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Statistical gain-scheduling method for aircraft flight simulation

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A B S T R A C T

A global polynomial variable scheduling method for aircraft controller is proposed to achieve runtime benefits with no degradation of controller stability. The method is benchmarked against two conventional methods: nearest neighbor and bilinear interpolation. An examination of conventional method constructs reveals recursive local approximation generation as the most expensive step, whereas discontinuities and lack of first derivative smoothness lead to poor approximations. The proposed method features a multivariate polynomial as the variable scheduling mechanism that addresses both drawbacks concurrently and achieves significant runtime improvements by virtue of its very simple functional form. The mathematical formulation of the proposed approach is discussed along with practical considerations for implementation. Numerical flight dynamics simulations are conducted with the three methods for four flight maneuvers and using four scheduling variable sets of increasing resolution. Results show the proposed method significantly reduces runtime relative to nearest neighbor, and even more so relative to bilinear interpolation. Results also indicate comparable controller stability in terms of deviation from margins of optimum solutions.

1. Introduction

In recent years airspace operational concepts of increasing complexity such free flight [4], airborne precision spacing [2], and self-separation [6,18] have gained much attention. Separation assurance for unmanned aircraft systems has also received significant attention, particularly with regard to sense and avoid capabilities to conduct self-separation [28] and collision avoidance [1,21,8]. For this type of applications explicit simulation of vehicle control and flight dynamics are requisite, but the number of simulations required for concept exploration and feasibility studies is typically very large. The need for computational cost improvements without incurring in controller performance degradations is the motivation underpinning this work.

Controllers in the aircraft dynamics model are typically approached with a gain-scheduling method or with a non-linear control method using dynamic inversion [12]. Gain-scheduling methods are more commonly used mainly due to the reduced computational burden associated with the local linearization of model dynamics inherent in this approach [26]. Gain-scheduling is typically included as part the stability augmentation system (SAS) that define control settings to follow the path trajectory defined by the navigation or autopilot system. The gain-scheduling approach transforms the non-linear aircraft dynamics into a linear time invariant (LTI) equation for given trim conditions and then optimally solves for the feedback gain set. The process is repeated for points of interest within the flight envelope so as to produce a finite one-to-one mapping between operating points and corresponding trim control input and gain values. A scheduling scheme utilizes the a-priori data to generate trim control input and gain values for any operating point within the flight envelope during the simulation. Different gain scheduling schemes with varying degrees of complexity exist. The nearest neighbor approach assigns the trim control input and gain values of the closest a-priori point. Interpolation and blending techniques are also commonly employed [15]. Gain scheduling presents some inherent shortcomings that have been noted in the literature. The controller can exhibit poor robustness and stability due to deficient gain approximations [10]. Higher order effects in dynamic behavior can be significant but are inherently absent in a linearized model. As a result all higher-order

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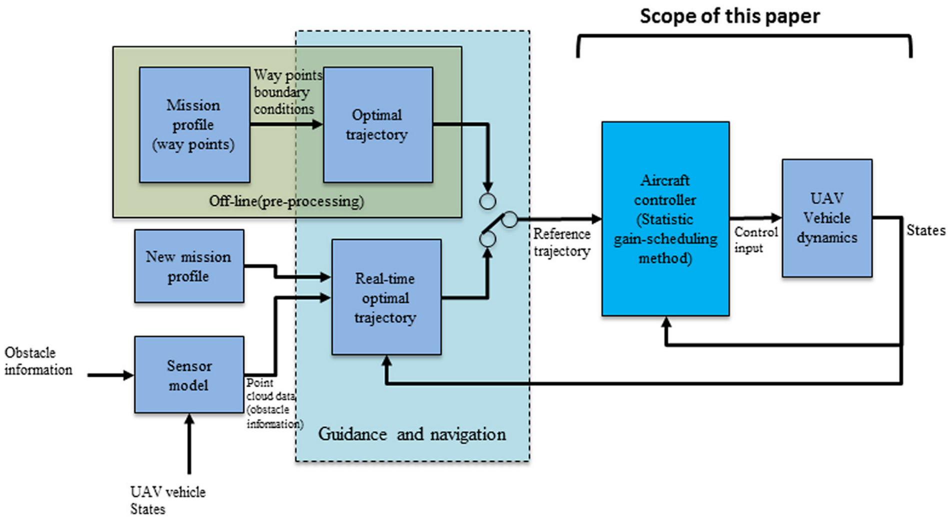

Fig. 1. UAV flight controller architecture.

effects, such as the non-linear actuator response or phantom yaw caused by asymmetric vortices, introduce uncertainty and error to the model [23]. To address the issue of higher-order contributions an augmented control structure with adaptive controller has been proposed that can produce more precise predictions of the aircraft dynamics [9]. As can be expected these improvements are attained with increased computation cost and greater complexity of the aircraft controller [25].

We propose a gain-scheduling approach to improve performance and address salient computational drawbacks of conventional gain-scheduling methods. A polynomial regression model is generated a-priori and used in place of nearest neighbor or bivariate interpolation schemes. The polynomial regression model provides accurate trim input solutions and control gain set estimates with a computationally efficient functional form that improves the cost of the overall simulation. Accordingly, we hypothesize that the proposed method offers improvements in computational cost without degradation of controller stability, relative to nearest neighbor and bivariate interpolation gain scheduling methods. In order to test our hypothesis and demonstrate the proposed gain-scheduling approach numerical analysis using flight simulation is performed and the results compared against the two aforementioned conventional gain-scheduling algorithms.

The remainder of this paper is structured as follows: Section 2 provides an overview of the flight dynamics model and controller architecture used for this work. A review of conventional gain-scheduling approaches is also presented, highlighting some of their shortcomings in terms of computational power for a fast- and real-time flight simulation. In Subsection 2.4 we introduce the proposed gain-scheduling approach with surrogate models addressing the mathematical formulation as well as the most pressing considerations for its implementation in practice. Our hypothesis addressing the expected benefits of the proposed method over established methods is also presented. The implementation of the aircraft dynamics model and controller design, as well as practical considerations for the implementation of the proposed approach are addressed in Subsection 2.5 and Subsection 2.6 respectively. Results and discussion are presented in Section 3, first addressing computational cost in Subsection 3.1, followed by controller stability and performance in Subsection 3.2. Conclusions and final remarks are in Section 4.

2. Flight controller for an unmanned aircraft

2.1. Flight controller architecture

For this work we assume an unmanned aircraft as a suitable application for the development of a flight simulation environment where the proposed gain scheduling method may be examined. The overall architecture, illustrated in Fig. 1, is part of a broader effort on autonomous unmanned aircraft simulation and features two primary components: guidance and navigation for trajectory generation, and aircraft controller. The trajectory generator includes an off-line component where the trajectory is defined a-priori in accordance with a prescribed mission profile, pre-defined waypoints, and known obstacle information. The online trajectory component regularly updates the trajectory based on the current vehicle state and sensor data to compensate for perturbations like wind gusts or the avoidance of unknown obstacles. The aircraft controller generates aircraft control commands to follow the reference trajectory and applies them to the vehicle flight dynamics. In this paper we are exclusively concerned with the latter, specifically to improve the computational runtime of the aircraft controller via gain scheduling. Accordingly all discussion that follow are limited to the aircraft controller and vehicle dynamics, and do not address any of the components of the guidance and navigation block or related sensor modeling.

2.2. Equations of motion

There is rich diversity in the platform architectures of unmanned aircraft; numerous planform-propulsion variants exist for fixed wing aircraft, rotorcraft, and airships. In addition, unconventional concepts such as hybrid wing-body or multi-rotor aircraft are much more pervasive for unmanned applications. This variety presents inherent burdens and difficulties in the development and treatment of flight dynamics and control for unmanned aircraft [13,7]. A conventional propeller-driven fixed wing architecture is selected for simplicity and in consideration of the large portion of unmanned vehicles that it applies to [13,14]. With a point-mass assumption, the free-body diagram for the aircraft is as shown in Fig. 2 and the equations of motion can be stated as follows:

$$\dot{x} = v \cos\gamma \cos\chi \tag{1}$$

$$\dot{y} = v \cos\gamma \sin\chi \tag{2}$$