

Preface

Unmanned aerial vehicles (UAVs) are finding wider applications including surveillance, rescue, navigation, formation, coordination, among others. Helicopter-type UAVs offer the best option in many open and/or built-up areas for their maneuverability through narrow alleys and sharp beds, and their ability to hover in place if, for example, there is a need to have a close look at a place of interest.

As with any vehicular design, control design for helicopters is non-trivial. For example, ensuring stability in helicopter flight is a challenging problem for nonlinear control design and development. Unlike many classes of mechanical systems that naturally possess desirable structural properties such as passivity or dissipativity, helicopter systems are inherently unstable without closed-loop control, especially when hovering. In addition, helicopter dynamics are highly nonlinear and strongly coupled such that disturbances along a single degree of freedom can easily propagate to the other degrees of freedom and lead to loss of performance, even destabilization.

The fundamental requirement for control system design is to guarantee the stability for helicopter systems. Many techniques have been proposed in the literature for the motion control of helicopter systems, ranging from feedback linearization to model reference adaptive control and dynamic inversion, and these techniques typically require reasonably precise knowledge of the dynamic models in order to achieve satisfactory performance. An important concern when designing controllers for helicopters is the manner on how to deal with unknown perturbations to the nominal model, in the form of parametric and functional uncertainties, unmodelled dynamics, and disturbances from the environment. Helicopter control applications are characterized by time-varying aerodynamical disturbances, which are generally difficult to model accurately. The presence of uncertainties and disturbances could disrupt the function of the feedback controller and lead to degradation of performance.

While autonomous vehicles performing solo missions can yield significant benefits, greater efficiency and operational capability can be realized from teams of autonomous vehicles operating in a coordinated fashion. Potential applications for multi-vehicle systems include space-based interferometers, future combat systems,

surveillance and reconnaissance, hazardous material handling, and distributed reconfigurable sensor networks. To realize the potential of a multi-helicopter team, coordination techniques between helicopters are needed. One fundamental problem in multi-helicopter cooperation is formation control, in which the helicopters are required to keep a desired formation configuration to complete the assigned tasks.

The proposed book is meant to provide a comprehensive treatment of helicopter systems, ranging from related nonlinear flight dynamic modeling and stability analysis, to advanced control design for a single UAV, to the coordination and formation control of multiple helicopters to achieve high performance tasks. This book can be a good reference and introduction to the modeling, control and coordination of helicopter systems.

The book starts with a brief introduction to the development of helicopter systems modeling, control and coordination in Chap. 1.

Chapter 2 focuses on nonlinear flight dynamic modeling for a general class of rotary-wing aircraft. Centred around the general rigid body equations of motion, the modeling process is based on modules that follow closely with physical sub-systems on the rotary-wing aircraft. These modules may include main and tail rotors, propeller, horizontal and vertical tails, wings, fuselage, and the flight control system. Aerodynamic interference among different modules can also be established. Besides the general modeling, performance calculation is also illustrated as it is a critical index in understanding the aircraft.

Following the flight dynamic modeling, trim study and stability analysis are conducted in Chap. 3. Trim is a state of the aircraft in which forces and moments reach equilibrium. Trim is the basis of many fundamental analysis, including stability analysis, control system design, handling qualities assessment, and simulation. A numerical procedure on how to obtain trim is described. With the trim condition established, a linearization process can be carried out to obtain a linearized model for the rotary-wing aircraft. Elements in the linearized model are called stability and control derivatives. A detailed description on the derivatives is provided, with the emphasis of their physical meanings. To illustrate, three examples are also presented in the chapter, which include a simplified single helicopter system and two hobby helicopters at hover.

Linearized models are not only useful for stability analysis, but also for control design, by blending them over different operating points with gain scheduling. However, this requires extensive modeling, which is expensive and time-consuming. There is a need for control systems that can operate with minimal model information and handle nonlinearities over the entire flight regime. Chapter 4 aims to address this need, by presenting a robust adaptive neural network (NN) control for helicopters. In particular, we focus on vertical flight, which can be represented in the single-input–single-output (SISO) nonlinear nonaffine form, because the coupling between longitudinal and lateral directional equations in this flight regime is weak. Although a nonaffine system can be rendered affine by adding an integrator to the control input, allowing many control methods for affine nonlinear system to be used, the disadvantage of this approach is that the dimension of the system is increased, and control efforts are not direct and immediate either. Subsequently, effective control

for the system may not be achieved. In this chapter, we focus on control design for the nonaffine system directly, without adding any integrators to the input. Differing from the approaches in the literature, which were based on approximate dynamic inversion with augmented NNs, we utilize the Mean Value Theorem and the Implicit Function Theorem as mathematical tools to handle the nonaffine nonlinearities in the helicopter dynamics. In cases where reasonably accurate knowledge of the dynamic inversion model is available, the method using approximate dynamic inversion has been shown to provide an effective solution to the problem. However, the construction of the dynamic inversion for a nonaffine system may not be an easy task in general. For such cases, our approach offers a feasible means of tackling the problem, since a priori knowledge of the inversion is not required.

In Chap. 5, neural network control is redesigned to track both altitude and yaw angle at the same time. We consider a scale model helicopter, mounted on an experimental platform, in the presence of model uncertainties, which may be caused by unmodelled dynamics, or aerodynamical disturbances from the environment. Two different types of NN, namely a multilayer neural network (MNN) and a radial basis function neural network (RBFNN) are adopted in control design and stability analysis. Based on Lyapunov synthesis, the proposed adaptive NN control ensures that both the altitude and the yaw angle track the given bounded reference signals to a small neighborhood of zero, and guarantees the Semi-Globally Uniformly Ultimate Boundedness (SGUUB) of all the closed-loop signals at the same time. The effectiveness of the proposed control is illustrated through extensive simulations. Compared with the model-based control, approximation-based control yields better tracking performance in the presence of model uncertainties.

Unlike previous chapters, which consider actuators with instantaneous response, Chap. 6 deals with a more realistic scenario where actuator dynamics are present. Backstepping technique, combined with NNs, is employed to design the robust attitude control for uncertain multi-input multi-output (MIMO) nonlinear helicopter dynamics. To the best of our knowledge, there are few works in the literature that take the actuator dynamics into account in the helicopter control, which is practically relevant but more challenging as well. In this chapter, helicopter models are considered as MIMO nonlinear dynamic systems, where the actuator dynamics in the first-order low-pass filter form are considered. Secondly, the possible singularity problem of the control coefficient matrix for the model-based attitude control case is tackled effectively by introducing a design matrix. Thirdly, approximation-based attitude control is developed to handle the model uncertainties (e.g. unknown moment coefficients and mass) and external disturbances. Rigorous stability analysis and extensive simulations results show the effectiveness and robustness of the proposed attitude control.

Beyond single-helicopter control, this book also touches on formation control of multiple helicopters. In Chap. 7, the concept of the Q-structure is introduced as a novel and flexible methodology to define and support a large variety of formations. The Q-structure allows automatic scaling of formations according to changes in the overall size of the helicopter team. The chapter begins by exploring the use of the Q-structure for formation control where perfect communication is present between

all members of the team. The second part of the chapter focuses on how the Q-structure can be adapted and used for teams where communication is imperfect. In this chapter, we examine the properties of Q-structures in relation to other formation representation schemes, and look at the ways Q-structures can be used with artificial potential trenches to improve the scalability of the formations and support a large number of different formations. In particular, the Q-structure does not require explicit representation of every single node of the formation and is able to ensure the formation maintenance of a large number of helicopters. The formation is also robust against possible communication breakdown and/or limited wireless communication ranges.

The Q-structure formation control is useful for motion planning at the kinematics level. For formation control that takes into account the dynamics of helicopters, a different approach is proposed. Chapter 8 presents synchronized altitude tracking control of helicopters with unknown dynamics by graph theory, while the desired trajectory is available to a portion of the team. Since only the neighbors' information is available to the helicopter, we use the weighted average of neighbors' states as the reference state of the helicopter in the control design. We prove that if the extended communication graph contains a spanning tree with the virtual vehicle as its root, then its Laplacian will be positive definite. This property is essential for the stability proven and it also makes the proof of the stability for the results easy and direct. The mathematical stability proof, which makes use of the positive definite property of the graph Laplacian, is provided for both full-state and output feedback cases.

This book is primarily intended for academics, researchers and engineers who are interested in modeling, control and coordination of helicopter systems, and autonomous systems at large because many of the techniques and concepts could be extended further and applied directly to many other systems of interest. It can also serve as complementary reading for nonlinear systems, robotics, and adaptive control at the postgraduate level.

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