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Robust Discrete-Time Flight Control of UAV with External Disturbances

Springer

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To our families for their love and support

Preface

This book is devoted to studying some discrete-time flight control schemes for the fixed-wing UAV system in the presence of system uncertainties, external disturbances, and the input saturation. On the basis of lemmas of the stability analysis of discrete-time nonlinear systems, approximation methods of system uncertainties, design technologies of nonlinear discrete-time disturbance observers (DTDOs), and tackling methods of input saturation, the main research motives of this book are given as follows:

(1) With the development of modern industrial production technology, the system mathematical model is more and more complex. In order to meet the high demand for practical control, the high performance computers have been widely used in the control field. Since computers can only process discrete-time digital signals for the data storage and calculation, the continuous-time signals need to be converted to discrete-time signals when the UAV system is controlled by computers. In addition, the actual control laws of the UAV system need to be realized by the digital controllers, so the studies of discrete-time flight control schemes are particularly important. On the other hand, the control performance of the digital controller based on the approximated discrete-time UAV model may be better than that of the digital controller obtained by discretizing the continuous-time controller. Therefore, in order to facilitate the digital realization of the flight control schemes, it is of practical significance to study discrete-time flight control methods.

(2) In practice, a large number of systems possess modeling errors and other uncertainties. System uncertainties may not only degrade the performance of the control plant but also even lead to instability of dynamics systems. Due to the coupling between each channel of the fixed-wing UAV and the nonlinear actuator, the model of the fixed-wing UAV cannot be accurately modeled, so there will be modeling errors between the accurate model and the constructed model. Thus, the control issue considering system uncertainties should be solved to improve the performance of the UAV system. Due to their inherent ability of universal approximation, the neural network (NN) is usually applied

to model the unknown nonlinear system functions. The existing research works demonstrate that uncertain nonlinear systems can be efficiently controlled by using adaptive NN control schemes.

(3) It is generally known that practical systems are often subject to external unknown disturbances, which can cause the performance degradation and instability of systems. Due to the variable flight environment of fixed-wing UAVs during flight missions, UAVs are often affected by wind disturbances. However, the Kalman filter cannot be used to tackle external disturbances if the external disturbance cannot be measured. It is well known that external disturbances are very difficult or even impossible to be measured physically by sensors. Disturbance observers (DOs) can well estimate external disturbances using the known information of controlled plants and the control law can include the outputs of disturbance observers. As a result, the disturbance rejection ability is ensured to improve the performance of the closed-loop system. Therefore, the development of DTDO-based control scheme is significant for the control of uncertain UAV systems with external disturbances.

(4) On the other hand, the system control performance of the UAV can be degraded under the input nonlinearities such as input saturation, dead-zone, and hysteresis, and the input nonlinearities even can lead to the close-loop system instability. Therefore, considering the input nonlinearities problem is very significant for the control of uncertain fixed-wing UAV system. Moreover, it is a challenging problem to design the discrete-time control scheme for the control of the uncertain fixed-wing UAV system in the presence of external disturbances and input saturation. Therefore, DTDO-based control schemes need to be further studied for uncertain UAV systems with external wind disturbances and input saturation.

(5) In previous studies, most of the control methods focused on how to guarantee that the tracking error converges to a bounded region or asymptotically converges to origin, which belongs to steady-state performance research. The study on transient performance including overshoot and convergence rate needs to be further considered. Actually, the transient performance plays an important role in improving the performance of the actual UAV system. The bigger overshoot may lead the actuators to exceed the physical limitation, consequently causing the instability of the closed-loop system. Therefore, the transient and steady-state performance should be further improved for the control of UAV systems in the presence of system uncertainties, external disturbances, and input saturation.

Based on the above research motivation, the main contributions of this book are shown as follows:

Firstly, on the basis of the previous research works, the continuous-time fixed-wing UAV attitude dynamics model under external wind disturbances is given. By using the Euler approximation method, the fixed-wing UAV attitude dynamics model with continuous-time form is transformed into an approximate discrete-time one. A discrete-time neural network (NN) control scheme based on the DTDO is proposed for the discrete-time fixed-wing UAV attitude dynamics model with external disturbances and system uncertainties. This scheme combines the DTDO, the NN approximation method, and the backstepping control (BC) technique to realize the discrete-time tracking control of the fixed-wing UAV, and the robustness of the resulted UAV control system is also enhanced. The feasibility of the discrete-time flight control scheme is demonstrated by the numerical simulation of the fixed-wing UAV attitude dynamics system.

Secondly, since the actuator is prone to occurring saturation, the input saturation problem is further considered in the design of the robust discrete-time flight control scheme, and a discrete-time robust anti-saturation control method based on the auxiliary system and the nonlinear DTDO is proposed to achieve the stable flight control of the fixed-wing UAV with external wind disturbances, the input saturation, and system uncertainties. On the basis of the BC technique, the stability of the closed-loop system is proven by using Lyapunov stability theory. The simulation results of the uncertain fixed-wing UAV attitude dynamics model show that the discrete-time-NN-based control scheme is effective.

Thirdly, for the trajectory control model under external wind disturbances and the uncertain discrete-time fixed-wing UAV attitude nonlinear model under wind disturbances and input saturation, a discrete-time robust control scheme is proposed for the uncertain fixed-wing UAV system based on an auxiliary system and the discrete-time sliding mode disturbance observer (SMDO). The scheme introduces an auxiliary system to suppress or eliminate the adverse effects of input saturation for the closed-loop flight control of the fixed-wing UAV, and the NN approximation is used to deal with the uncertainties in the fixed-wing UAV system, and a NN-based discrete-time SMDO is employed to compensate for the negative effects of external disturbances, and a discrete-time robust controller is designed by utilizing the BC technique. The numerical simulation results verify that the flight control performance is satisfactory under the proposed NN-based discrete-time control method.

Fourthly, the system uncertainties and the problem of the prescribed performance are considered in the design of discrete-time fractional-order (DTFO) control scheme for the fixed-wing UAV attitude system with external disturbances, and the control problems of the steady state and the transient performance for the fixed-wing UAV attitude closed-loop system are comprehensively studied, and then by combining the prescribed performance control method, the NN-based DTDO and the discrete-time fractional-order calculus (FOC) theory, the DTFO tracking controller based on the DTDO and the NN was designed with the BC technique. On the basis of the designed DTFO tracking controller, the flight control of the fixed-wing UAV system in the presence of external disturbances and system uncertainties is realized. The simulation results show that the designed DTFO tracking controller can ensure that the fixed-wing UAV closed-loop system satisfies the steady state and the transient performance, and the designed DTDO can guarantee that the disturbance estimation errors are bounded.

Finally, aiming at the DTFO control problems for the trajectory control system and the attitude system of the fixed-wing UAV with external wind disturbances, a DTFO control method is proposed for the fixed-wing UAV system. In this method, the DTFO control method based on the designed DTDO is proposed by using the BC technique, and then the DTFO tracking control of the fixed-wing UAV system is realized. Simulation results show the effectiveness of the proposed DTFO control scheme based on DTDO.

This book intends to provide the readers a good understanding on how to achieve the discrete-time tracking control schemes of the fixed-wing UAV system with system uncertainties, external wind disturbances, and input saturation. The book can be used as a reference for the academic research on uncertain UAV systems or used in Ph.D. study of control theory and engineering.

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Contents

Acronyms

$\Re$	The field of real numbers
$\Re^r$	The r-dimensional real vector space
$\lvert\cdot\rvert$	The absolute value
$\lvert\lvert\cdot\rvert\rvert$	The 2-norm
$\lambda_{\max}(\cdot)$	The maximal eigenvalue
$\lambda_{\min}(\cdot)$	The minimal eigenvalue
sign	The signum function
sat	The saturation function
diag	The diagonal matrix
sec	The second
deg	The degree
M	The quality of UAV
T	The transposition
$\overline{V}_A$	The flight velocity of UAV
χ	The track azimuth
γ	The track inclination
β, α, μ	The sideslip angle, attack angle, and roll angle
$\overline{T}$	The engine thrust
p_b, q_b, r_b	The roll, pitch, and yaw angular velocity
$\overline{x}_g, \overline{y}_g, \overline{z}_g$	The position of UAV in the ground coordinate system
I_{xx}, I_{yy}, I_{zz}	The rotational inertia
I_{xz}	The product of inertia
g_0	The gravitational constant
g	The vertical gravity component
$\overline{R}$	The equatorial radius of earth
$\overline{D}$	The resistance
$\overline{L}$	The lift force
$\overline{X}, \overline{Y}, \overline{Z}$	The aerodynamic
$\overline{q}$	The aerodynamic pressure
S_r	The wing area of UAV

$\overline{\rho}$	The current density
ρ_0	The sea level air density
$\overline{\overline{T}}$	The temperature
$C_{X_{\overline{T}}}$	The axial force coefficient
h_e	The engine angular momentum
$C_{Y_{\overline{T}}}$	The lateral force coefficient
$C_{Z_{\overline{T}}}$	The normal force coefficient
$\overline{b}$	The wing length of UAV
$\overline{c}$	The average aerodynamic chord length
$\delta_e, \delta_a, \delta_r$	The pneumatic rudder surface deflection angle
$C_{l_{\overline{T}}}, C_{m_{\overline{T}}}$	The total rolling and pitching moment coefficients
$C_{n_{\overline{T}}}$	The total yaw moment coefficient
$C_{n\delta_r}$	The moment coefficient
$C_{l\delta_a}, C_{l\delta_r}$	The moment coefficients
$C_{m\delta_e}, C_{n\delta_a}$	The moment coefficients
UAVs	Unmanned aerial vehicles
DO	Disturbance observer
DTDO	Discrete-time disturbance observer
NN	Neural network
BC	Backstepping control
SM	Sliding mode
SMC	Sliding mode control
SMDO	Sliding mode disturbance observer
FO	Fractional-order
DTFO	Discrete-time fractional-order
DTDO	Discrete-time disturbance observer
FOC	Fractional-order calculus
FBL	Feedback linearization
DI	Dynamic inversion
ABC	Adaptive backstepping control
MIMO	Multiple-input-multiple-output
CTDO	Continuous-time disturbance observer
FL	Fuzzy logic
FOPID	Fractional-order proportion integration differentiation
RBFNNs	Radial basis function neural networks