved MCLAWS was evaluated on an EH-60L research helicopter for near-earth operations as the pilot's visual cues degrade [27]. Two characteristics make this MCLAWS different from [26]: (1) this MCLAWS implements an ACAH response type using only the 10% SAS

(Stability and Augmentation System) series servos with no trim actuators; (2) the application of a modern integrated toolset (MATLAB/Simulink, CIFER, CONDUIT, etc.) plays a central role in this MCLAWS design process and facilitates the MCLAWS development. Afterwards, the modern integrated package is widely used as design and analysis tool for AH-64D [3, 29]. In 2012, related works of the UH-60 MCLAWS continued to incorporate updates upon flight control design optimization methods and handling quality researches, and the FCS improvements have been addressed over two new iterations of the UH-60 MCLAWS [28, 30]. In 2016, an outer-loop position hold with velocity command mode and landing logic were integrated into the standard MCLAWS to further improve handling qualities in simulated DVE [31].

The testing results substantiate that explicit model following control guarantees excellent command tracking performance and control input decoupling, but the low order linear inverse plant model is invariant with flight conditions, which is incapable of canceling high frequency dynamics such as those associated with the main-rotor and actuators, illustrating the importance of accurate modeling of high frequency characteristics for high-bandwidth FCS [32]. Besides, unmodeled rotor dynamics and high frequency structural modes make the controller sensitive to uncertainties, which

points out that controller robustness should be improved against model mismatches and neglected dynamics to obtain good model following performance.

3.1.3. Gain-Scheduling Control. Large-scale helicopter has a strongly nonlinear behavior and is running at different operating points, resulting in nonuniformly desired control response through the entire flight envelope. Therefore, the operating-point-oriented controller parameters are required to be optimal to keep the dynamic response within the neighborhood of each fixed operating point.

To cope with nonlinear process and large parameter varying, gain-scheduling control policy is proposed. This strategy grids the flight envelope into several operating points based on which the linear controller is designed, and interpolation algorithm is adopted so that smooth transitions are possible between the operating points. The realization of gain-scheduling strategy is essentially an engineering problem, since the applied control technique is mainly based on linear control methods (PID control or explicit model following control) and the primary task is to tune the gain-scheduled control parameters that are scheduled as a function of flight conditions (airspeed, altitude, dynamic pressure, etc.) in modern helicopter. Manual tuning of control system parameters to meet handling qualities and performance specifications has always been time-consuming and complicated. Instead, the control engineers resort to engineering tools and take advantage of the automated tuning feature, making the design applicable to nonlinear helicopters.

A state-of-the-art engineering tool, the Control Designer's Unified Interface (CONDUIT) software package, allows the designer to tune selected design parameters for the optimal performance against helicopter-oriented specifications [33]. Since the late 1990s, many FCS designs, such as those of the RASCAL JUH-60A Black Hawk and AH-64 Longbow Apache and OH-58D Kiowa Warrior helicopters, have been implemented using the CONDUIT. In 2016, the CONDUIT toolset is integrated into the recently developed SIMPLI-FLYD framework (a collection of tools) which is designed to perform modeling and analysis for the assessment of flight dynamics and control aspects of the handling qualities of rotorcraft conceptual designs [34]. Moreover, the SIMPLI-FLYD evaluation process also provides pathways to decrease the computational cost of running complete CONDUIT optimization.

In the multivariable control system design, a coupling numerator theory and quantitative feedback theory based precompensation technique is applied to minimize the helicopter cross-coupling response [35]. The resulting dynamic crossfeeds are used for gain-scheduled controller designs. To implement such a technique in existing helicopters, the designer selects the desired time domain/frequency domain coupling specifications (e.g., a time domain pitch/roll coupling specification is CouPRH1 [36]) and other specifications from the CONDUIT libraries to incorporate them in the FCS design problem, and then, the designer graphically selects gain-scheduled control parameters and crossfeeds that will be used by CONDUIT in the tuning process. These design parameters are optimized against a combination of

specifications, such as stability, coupling, bandwidth, and actuator activity. Finally, the performance of the helicopter FCS is evaluated and ensures that Level 1 design specifications can be achieved.

The overall physical configuration for the implementation of gain-scheduling control method is deployed in a hierarchical architecture. Controller tuning is executed in the CONSOL-OPTCAD environment which is already integrated into the CONDUIT, and the CONDUIT resides in the computer operating system on engineering workstations. An automatic coding of the optimized control law is employed to facilitate piloted simulations following CONDUIT analyses. The pilot-in-the-loop evaluations are conducted on engineering simulators (e.g., VMS and RACAS [37]), including inceptors with control loading, to further evaluate the gain-scheduling flight control laws. Moreover, the gain-scheduling needs only small capacity of the dual Intel® Xeon® processors and requires relatively less calculating time.

Gain-scheduling is a beneficial strategy to adjust controllers to each operating point, if a nonlinear system exhibits different behaviors across different flight regimes. However, the robustness properties of the control system are not guaranteed only by designing each controller for its best performance, since no satisfactory mathematical theory approves that the sum of local optimal results will definitely contribute to the system's global optimum. To cope with this problem, the engineering tool CONDUIT uses multiobjective optimization, which allows the relative importance of each design specification to be determined, to ensure that the best feasible solution of the proposed control system is achieved within all robustness constraints. Besides, other techniques being developed are also applied to study multidisciplinary design optimization of FCS parameters [38] and automated procedure for gain-scheduled flight control law design [39]. Future development of the engineering toolset will directly provide designers rapid insight on control system response and accelerate the R&D process for helicopter industry.

3.2. Modern Control. This part reviews the modern control methods, with an emphasis on discussing those that have been tested through engineering simulations. These methods are H_∞ optimal control and Incremental Nonlinear Dynamic Inversion (INDI) control. The primary implementation of observer feedback control is presented in Section 3.2.3. Other representative modern control methods (see Table 1) are still in developing stage and only verified via desktop simulation.

3.2.1. H_∞ Optimal Control. H_∞ optimal control method is designed to minimize the infinity norm of weighted transfer functions on satisfying important frequency domain requirements often referred to as loop shaping. Loop shaping is used to shape sensitivity function, complementary sensitivity function, and control activity by selecting frequency dependent weights.

In the 1990s, McFarlane and Glover introduced a particular loop shaping method to guarantee close-loop stability and a level of robust stability at all frequencies against a

TABLE 1: Summary on modern control methodologies.

Control methods	Advantages	Disadvantages
LQR/LQG Control	Guaranteed stability margins for state feedback LQR; good transient response and disturbance rejection.	Full state feedback requires significant usage of sensors; Kalman filter degrades the frequency domain properties.
Eigenstructure Assignment Control	Close-loop performance index can be designed directly; the control method is relatively simple to implement without requiring high order dynamic compensators.	An analytical linear plant is required; stability and robustness is not guaranteed; dynamic cross-coupling between inputs and outputs cannot be canceled.
Adaptive Control	Control gains can be adjusted automatically using on-line adaption; robustness is achieved within bounded system uncertainties; the regulated output dynamics are allowed to be non-minimum phase.	Parameter drift is caused by process noise; high frequency flexible modes are difficult to control; large rates of adaption are practically non-realizable.
LPV Control	Nonlinear natures of the plant are captured accurately using LPV modeling; controller robustness is improved over conventional gain-scheduled controllers.	The complexity of LPV controller is significantly increased; system uncertainties caused by rapid varying flight parameters cannot be completely eliminated.
Sliding Mode Control	Different control laws can be adopted corresponding to the changes of system trajectories; the controller performance is insensitive to modeling errors and parameter uncertainties.	Chattering is induced by frequent controller switches; highly nonlinear sliding mode surface results in difficulties of analyzing system stability and reachability.
Backstepping Control	The exponential stability of dynamic errors guarantees asymptotic tracking of the desired command.	Calculating the derivative of pseudo control inputs results in huge computation.
MPC	External constraints are incorporated into the design process naturally; improved transient response is achieved using prediction models.	Close-loop property depends on the performance of reference model; on-line optimization is time-consuming.

coprime factor uncertainty [40]. The coprime factor robust stabilization problem is illustrated in Figure 3.

A linear, time-invariant plant is given in the following:

$$\Sigma_G : \begin{cases} \dot{x} = Ax + Bu + Ew, \\ z = Cx + D_1u + D_2w. \end{cases} \quad (1)$$

It is required to design the dynamic compensators W_1 and W_2 of the form

$$\Sigma_W : \begin{cases} \dot{x}_c = Hx_c + Fy, \\ u = Mx_c + Ny, \end{cases} \quad (2)$$

such that after applying the feedback Σ_W to the system Σ_G , the resulting H_∞ norm of the closed-loop system is less than a positive bound γ . In Figure 3, the nominal plant is

$$G = M^{-1}N \quad (3)$$

and a perturbed plant G_Δ is written as

$$G_\Delta = (M + \Delta_M)^{-1} (N + \Delta_N), \quad (4)$$

where M, N are a left coprime factorization of G and Δ_M, Δ_N are uncertainties. The nominal plant G and the dynamic

FIGURE 3: The Glover-McFarlane H_∞ loop shaping design.

compensators W_1 and W_2 are combined to form the shaped plant $G_s = W_2 G W_1$. The shaped open loop frequency response G_s is then used to seek a static feedback controller K such that

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I + G_s K)^{-1} M^{-1} \right\|_\infty \leq \gamma. \quad (5)$$

This can be rewritten in the framework of an LMI based H_∞ optimization problem [8] and ensure that the closed-loop H_∞ optimal index $\gamma_{\min}$ is small enough. The final feedback

FIGURE 4: Implementation of ACAH mode into Bell 205's H_∞ control architecture.

controller K_∞ is then constructed using the static output feedback controller K with the compensators W_1 and W_2 such that $K_\infty = W_1 K W_2$.

The Glover-McFarlane H_∞ loop shaping method guarantees that the nominal input-output characteristics are kept unchanged. Besides, an unstable system with right half plane poles can be canceled out using coprime factorization, and the existence of solution for compensators is guaranteed corresponding to particular robustness conditions. These advantages make this coprime factorization based H_∞ control better than the standard H_∞ optimal control strategy.

In 1993, Mammari and Duc proposed a loop shaping procedure using a normalized coprime factors robust stabilization. This design approach has been successively verified in solving the stabilization problem of a helicopter [41]. The first H_∞ controlled helicopter was reported in 1997 [6]. In order to implement an ACAH flight mode (see Figure 4) in hover and low speed, University of Leicester designed H_∞ controller against coprime factor uncertainties using a loop shaping procedure followed by a robust stabilization. Piloted simulations were conducted on the ground-based Large Motion System (LMS) simulator and in-flight evaluation was performed on the National Research Council of Canada's (NRCC) Bell 205 airborne simulator. The piloted simulations were a milestone in the development of H_∞ control policy, and positive evaluations on flying the H_∞ controlled system are provided. After that, the robustness properties of the nominal H_∞ control architecture were improved by including high-order rotor dynamics, used to eliminate the need for designing predictor-type filters, in the controller design process [7]. In 2005, Prempain and Postlethwaite proposed a static LMI based H_∞ loop shaping controller for the NRCC FBW Bell 205 in-flight simulator, and flight tests proved to be successful in achieving high-level performance [8].

The implementation of H_∞ control theory makes considerable efforts to close the gap between robust control theory and practical implementation and stimulates the theoretical development of multivariable H_∞ control methodology. However, H_∞ control method has deficiencies in system's dynamic response: (1) the controller generates slow response, especially in the yaw channel; (2) interaxis coupling is present, such as pitch-yaw coupling and heave-yaw coupling; (3) the H_∞ control method causes large undershoot in acceleration response if the plant is nonminimum phase.

On the contrary, H_2 control strategy enjoys its advantage over dynamic performance, but it has drawbacks in robust stability and disturbance rejection. In this case, a mixed H_2/H_∞ control strategy combines superiorities of

both approaches. Extensive theoretical studies have been conducted on H_2/H_∞ strategy since 1990s [42–46]. Only a limited number of researches applied this control theory to air vehicles [47–53], and few achievements have been engineering tested.

In 2013, Rigsby et al. introduced a mixed H_2/H_∞ robust feedback controller, utilizing measurements of the external load dynamic states, for helicopters handling externally slung loads [54]. Piloted simulations were conducted on the Sikorsky simulation facility, and test results indicated that this control methodology is effective in reducing load swing and pilot workload [55]. This novel FCS, augmented with active external load controller, addresses special requirements for engineering simulation of flight control technology and provides insights on mission-oriented FCS design.

In general, most controller designs, including H_∞ and H_2/H_∞ , are based on linear models utilizing the widely adopted concept of stability derivatives. Conservativeness of linear controller design lies in the assumption of small deviations from nominal conditions. This assumption is not always satisfied, which results in significant gain-scheduling, linear interpolation, and model switches. In this case, the airspeed dependent dynamics are difficult to capture under all circumstances, resulting in degraded dynamic response. Therefore, investigations on nonlinear controllers have been making contributions to understanding limitations of linear controllers and to analyzing the nonlinear nature of helicopter dynamics.

3.2.2. INDI Control. The nonlinear controller designs are mostly valued for their theoretical contribution to the helicopter flight control problem, but their applicability is an open challenge mainly due to the increased order and nonlinear structure of the controller [14]. It is the cooperative program between TU Delft and Boeing Mesa on developing advanced control laws for AH-64D helicopter that significantly contributes to the practical implementation of a nonlinear control scheme, the INDI methodology [56]. Engineering simulations of INDI were tested on SIMONA Research Simulator (SRS), indicating that this advanced nonlinear control strategy is potential for further practical implementation to helicopters.

The INDI is an incremental version of NDI. Basically, the NDI allows generating a control input via nonlinear feedback control and state transformation such that, when it is applied to the nonlinear system, the relation between a virtual control input and the output of the system becomes linear [57]. However, the high sensitivity to model uncertainties is the

FIGURE 5: Implementation of RC mode into AH-64's INDI control architecture.

main shortcoming of the NDI [58], which motivates the development of INDI. In the past few years, many achievements have been applied to solve flight control problems for fixed-wing UAV [59], spacecraft [60], large-scale helicopter [61], tiltrotor UAV [62], quadrotor MAV [63], and so forth.

According to Figure 5, the INDI control architecture implements an RC mode using Apache's limited authority setting. Instead of using the nominal virtual input to compute the complete control input, it is possible to determine only the required variation with respect to the previous inputs. In order to form the required command signals, a unit delay operator z^{-1} is used to access the current values of the control inputs. The implementation of INDI is based on the onboard measurements of state derivatives without acquiring the state-dependent part of the plant.

However, accurate and almost instantaneous measurements or estimations of acceleration are not readily available. It is very to employ sensors to feedback angular/translational acceleration, but this approach introduces measurement noise and time delays, which results in additional designs of compensators and filters. Besides, it is also feasible to integrate observers into the INDI controller, but full order observer may degrade stability robustness properties of controller designs. These technical concerns bring to the application of INDI some difficulties.

3.2.3. Observer Feedback Control. In many practical helicopter FCS designs, the problem with state feedback control is that all of the state variables are rarely accessible for measurement. On the other hand, a large number of transducers are used to sense the state variables, making the application of the state feedback control strategy costly and impractical. To implement the state feedback control scheme, observers are required to reconstruct the states using available helicopter sensors. An observer is a dynamic system that takes the sensor signals as inputs and produces state estimates as outputs. The form of the observer is closely

related to the particular complement of sensors available and often comprises the most complicated part of the controller architecture [64].

The Kalman filter is widely used to solve state estimation problems and it has numerous applications in technology. However, when used to estimate the state in output feedback control design problems, the optimal state estimator may not exhibit the best overall control properties [65]. Therefore, a tuning process called Loop Transfer Recovery (LTR) is designed to asymptotically recover the state feedback frequency domain properties. The LQG/LTR framework is verified to be a useful tool for linear control law design of a combat helicopter [66].

For the problem of nonlinear estimator designs, the Kalman filter is extended to nonlinear systems to obtain the Extended Kalman Filter (EKF). In 1986, an EKF was developed to track the states of Bell Jet Ranger helicopter during flight test. In particular, this EKF can also supply filtered state variables to a full state feedback framework or stability augmentation system [67]. In 1990, the University of Alabama Flight Dynamics Lab (UAFDL) proposed a variation of a Linearized EKF to accurately recreate the performance of UH-60 helicopter which was flown with stability augmentation system and flight path stabilization system operational [68]. Piloted simulations were conducted on the UAFDL helicopter simulator and experimental results indicated that the proposed compensator exhibits precise state tracking abilities and robustness to measurement sample rate and initial error conditions. Abraham and Costello applied the EKF framework to provide real-time estimates of weight and mass center for OH-6A helicopter, and the resulting in-flight estimates are used to improve state feedback flight control system performance [69].

It is denoted that, for helicopter systems, the EKF has proven to be a useful method of obtaining accurate estimates of the state variables. However, the EKF is obtained using a linear approximation of a nonlinear system, no guarantees of

optimality are ensured in the sense of a mean squared error, and the convergence problem relies on how close we can drive the linearized point to the actual operating condition of the nonlinear system. Therefore, some reduced observer designs are applied to replace the complex structure of Kalman filter-type observers and to increase the need for an enhanced sensor complement.

In 2005, a viable practical feedback controller, using inertial rate feedback sensors coupled with a Luenberger reduced order observer, was designed to improve the helicopter handling qualities in pitch and roll axes [70]. The observer-based flight control law was excised on the BO-105 helicopter and it achieved good robustness to structured model perturbations. Utilizing the actual flight data of the Rooivalk attack helicopter, Hager et al. applied a reduced Brunovsky canonical observer to improve prediction capabilities in pitch axis [71]. In 2015, Greiser introduced a disturbance observer-based controller to suppress the roll oscillation for a highly modified research helicopter ACT/FHS [72]. The reduced order observer with disturbance compensation was tested on a ground-based simulator which simulates a highly sophisticated nonlinear model of ACT/FHS, and the desired experimental results will definitely motivate flight tests with the ACT/FHS for further validation.

To summarize, most of the observer designs use a Kalman filter-type scheme and experimental results show that the controller performance is highly dependent on the observation signal. However, a complete Kalman filter is complex, since models of the random process and measurement noise are required to perturb the helicopter system. Future developments of real-time helicopter state estimators would aim for the simplified observer structure which is particularly well suited to state feedback control problems where the Kalman filter-type filter is costly and additional sensors are demanded.

3.2.4. Other Modern Control Methodologies. LQR/LQG and Eigenstructure Assignment control approaches are linear control strategies. The former one is applied to adjust penalty matrices against a particular performance index by solving Algebraic Riccati Equations (ARE), and the latter one is used to assign the dominant eigenvalues and associated eigenvectors to achieve the desired transfer functions between commands and outputs. The effectiveness and reliability of both methods are demonstrated on controlling linearized helicopter dynamics [73–77]. However, both control approaches provide inadequate robustness to uncertainties and nonlinear effects begin to dominate the system response once actuator is saturated.

Adaptive control methods are able to control both linear and nonlinear systems with nonlinear uncertainties in their dynamics. This online control policy is effective to solve flight control problems where the aircraft aerodynamics are analytically nontractable and to capture rapid varying dynamic responses which are caused by system failure, flexibility, and battle damage. In the past two decades, newly developed adaptive controllers have been evaluated on nonlinear large-scale rotorcraft models, including UA-60A [78], BELL-412EP [79], BO-105 [80], PUMA-XW241 [81], UH-1H [82], and

XV-15 [83–85]. Adaptive control provides the possibility of reducing the cost of gain-scheduling and to better understand helicopter aerodynamics across full flight envelop using online identification.

Another widely accepted approach to deal with large parameter varying is linear parameter varying (LPV) control. LPV controller can be synthesized as a single controller (control gains are continuous functions of scheduled variables) rather than a group of controllers. The LPV controller operates over the whole range of flight conditions without having to create a scheduling scheme. There are several researches applied LPV control method to fixed-wing aircraft [86–91], and few investigations are conducted on rotorcrafts [92, 93] because of the following reasons: (1) the nonlinear helicopter model is not affine in control inputs because of the main-rotor dynamics; (2) the rapid variation of flight parameters requires fast transient response, which provides rigorous constraints for controller synthesis; (3) the selection of effective scheduling variables is challenging, since inner dynamics, such as inflow dynamics and blade flapping dynamics, have to be considered.

In addition, other nonlinear control methodologies, including sliding mode control, backstepping control, and model predictive control (MPC), are also designed for controlling full-size helicopters, but only a few researches are conducted on sliding mode control and backstepping control [94–97].

MPC is an optimization based framework for learning a stabilizing control sequence which minimizes a specified cost function [98]. MPC has been successfully used in many fields, and its application to piloted rotorcrafts is increasing in the past five years.

Bogdanov et al. designed a neural-MPC trajectory tracking controller for a high-fidelity helicopter model [99]. He et al. developed a constraint reduction algorithm for rotorcraft MPC [100]. Ngo and Sultan studied ship landing control for a full-size helicopter model using MPC [101]. In 2016, Cooper et al. developed a partial authority Receding Horizon Optimal (RHO) controller to improve rotorcraft handling qualities in DVE [102]. The control law was evaluated on a 22 states EH-60L rotorcraft model. Simulation results verified the efficacy of RHO control strategy and validated its candidacy as a potential rotorcraft control architecture.

3.3. Intelligent Control. Developing a high-fidelity nonlinear helicopter model is usually time-consuming. The intelligent control methodology requires no assumptions about the internal structure of the plant and the reliance on exact model can be alleviated. Two dominant intelligent control methodologies are based on either fuzzy logic or artificial neural networks (ANN). Further illustrations are given in the following.

3.3.1. Fuzzy Control. Fuzzy control, also called rule-based control, adjusts its outputs on errors by applying fuzzy logic, linguistic variables and fuzzy inference to imitate the thinking process of human brains. The advantages of fuzzy control are as follows: (1) it can be built up from rules of logic that have physical meaning to the designer; (2) this control

policy relaxes the requirements of obtaining an accurate and analytical model.

The work on designing fuzzy controller for helicopters dates back to the 1990s. Jiang et al. combined a fuzzy controller with a nonlinear model-based controller to track attitude commands for the AH-64 helicopter [103]. Numerical simulations indicated that the inversion error is canceled out and close-loop system stability is guaranteed. Mulgund and Zacharias developed a hybrid neural network/fuzzy logic control approach for detection and prevention of helicopter flight limit exceedances, and it was tested on the numerical model of the UH-1H helicopter [104]. Amaral and Crisóstomo proposed a neurofuzzy inference controller used to control a Sikorsky S-61 full-size helicopter in hover and forward flight [105]. Simulation results showed that fuzzy logic theory is applicable to control nonlinear systems with very promising results. A fuzzy switching controller, using fuzzy logic theory and H_∞ control, was designed for the UH-60A helicopter to satisfy ADS-33D level 1 requirements in the full flight envelop [106, 107]. Yu designed a LQ optimal controller with T-S fuzzy gain-scheduler and applied this control strategy to the nonlinear BO-105 helicopter [108]. The turning rate regulation and forward velocity tracking response demonstrate the effectiveness of fuzzy gain-scheduling. Lower et al. developed a fuzzy regulator based on expert knowledge for hover control of a single-rotor helicopter, PZL Kania [109]. In 2015, Sunberg et al. studied the autorotation control using a new fuzzy logic-based controller [110]. This control law was validated on a high-fidelity model of full-size attack helicopter, and simulation results proved that safely decent landing was achieved successfully under the vast majority of flight conditions.

It is concluded that the application of a single fuzzy controller is not adequate to stabilize a helicopter because of its complex nonlinear dynamics and dramatic changes of flight conditions, which addresses the point that fuzzy logic controller should be augmented with model-based control, robust control, neural network control, or other control methods to enhance its nominal performance. Most of the FCS designs using fuzzy logic have been tested only through digital simulations, indicating that there still exists a big gap between fuzzy control theory and its practical implementation. Moreover, the fuzzy treatment of knowledge reduces the controller efficiency and results in degraded dynamic response.

3.3.2. ANN Control. ANN is a distributed parallel computational system comprised of interconnected neurons, capable of self-learning and self-adapting, for information processing. The computational requirements for executing trained ANN are generally small and can be readily implemented for real-time control. ANN can also be trained to perform a task without having to exactly model the underlying dynamics [111]. This is tempting for controlling complicated nonlinear systems whose characteristics are poorly understood.

The ANN control strategy has been applied to unmanned small-scale helicopters since 1990s [112–117], and several researches were conducted on AH-64 helicopter to evaluate the ANN control policy [84, 118–121]. In 1994, Calise et al.

proposed a neural network controller based on feedback linearization approaches to compensate for inversion error and approximate dynamic changes induced by imprecise modeling [118]. Kim and Calise developed a training algorithm based on Lyapunov stability, which is used to train the NN online to approximate the inversion errors [84]. Leitner et al. designed an online adaptive NN control architecture with the adaptation gain parameter to improve command tracking performance in the presence of significant modeling errors for complicated maneuvers [119]. They also developed a robust trajectory tracking controller, enhanced with a simple two layer adaptive NN, to mitigate uncertainties and rapid varying nonlinear dynamics [120]. A model-free online learning control scheme, neural dynamic programming, was introduced in [121], and it was applied to stabilize a high-fidelity Apache helicopter in the presence of turbulence and gusts.

In 2001, the NASA-Ames conducted a research on designing a close-loop optimal NN controller (ONNC) to optimize rotorcraft aeromechanical behavior. A modern constrained optimization method is used to determine and update the constants in the NN plant model. Moreover, the ONNC was coded and loaded to digital processors [122]. Sahani and Horn designed a limit prediction algorithm based on neural networks, which provides envelope limiting avoidance through the AFCS by constraining the collective input. Simulations were conducted on a high-fidelity UH-60A model, indicating that this technique provides potential for implementing helicopter flight envelope protection system [123].

Previous researches indicate that ANN can act as excellent function interpolators but cannot be applied to regions where they have not been trained [111]. In other words, the controller performance largely depends on the training algorithm, which is still an open issue to scholars since the quantity of training data, effectiveness of training strategy, and computational efficiency have to be considered. Moreover, the ANN significantly increases the complexity of controller structure and proved to be challenging for practical implementation.

4. Conclusions

To sum up, various state-of-the-art control technologies assume an indispensable role in research and development for large-scale helicopters since they directly benefit the current and ongoing FCS designs. The design and application of the helicopter FCS was driven by various aspects, such as control theories, the complexity of controller architecture, simulation devices, and helicopter mission elements. However, only a few controller designs are applicable when considering engineering implementation for actual helicopters. In this survey, some important research issues are discovered. The further research is being conducted to incorporate the following topics.

(1) *Parameter Design upon Command Model.* Command models are required whether linear or nonlinear control policy is adopted. Engineers mostly design the command model manually and they mainly refer to the ADS-33E.

Further researches can be conducted on investigating the design criteria and tuning strategies to help engineers reduce their workload.

(2) *Problems of Actuator Saturation during Automatic Flight Mode Transitions.* Actuator saturation could occur during flight mode transitions, especially for highly maneuverable attack helicopters which produce flight transitions among various flight modes. However, only a few surveys are conducted on actuator saturation problems without considering the influence of multimode transitions. An efficient switching control logic that aims to eliminate actuator saturation for high-bandwidth helicopter FCS is worth investigating.

(3) *Helicopter Dynamic Modeling.* A high-fidelity nonlinear helicopter model gives a more accurate description on dynamic responses and input-output relations than a linear model, but it makes the controller design more challenging because of the rapid changing parameters and system nonlinearities. The LPV model is able to approximate the original system quite closely, but only the affine format of LPV model is appropriate for controller synthesis, which is not always the case for large-scale helicopter. Besides, the LPV model also increases the controller complexity within constraints. Thus, further investigations of simplified nonlinear modeling techniques would provide insights to controller design and evaluation.

(4) *Gaps between Optimized Gains and Unexpected Simulation Results.* Simulation studies present a problem that optimized control gains results in less than optimum performance in piloted simulations. It seems that, only through trial and error that could close this gap, different design criteria lead to various testing results. Detailed analysis and investigations should be conducted on this discrepancy to shorten the distance between simulation and application.

The future implementation of advanced control methodologies, such as model predictive control and intelligent control, is expected to provide potential efficacies as practical helicopter flight control strategies. Besides, newly developed ground-based simulation devices, with complex mechanical structures, are designed to perform more complicated maneuvers and evaluate more sophisticated control algorithms. Furthermore, with the development of avionics, FBL control systems, and sensors, novel in-flight simulations will permit more realistic representation of helicopter aerodynamic response and shed light on FCS design as well.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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