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Time-varying linear control for tiltrotor aircraft

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Abstract Tiltrotor aircraft have three flight modes: helicopter mode, airplane mode, and transition mode. A tiltrotor has characteristics of highly nonlinear, time-varying flight dynamics and inertial/-control couplings in its transition mode. It can transit from the helicopter mode to the airplane mode by tilting its nacelles, and an effective controller is crucial to accomplish tilting transition missions. Longitudinal dynamic characteristics of the tiltrotor are described by a nonlinear Lagrange-form model, which takes into account inertial/control couplings and aerodynamic interferences. Reference commands for airspeed velocity and attitude in the transition mode are calculated dynamically by visiting a command library which is founded in advance by analyzing the flight envelope of the tiltrotor. A Time-Varying Linear (TVL) model is obtained using a Taylor-expansion based online linearization technique from the nonlinear model. Subsequently, based on an optimal control concept, an online optimization based control method with input constraints considered is proposed. To validate the proposed control method, three typical tilting transition missions are simulated using the nonlinear model of XV-15 tiltrotor aircraft. Simulation results show that the controller can be used to control the tiltrotor throughout its operating envelop which includes a transition flight, and can also deal with vertical gust disturbances.

1. Introduction

A tiltrotor aircraft, which combines the characteristics of helicopters and fixed-wing aircraft, consists of an aircraft body (including the fuselage and wings), engine nacelles, and rotors.

Unlike a traditional aircraft, a tiltrotor aircraft is a complex multibody system which can change its configuration by tilting the nacelles, and it owns three different flight modes, namely helicopter mode, airplane mode, and transition mode. The transition mode, which means the conversion between the other two flight modes, is a special mode of tiltrotors. A tiltrotor aircraft with two side-by-side rotors such as the XV-15 tiltrotor is studied in this paper.

A tiltrotor owns the advantages of both helicopters and fixed-wing aircraft. Firstly, a tiltrotor can fly freely in different directions like a helicopter, and can also hover in the air. Secondly, a tiltrotor has a faster cruising speed than that of a helicopter. Thirdly, a tiltrotor can enhance civil or military

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transportation capability because it has three flight modes. However, a tiltrotor aircraft has some disadvantages such as low safety and low reliability. Firstly, the flight dynamics of a tiltrotor is much more complex than that of a traditional aircraft since the tiltrotor demonstrates different flight dynamic characteristics in different flight modes, and there exist inertial couplings between the aircraft body and nacelles. Secondly, a tiltrotor has low reliability because there are control couplings between its control action paths. Thirdly, the pilot workload of a tiltrotor would be higher especially in the transition period, because it has the characteristics of complex flight dynamics, inertial couplings, and control couplings. This paper studies the flight control for tiltrotor aircraft to deal with the complex flight dynamics and inertial couplings.

To obtain a reasonable and reliable dynamic model is crucial for aircraft controller design. A large amount of literature considers a tiltrotor as a single rigid body, and describes its dynamic characteristics through three-Degree-Of-Freedom (DOF) longitudinal modeling or six-DOF modeling, which is similar to that for traditional aircraft.[1–3] However, a tiltrotor is a kind of morphing aircraft which tilts its nacelles in its special transition mode, so a traditional flight dynamic model cannot reveal the inertial couplings and dynamic characteristics in the transition mode. Certain literature regards a tiltrotor as a multi-rigid-body system in view of the inertial couplings. For example, Li et al. considered a tiltrotor as multiple entities, and developed a twelve-DOF dynamic model for tiltrotors based on multibody dynamics.[4] The multibody model can clearly characterize the inertial couplings and complex flight dynamics of a tiltrotor, but its expression is too complicated for controller design. Later on, based on the Lagrange's equation, Zhang et al. built a multibody longitudinal nonlinear model of a tiltrotor, and the derived model is in a more concise form and more suitable for the longitudinal controller design of the tiltrotor.[5] It is worth noting that modeling of multibody systems has experienced a remarkable development in space flight.[6,7] Furthermore, founding an aeroelastic model is beneficial to analyzing the stability of the tiltrotor.[8]

The literature about tiltrotor aircraft control can be classified into two categories: linear control and nonlinear control. Firstly, linear controllers were designed on the basis of a linear dynamic model and the information of certain flight conditions, and references are organized chronologically. A Model Predictive Control (MPC) method was adopted to design a flight controller for the hovering mode and three other typical flight scenarios of a tiltrotor.[9] An attitude controller for a tiltrotor in the helicopter hovering mode was designed using MPC.[10] An optimal control approach was proposed to deal with gusts effects on a tiltrotor in helicopter and airplane modes.[11] Minimum energy controllers were designed based on the helicopter mode and the airplane mode, respectively.[12] Based on optimal preview control, an attitude controller was developed for a particular flight state in the transition mode of a tiltrotor.[13] In consideration of model errors, a controller was designed for the airplane mode of a tiltrotor based on a sliding mode method.[14] It should be noted that the above mentioned linear controllers were mainly designed for one or several particular flight states of a tiltrotor, and they need gain scheduling to achieve control of the whole conversion process of the tiltrotor. Secondly, nonlinear control approaches have the advantage that the nacelle angle does not need to be assumed fixed when designing tiltrotor flight controllers. In Ref. 15, a robust nonlinear controller was designed for a tiltrotor in the hover mode. Considering system uncertainties and disturbances, an adaptive control method was developed based on Neural Networks (NNs),[16] but it requires using different NN weights for different flight states, e.g., different nacelle angles. Based on the work,[16] an online NN modelling method was introduced to develop a fully adaptive flight control method, which achieves not only longitudinal control but also lateral control of a tiltrotor. It should be mentioned that this method needs to update the entire full-state nonlinear model of a tiltrotor for different flight states.[17] Considering the control difficulty brought by the tiltrotor mode switching process and the tiltrotor configuration change during the transition mode, Ref. 18 presented a nonlinear control method and specifically studied the transition process control. Nevertheless, the tiltrotor controller designed in Ref. 18 fails to consider input constraints and control couplings.

A tiltrotor aircraft, especially in the transition mode, is a time-varying and strongly nonlinear system, and there exist couplings between different control action paths. As an alternative to linear controllers with a gain scheduling mechanism and nonlinear controllers mentioned above, it is a wise choice to convert a time-varying highly nonlinear system into a Time-Varying Linear (TVL) system, and then design a controller based on the TVL model. There exist a large number of approaches in literature considering founding a TVL model and TVL control.[19–22] The Linear Parameter Varying (LPV) control method, which approximates a nonlinear system as a TVL system, is a classical control method which has been widely applied to aircraft with a variable structure.[23–27] However, a single LPV controller designed for a single flight state cannot accomplish the whole transition control of tiltrotors operating in the transition mode. Moreover, the switching LPV control method based on the Lyapunov function is computationally expensive because it needs to solve a large number of linear matrix inequalities.[28]

The objective of this paper is to propose a control approach which is competent for achieving effective control for tiltrotor aircraft in the transition mode. More specifically, this paper contributes to online model linearization, dynamic generation strategy of reference commands, and real-time optimization based optimal control of a tiltrotor. Firstly, a nonlinear and time-varying Lagrange-form tiltrotor model is presented, which takes the control couplings of tiltrotor aircraft into account. Secondly, how to derive a TVL model from the time-varying nonlinear model is addressed. Note that the TVL model updates its parameters at each sampling instant according to the flight conditions. Thirdly, a trim-condition based approach is developed to calculate the reference commands for airspeed velocity and attitude. To update the reference commands in real-time, a library for the flight envelope of the tiltrotor and the static characteristics curves of the pitch angle is founded. Fourthly, inspired by the MPC concept, an online optimization based optimal control approach is proposed for tiltrotor aircraft, especially when considering transition-mode flight missions. Moreover, the proposed control approach allows for conducting input constraints, and the control inputs are the solution of a constrained online optimization problem.

The structure of this paper is organized as follows. Section 2 presents the longitudinal dynamic model of a tiltrotor which is used for designing a controller. In Section 3, how to calculate

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