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Adaptive flight control design for nonlinear missile

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Abstract

The focus of this work is to investigate the possible benefits of modern nonlinear control design methods for missile autopilot design. The basic requirement for an autopilot is firstly fast responses because of the short amount of time involved in the end-game. A slow response could easily cause a miss if the target has the capacity to perform high-g evasive manoeuvers. Secondly, minimum error is an obvious requirement if the missile is to achieve a kill. Finally, robustness to model uncertainties is important in order for the missile to achieve its objective in the physical environment.

In the first part of this paper input–output approximate linearisation of a nonlinear missile has been studied. A method for controlling the nonlinear system that is input–output linearisable is examined that retains the order of the system in the linearisation process, hence producing a linearised system with no internal or zero dynamics. Desired tracking performance for lateral acceleration of the missile is achieved by using a nonlinear control law that has been derived by selecting the lateral velocity as the linearisation output. Simulation results are shown to exercise the final design and show that the linearisation and controller design are satisfactory. Then an adaptive nonlinear controller is designed that guarantees tracking performance when the uncertain parameters vary within a stability bound. An autopilot combining an indirect adaptive controller with approximate feedback linearisation is proposed in order to achieve asymptotic tracking. Adaptation is introduced to enhance closed-loop robustness, while approximate feedback linearisation is used to overcome the problem of unstable zero dynamics. Computer simulations show that this approach offers a possible autopilot design for nonlinear missiles with uncertain parameters.

Keywords: Nonlinear control; Feedback linearisation; Flight control; Missile system; Adaptive control

1. Introduction

The performance of aerospace systems such as aircraft, spacecraft and missiles is highly dependent on the capabilities of the guidance, navigation and control systems. To achieve improved performance in such aerospace systems, it is important that more sophisticated control systems be developed and implemented. In particular, as the performance envelope is expanded, the control schemes must become adaptive and nonlinear, to provide performance over a greater range, in the face of uncertain or changing operating conditions.

The tracking performance of a missile is also dependent on the location within the flight envelope and varies with factors such as Mach number and dynamic pressure. Several approaches, including adaptive control (Lin & Cloutier, 1991), nonlinear control (White, Tsourdos, & Blumel, 1998) and gain scheduling (Shamma & Cloutier, 1993) have been used to alleviate these tracking problems. While gain scheduling is conceptually simple and has been proven successful, it has virtually no guarantee of stability in the transitional periods between operating points and relies on the fact that the scheduling variables should only change slowly. Furthermore, there is a heavy design overhead due to the large number of linear controllers which must be derived and, as the performance demands of modern-day missile systems become more stringent, alternatives to linear control are of increasing practical significance.

Feedback linearisation is a popular method used in nonlinear control applications, and there have been several flight control demonstrations (Snell, 1992). Dynamic model inversion is the feedback linearisation method employed to design the missile autopilot. This

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method is very effective in applications to aircrafts and missiles. The main drawback of dynamic model inversion is the need for high-fidelity nonlinear force and moment models that must be invertible in real time, which implies a detailed knowledge of the plant dynamics, and the approach tends to be computationally intensive. In general, dynamic model inversion is sensitive to modelling errors. The application of robust and/or adaptive control can alleviate this sensitivity and, therefore, the need for detailed knowledge of nonlinearities.

In this paper an adaptive nonlinear control design technique is applied to the autopilot for the missile model which is aerodynamically controlled. Missile motion is modelled to be nonlinear with unknown parameters. Based on the model, we adopt a design procedure similar to Sastry and Bodson (1989), basically an adaptive feedback linearisation method. In this scheme, unknown parameters are estimated and based on these estimates, control parameters are updated. Computer simulations show that this approach is very promising to apply the autopilot design for the missiles which are highly nonlinear in aerodynamics with unknown parameters.

The missile model can be represented in the general nonlinear state space

$$\dot{x}(t) = f(x, \theta) + g(x, \theta)u,$$
$$y(t) = h(x, \theta). \quad (1)$$

Typically the control law is based on a vector $\hat{\theta}$ which is an online estimate of the true parameter vector θ. The update laws for these adjusted parameters are determined as part of the design and shall be such that the closed loop system stability is preserved. The convergence of these parameters estimate to their true value θ is a necessary condition in the indirect schemes of adaptive control.

An indirect adaptive controller consists of a parameter identification scheme and a controller whose gains are calculated on-line based on estimates of the plant model parameters. The structure of the plant is assumed a priori, but the coefficients or parameters involved are estimated based on the available input/output information. Fig. 1 shows the schematic diagram for indirect adaptive control schemes. The identification block estimates the plant parameters from the control signal and the output measurement. The estimated parameters are then used to update the controller gains according to one of the several control methodologies.

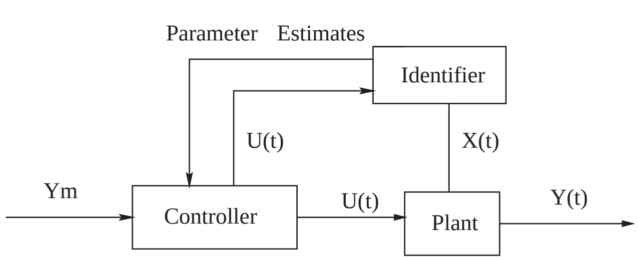

Fig. 1. Schematic diagram for indirect adaptive control schemes.

The parameter identifier is used in the outer loop design and continuously adjusts the parameter estimates based on observation error. The certainty equivalence principle suggests that these parameter estimates that are converging to their true values may be employed to asymptotically achieve the desired objective as parameter estimates converge to their true value. The adaptive scheme developed for the lateral missile flight control system is presented in the following sections.

Other adaptive schemes such as direct adaptive control schemes are discussed in details in Sastry and Bodson (1989). In the schemes of that form, parameters do not need to converge to their true value but they are required to stay bounded and converge to some constant. Typically, if the system is persistently exciting, then all the parameters will converge to their true values.

2. Missile model

The missile model used in this study derives from a nonlinear model produced by Horton of Matra-British Aerospace (Horton, 1992). This study will look at the reduced problem of a 2 DOF controller for the pitch and yaw planes without roll coupling. The angular and translational equations of motion of the missile airframe are given by

$$\dot{r} = \frac{1}{2} I_{yz}^{-1} \rho V_0 S d \left(\frac{1}{2} d C_{nr} r + C_{nv} v + V_0 C_{n\zeta} \zeta \right),$$
$$\dot{v} = \frac{1}{2m} \rho V_0 S (C_{yv} v + V_0 C_{y\zeta} \zeta) - Ur, \quad (2)$$

where the variables are defined in Fig. 2 and Tables 1 and 2. Eqs. (2) describe the dynamics of the body rates and velocities under the influence of external forces (e.g. C_{yv}) and moments (e.g. C_{nr}), acting on the frame. These forces and moments are derived from wind tunnel measurements and by using polynomial approximation algorithms, C_{yv}, $C_{y\zeta}$, C_{nr}, C_{nv} and $C_{n\zeta}$ (Horton, 1992) can be represented by polynomials which can be fitted to the set of curves taken from look-up tables for different flight conditions. A detailed description of the model can be found in Horton (1992).

The aerodynamic forces and moments acting on the airframe are nonlinear functions of Mach number, longitudinal and lateral velocities, control surface deflection, aerodynamic roll angle and body rates. Control of the missile will be accomplished in this paper by controlling an augmented version of lateral acceleration.