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A probabilistic approach for designing nonlinear optimal robust tracking controllers for unmanned aerial vehicles ☆

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ABSTRACT

In this study, we propose a probabilistic approach for designing nonlinear optimal robust tracking controllers for unmanned aerial vehicles. The controller design is formulated in terms of a multi-objective optimization problem that is solved by using a bio-inspired optimization algorithm, offering high likelihood of finding an optimal or near-optimal global solution. The process of tuning the controller minimizes differences between system outputs and optimal specifications given in terms of rising time, overshoot and steady-state error, and the controller succeed in fitting the performance requirements even considering parametric uncertainties and the nonlinearities of the aircraft. The stability of the controller is proved for the nominal case and its robustness is carefully verified by means of Monte Carlo simulations.

1. Introduction

Unmanned aerial vehicles and their control forms are an actual and important research subject. This technology can be used to solve many social problems, and this explains the great interest that the area has received from different research groups and organizations throughout the world. Examples of research related to unmanned aerial vehicles are path planning [27,52], squadrons formation reconfiguration [16], wireless networks [28], autopilot design [5], multiple unmanned aircraft coordination [30], formation [22], task assignment [35], trajectories generation [34], patrolling or surveillance [2], searching [11], tracking [48], flight control [24] and source seeking [53].

Despite using unmanned aerial vehicles, the aircraft has to be capable of following references, which are commands that determine the motion of the aircraft. These references can be created by defining trajectories [20] that an unmanned aerial vehicle has to follow. When trajectories are defined, performance requirements can be established by directly considering these trajectories. For instance, an aircraft controller can be designed so that the aircraft is able to follow a trajectory with optimal values for rising time, overshoot and steady-state error for its controlled variables.

In this work, we are interested in developing an unmanned aerial vehicle that is capable of following a set of trajectories such as those illustrated in Fig. 1. These trajectories exhibit interesting properties. For instance, the trajectories shown in Fig. 1a and b focus on testing latitudinal and longitudinal movements, while angle of heading is considerably modified in both cases. The trajectory shown in Fig. 1c illustrates a movement that emphasizes variations for height and angle of attack, while control of velocity is prioritized in Fig. 1d. As a consequence, all state variables of the dynamic model are substantially stressed in one way or another. Besides, optimal values for rising time, overshoot and steady-state error are desired features of response for the cases considered. There is a challenging problem to determine optimal values for these metrics by taking into account all trajectories, considering nonlinearities of the aircraft dynamic model, stability assurance, and parametric uncertainties of the plant. For example, the task of analytically designing a controller by taking into account all worst-case parametric uncertainties of the aircraft dynamic model becomes very hard, since the problem is NP-hard [49].

The problem considered in this study can be posed as follows: Design a tracking controller for unmanned aerial vehicles by taking into account the set of trajectories shown in Fig. 1. The performance of the controller for each aircraft controlled variable must be global near-optimal in terms of a weighted average among rising time,

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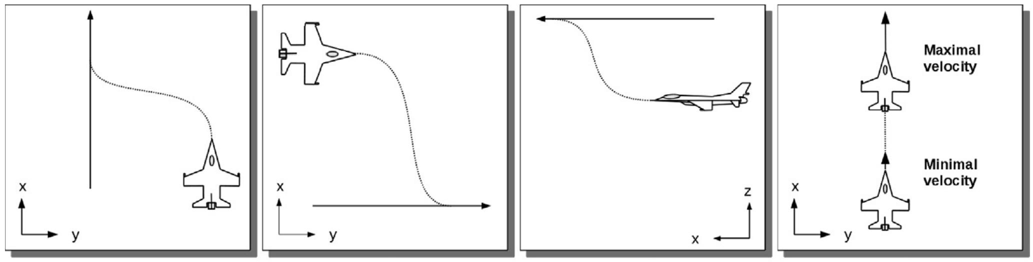

(a) Latitudinal variation (b) Longitudinal variation (c) Vertical variation (d) Velocity variation

Fig. 1. Trajectories to be tracked. This set of trajectories objects to stressing all variables of the aircraft dynamic model, thereby making that all variables are properly considered during the multi-objective optimization process.

overshoot and steady-state error for all trajectories illustrated in Fig. 1, and it must be capable of dealing with nonlinearities of the aircraft dynamic model even considering parametric uncertainties of the plant. The stability must be proved, and the robustness has to be carefully analyzed.

Aircraft dynamics are typically nonlinear, and there are many ways of designing tracking controllers for nonlinear systems. Linearization is one of the possible alternatives. The linearized controller is designed for several points of operation, and a gain schedule is used to complete interpolation between each pair of these points. Although this technique has been broadly used, it exhibits some problems. For instance, it requires a lot of work because several designs must be completed for each point of operation [49], while scheduling the gains from point to point during regime operation is a difficult task [17]. The stability cannot be formally proved when considering this approach [40]. On the other hand, the proposed approach considerably simplifies the design because it is based on dynamic inversion, which acts as a universal gain scheduler [39], whose nonlinearities are canceled without approximations, thereby enabling its proof of stability by using linear control theory.

Several approaches have also been proposed for dealing with robust path tracking controllers for nonlinear systems. Common approaches along this line of research are backstepping [31], adaptive control [47], model predictive control [37], H-2/H-∞ control [32], Lyapunov's direct method [18], sliding mode control [50], and linear quadratic Gaussian control [41].

With regard to the backstepping approach, it is used in [31] for designing a tracking controller for underactuated unmanned surface vessels. Although good dynamic performance and robustness can be achieved by using this approach, it has some drawbacks. For instance, repeated differentiations and recursive design [7] can significantly increase the complexity of the approach and make it difficult to apply to multiple state control systems [13]. Otherwise, the proposed probabilistic approach does not present such complexity because the gains of the controller are determined by using an optimization algorithm capable of solving non-convex and multi-objective optimization problems, whose fact significantly simplifies the design.

In [47], adaptive control is used for tracking nonholonomic mechanical systems. By using this approach, it is possible to asymptotically track the desired trajectory and the tracking error can be bounded within a controllable bound. However, this approach is criticized because the robustness of its transient response cannot be ensured [12], and it is quite sensitive to changeable uncertainties of the system [29]. Besides, adaptive control requires quite comprehensive theoretical background [8]. These are some reasons why adaptive control has still been subject of research. On the other hand, the proof of stability of the proposed approach is made by using linear control theory, which is simple and well-known. Besides, the design is formulated in terms of a multi-objective optimization problem, and this helps to reduce the conservatism by using a bio-inspired optimization algorithm that has very high likelihood of finding global optimal or near-optimal results for problems that can even be non-convex.

Model predictive control is another relevant control design. An example can be found in [37], where this approach is used to control an autonomous ground vehicle that has to track trajectories. Considering advantages [37], model predictive control is capable of dealing with performance criteria, and it is able to generate trajectories that are optimal according to these criteria. Besides, constraints can be explicitly considered and tuning of the parameters can be intuitively performed. However, model predictive control depends on the precise knowledge of the system parameters [36], and it may require significant computational effort to be implemented [36], whose fact may be prohibitive for systems that require fast sampling rates [1]. As a consequence, model predictive control can require some special treatment in order to avoid these problems. Otherwise, the proposed approach is not so dependent on the precise knowledge of the system parameters because the designing is performed by taking into account a significant number of parametric uncertainties of the plant. Besides, the gains of the controller do not change during operation, thereby reducing the required computational effort, and making the proposed approach interesting for real-time implementations.

In [32], robust H-2/H-∞ control is used to design an unmanned helicopter controller for tracking trajectories. As some benefits [32], robust H-2/H-∞ approach can run very fast in modern embedded systems, and its stability and performance criteria can be ensured even considering disturbances. Nevertheless, H-∞ approaches have been criticized for some reasons. Although weighting functions are crucial in order that H-∞ controllers reach some of their control objectives, there is no direct way of choosing weighting functions and some trial and error iterations may be necessary to determine them [51]. In addition to this fact, the order of H-∞ controllers is usually high [33]. This helps to explain why robust H-2/H-∞ control has still been subject of research. In contrast, the proposed approach does not present any of these problems. Although the optimization algorithm used in this study can require little adjustments while tuning the controller, it does not need trial and error iterations, and all analytical expressions can be directly determined since dynamic inversion is applicable. Besides, dynamic inversion does not result in high order controllers.

Another approach to solve the problem is the Lyapunov's method, as in [18], where a micro aerial vehicle is capable of tracking roads by using a control switching mechanism. Lyapunov's approach play an important role in nonlinear systems control theory because it is able to readily ensure the closed-loop system stability [10], without solving ordinary differential equations [23], thereby reducing its dependence on the problem. Although this fact makes Lyapunov's approach applicable to the solution of a wide range of linear and nonlinear problems, one of its main drawbacks