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Global and robust attitude control of a launch vehicle in exoatmospheric flight

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ABSTRACT

The goal of this research is to design global and robust attitude control systems for launch vehicles in exoatmospheric flight. An attitude control system is global when it guarantees that the vehicle converges to the desired attitude regardless of its initial condition. Global controllers are important because when large angle maneuvers must be performed, it is simpler to use a single global controller than several local controllers patched together. In addition, the designed autopilots must be robust with respect to uncertainties in the parameters of the vehicle, which means that global convergence must be achieved despite of those uncertainties. Two designs are carried out. In the first one possible delays introduced by the actuator are neglected. The design is performed by using a Lyapunov approach, and the obtained autopilot is a standard proportional-derivative controller. In the second one, the effects of the actuator are considered. Then the design is based on robust backstepping which leads to a memory-less nonlinear feedback of attitude, attitude-rate, and of the engine deflection angle. Both autopilots are validated in a case study.

1. Introduction

Designing an autopilot for a launch vehicle is a challenging task due to its nonlinear and time-varying properties (see [1]). Several attitude controllers have been proposed over the years. For example, baseline Proportional-Derivative (PD) controllers are designed in [1, Section 5.3]. An intelligent adaptive autopilot is presented in [2]. Paper [3] proposes a design based on adaptive predictive control. Model reference adaptive control is employed in [4] to design PD and Proportional-Integral-Derivative (PID) autopilots. In addition, in the last decades many designs based on modern robust control have been proposed. For instance, H_∞ control is used in [5–7], whereas μ-synthesis in employed in [8]. In paper [9] a method known as Wave-Based Control is applied to designing an autopilot capable of compensating for the effects of fuel-sloshing. All the above design methods are based on linearized models of the vehicle. As a results, those methods assure only local convergence. Then, from an analytical standpoint, the attitude is guaranteed to converge to the desired one only if the initial condition of the vehicle is sufficiently close to that attitude.

The goal of the present work is to address the latter issue by designing autopilots that achieve global convergence so that it is analytically assured that the desired attitude is reached starting from any initial condition. Global autopilots are particularly convenient when a launch vehicle must perform large angle maneuvers. In fact, in such a scenario, one can use a single global attitude controller instead of several local controllers patched together through some scheduling strategy. The latter fact simplifies the actual implementation of the autopilot on the on board computer. In addition, the designed autopilots must be robust with respect to uncertainties in the parameters of the vehicle, which means that global convergence must be achieved despite of those uncertainties. The latter uncertainties are a consequence of slow variations of some parameters during flight and of limited accuracy in the determination of their values.

A global autopilot has been recently presented in [10]. The latter controller has been designed for the atmospheric flight of a launch vehicle modeled as a rigid body. In this paper global autopilot design is carried out for an upper stage of a launch vehicle flying above atmosphere. Global attitude controllers are more useful during the exoatmospheric flight than during the atmospheric one. This is a consequence of the fact that they are especially suited for performing large angle maneuvers which can occur only above the atmosphere. In fact, during the atmospheric flight launch vehicles cannot perform those maneuvers because of constraints imposed by aerodynamic loads. In particular, large angle maneuvers often occur at the beginning of the exoatmospheric flight for the following reason. During atmospheric flight launch vehicles are mostly

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Nomenclature

g	gravitational acceleration .... m/s^2	W	component of velocity of center of mass along the z body axis .... m/s
I	moment of inertia of launch vehicle about y body axis .... $kg\,m^2$	Δ	engine deflection angle .... rad
l_c	distance from the center of mass to engine swivel point .... m	$\overline{\Delta}$	maximum amplitude of engine deflection angle .. rad
m	mass of launch vehicle .... kg	Δ_c	commanded engine deflection angle .... rad
Q	pitch rate .... rad/s	τ_a	time constant of electro-hydraulic servoactuator .... s
T_c	control (gimbaled) thrust .... N	Θ	pitch angle .... rad
U	component of velocity of center of mass along the x body axis .... m/s	Θ_c	commanded pitch angle .... rad

guided in gravity turn mode to reduce the aerodynamic load [11, 12]. Thus, at the beginning of the exoatmospheric flight, it often happens that the vehicle is distant from the desired trajectory, and consequently large angle attitude maneuvers are necessary for having it converge to that trajectory. Additional differences of this research with respect to [10] are as follows. The designs in this study take into account the limit values for the engine deflection angle, and one of the designs considers the effects of the electrohydraulic actuator on the vehicle dynamics. Both latter aspects have been neglected in [10].

In this work a motion occurring on a vertical plane is considered since the flight of most launch vehicles is basically confined to such a plane (see [13, Chapter 4]). As a result, significant attitude maneuvers must occur in the trajectory plane, whereas only minor attitude corrections must be performed off that plane. The launch vehicle is here modeled as a rigid body. In fact, for some upper stages the nonlinear effects due to flexibility, liquid sloshing and engine inertia are not significant. As a matter of fact, flexibility is often negligible for upper stages because of their reduced length and because of the absence of aerodynamic loads. In addition, fuel sloshing effects are negligible for launch vehicles with baffles inside the tanks or in which the tank is divided into several smaller ones. Finally, engine inertia effects are not significant when the mass of the swiveling engine is negligible with respect to the mass of the main body.

The rest of the paper is organized as follows. In section 2 the model of the launch vehicle is presented. In section 3 a global and robust attitude controller is designed not considering the dynamics of the actuator. As a result, the latter design is effective when the actuator is much faster than the designed autopilot. In section 4 the design is carried out including a simple dynamic model for the actuator. Thus, the latter design is important when the actuator is not substantially faster than the designed controller. Both proposed designs are validated in a case study presented in section 5.

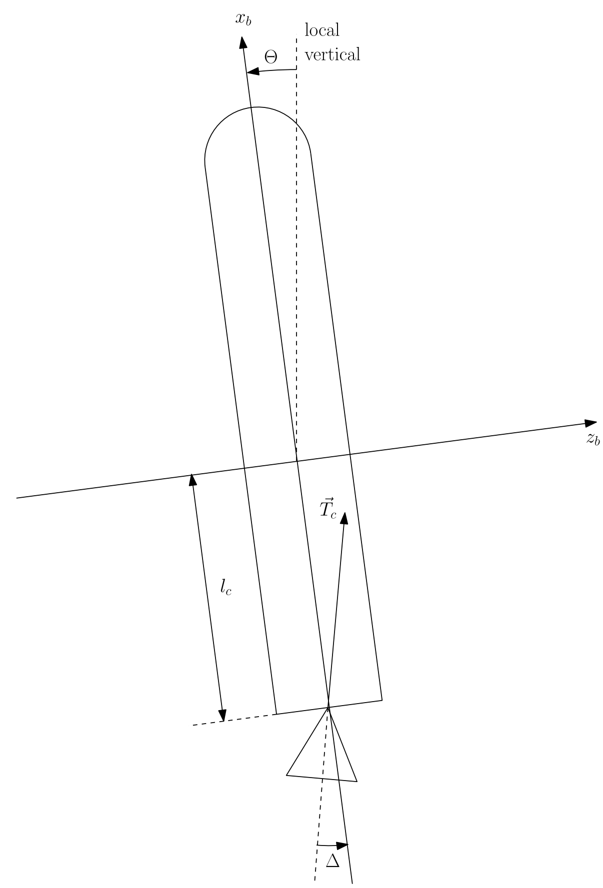

Fig. 1. Schematic diagram of launch vehicle.

2. Model of the launch vehicle

Consider an upper stage of a launch vehicle flying in vertical planar trajectory above the atmospheric level. Thrust vector control is used to control the attitude. The pitch plane dynamics (see Fig. 1) are given by (see Chapter 1 of reference [1])

$$-mg\cos\Theta + T_c\cos(\mathrm{sat}_{\overline{\Delta}}(\Delta)) = m(\dot{U} + QW) \tag{1}$$

$$-mg\sin\Theta + T_c\sin(\mathrm{sat}_{\overline{\Delta}}(\Delta)) = m(\dot{W} - QU) \tag{2}$$

$$l_c T_c \sin(\mathrm{sat}_{\overline{\Delta}}(\Delta)) = I\dot{Q} \tag{3}$$

$$\dot{\Theta} = Q \tag{4}$$

The meaning of the variables and parameters used in the above equations is indicated in Nomenclature. Symbol $\mathrm{sat}_{\overline{\Delta}}$ denotes the following saturation function that is introduced to take into account of the limit $0 < \overline{\Delta} < \pi/2$ on the amplitude of the engine deflection angle

$$\mathrm{sat}_{\overline{\Delta}}(\Delta) \triangleq \begin{cases} -\overline{\Delta} & \text{if } \Delta < -\overline{\Delta} \\ \Delta & \text{if } -\overline{\Delta} \le \Delta \le \overline{\Delta} \\ \overline{\Delta} & \text{if } \Delta > \overline{\Delta}\,. \end{cases} \tag{5}$$

In designing the controller, parameters I, l_c, m, and T_c are considered constant but subject to uncertainty due to both their possible slow variations with time, and to limited accuracy in determining their values.

The goal is controlling pitch angle Θ acting on engine deflection angle Δ through a servoactuator. Measures of pitch angle Θ, pitch rate Q, and of the engine deflection angle Δ are considered available to the autopilot.