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Adaptive Backstepping Autopilot Design for Missiles of Fast Time-varying Velocity

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Abstract: An adaptive backstepping control scheme is proposed to design a missile autopilot during boost-phase. In the boost-phase, accurately controlled missiles experience fast velocity variations that make the missile dynamics be highly nonlinear. Missile parameters including the mass, the moment of inertia, and a center of gravity, which are usually considered as constants or slowly-varying, change very fast. The time-varying effects combined with nonlinear dynamics yield severe parametric uncertainties in missile dynamics. Therefore, the nonlinear dynamics as well as parametric uncertainty should be carefully treated in autopilot design. To deal with this problem, an adaptive nonlinear controller is designed based on backstepping procedure. Adaptation laws are properly designed so that robustness to the uncertainty as well as the closed-loop stability can be guaranteed using Lyapunov stability theorem. To demonstrate the performance of the proposed controller, numerical simulation is carried out.

Keywords: Missile Autopilot, Adaptive Control, Fin-controlled Missile, Backstepping.

1. INTRODUCTION

Missile control is one of the major research topics in aerospace applications, and many researchers have proposed various design schemes (Schumacher, C., and Khargonekar (1998); Shamma, J. S., and Cloutier (1993)). Since missions of missile require fast responses considering nonlinearity in missile dynamics, the classical approach so called gain-scheduling has been replaced by several nonlinear control schemes (Thukral, A., and Innocenti (1998); Steinicke, A., and Michalka (2002); Cimen (2011)) or adaptive control schemes (McFarland, M. B., and Calise (2000); Sonneveldt et al. (2008); Lee et al. (2015a)). Especially, a missile in boost-phase experiences wide range of flight envelope and undergoes a fast change of the speed. The wide flight envelope may include hard conditions where the dynamic pressure or aerodynamics is fairly weak, and propellent consumption in the boost-phase also causes severe parametric variations including mass, moment of inertia, and center of gravity. These variations result in severe nonlinearity and parametric uncertainty. Combined with the fast-varying velocity and highly nonlinear dynamics, uncertainties become very complicated. Therefore the autopilot design during the boost-phase is more challenging, and it is necessary to use nonlinear control scheme in autopilot design. Most of the previous works, however, considered simple structures of uncertainty, or function approximation using neural networks.

In this study, an adaptive backstepping controller is proposed for roll-pitch-yaw integrated missile autopilot during boost-phase. The autopilot is constructed as a two-loop cascaded system, and the backstepping scheme is utilized for the nominal controller. It has been known that the backstepping design approach can improve the transient response (Steinicke, A., and Michalka (2002)), and the autopilot can be designed systematically by using the backstepping scheme. To deal with possible uncertainties in the boost-phase. uncertainty parameterization is used to construct the uncertainty, and an adaptation law is augmented to the nominal backstepping controller. Numerical simulation with a nonlinear six degree-of-freedom missile model is carried out to demonstrate the performance of the proposed controller.

This paper is organized as follows. In section 2, problem formulations are provided. In section 3, autopilot design and stability analysis are shown in detail. In section 4, numerical simulation is performed to demonstrate the

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proposed autopilot, and conclusion is presented in section 5.

2. PROBLEM FORMULATION

2.1 Equations of Motion

In this study, a fin-controlled aerodynamic missile steered by STT(Skid-to-Turn) maneuver is considered. The non-linear equation of motion with respect to the body-fixed coordinate can be represented as follows (Lee et al. (2015b)):

$$
\begin{aligned}
\dot{\alpha} &= q - (p\cos\alpha + r\sin\alpha)\tan\beta \\
&\quad + \frac{1}{M_a\cos\beta}(a_x\cos\alpha - a_z\sin\alpha) \\
\dot{\beta} &= p\sin\alpha - r\cos\alpha \\
&\quad - \frac{1}{M_a}(a_x\cos\alpha\sin\beta - a_y\cos\beta + a_z\sin\alpha\sin\beta) \\
\dot{\mu} &= p\frac{\cos\alpha}{\cos\beta} + r\frac{sin\alpha}{\cos\beta} + \frac{1}{M_a}(a_{11}a_x + a_{12}a_y + a_{13}a_z) \\
\dot{p} &= \frac{L}{I_{xx}} \\
\dot{q} &= \frac{I_{zz}-I_{xx}}{I_{yy}}pr + \frac{M}{I_{yy}} \\
\dot{r} &= \frac{I_{xx}-I_{yy}}{I_{zz}}pr + \frac{N}{I_{zz}} \\
\dot{M_a} &= \frac{1}{a}(a_x\sin\alpha\cos\beta + a_y\sin\beta + a_z\sin\alpha\cos\beta)
\end{aligned} \tag{1}
$$

where m is the mass, (I_{xx}, I_{yy}, I_{zz}) are the moments of inertia, (α, β, μ) are angle of attack, sideslip angle, and roll angle, respectively, (M_a, a) represent mach number and speed of sound, (p, q, r), are angular velocity with respect to body frame, (a_x, a_y, a_z), represent acceleration with respect to body frame, (L, M, N) are aerodynamic moments, and (a_{11}, a_{12}, a_{13}) are given by

$$
\begin{aligned}
a_{11} &= \sin\alpha\tan\beta + \sin\alpha\tan\gamma\sin\mu - \cos\alpha\sin\beta\tan\gamma\cos\mu \\
a_{12} &= (\cos\beta\tan\gamma\cos\mu) \\
a_{13} &= -(\sin\alpha\sin\beta\tan\gamma\cos\mu + \cos\alpha\tan\beta + \cos\alpha\tan\gamma\sin\mu)
\end{aligned} \tag{2}
$$

where γ is flight path angle. During the boost-phase, the moments of inertia and the mass change drastically. Therefore, the parameters are regarded as fast-varying with respect to time, and the effects of the parameters are included in the missile dynamics in Eq. (1). Let us define a parameter vector $\bar{p}(t) = [m\; I_{xx}\; I_{yy}\; I_{zz}]^T$, and state vectors $x_1 = [\alpha\,\beta\,\mu]^T$, $x_2 = [p\,q\,r]^T$, $x_3 = M_a$, and a control variable vector $u = [\delta_r\,\delta_p\,\delta_y]^T$. Then, the missile dynamics can be represented as state-space forms.

$$
\begin{aligned}
\dot{x}_1 &= f_1(x_1, x_3, \bar{p}) + g_1(x_1)x_2 \\
\dot{x}_2 &= f_2(x_1, x_2, x_3, \bar{p}) + g_2(x_1, x_2, x_3, \bar{p})u \\
\dot{x}_3 &= f_3(x_1, x_3, \bar{p})
\end{aligned} \tag{3}
$$

2.2 Aerodynamic model

Due to the extensive flight envelope, the aerodynamics should be carefully modeled. Forces and aerodynamic moments can be modeled as follows:

$$
\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \frac{1}{m}\begin{bmatrix} T - QSC_x \\ QSC_y \\ QSC_z \end{bmatrix}, \quad \begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} QSdC_l \\ QSdC_m \\ QSdC_n \end{bmatrix} \tag{4}
$$

where T is a thrust force, (Q, S, d) represent the dynamic pressure, characteristic area, and characteristic length, respectively. The aerodynamic coefficients are obtained from experimental database, which can be modeled as follows:

$$
\begin{aligned}
C_x &= C_{x_0} + C_{x_{M_a}}M_a + C_{x_\alpha}\alpha + C_{x_\beta}\beta + \Delta C_x(\delta_r, \delta_p, \delta_y) \\
C_y &= C_{y_0} + C_{y_{M_a}}M_a + C_{y_\alpha}\alpha + C_{y_\beta}\beta + \Delta C_y(\delta_r, \delta_p, \delta_y) \\
C_z &= C_{z_0} + C_{z_{M_a}}M_a + C_{z_\alpha}\alpha + C_{z_\beta}\beta + \Delta C_z(\delta_r, \delta_p, \delta_y) \\
C_l &= C_{l_0} + \frac{d}{2V}C_{l_p}p + C_{l_{\delta_r}}\delta_r + C_{l_{\delta_p}}\delta_p + C_{l_{\delta_y}}\delta_y + \Delta C_l \\
C_m &= C_{m_0} + \frac{d}{2V}C_{m_q}q \\
&\quad + C_{m_{\delta_r}}\delta_r + C_{m_{\delta_p}}\delta_p + C_{m_{\delta_y}}\delta_y + \Delta C_m \\
C_n &= C_{n_0} + \frac{d}{2V}C_{n_r}r \\
&\quad + C_{n_{\delta_r}}\delta_r + C_{n_{\delta_p}}\delta_p + C_{n_{\delta_y}}\delta_y + \Delta C_n
\end{aligned} \tag{5}
$$

where $(\Delta C_x, \Delta C_y, \Delta C_z)$ attribute the non-minimum phenomenon, and the effects can be negligible compared with other terms. $(\Delta C_l, \Delta C_m, \Delta C_n)$ are uncertainties in moment coefficients due to modeling errors. These terms will be compensated by adaptive control scheme.

2.3 Uncertainty Model

To reflect the realistic nature of missile dynamics, inertial properties including mass and the moments of inertia as well as aerodynamic errors are considered as uncertainty parameters. The system dynamics can be rewritten considering the uncertainties as follows:

$$
\begin{aligned}
\dot{x}_1 &= f_1(x_1, x_3, \bar{p}) + g_1(x_1, \bar{p})x_2 + \Delta_1 \\
\dot{x}_2 &= f_2(x_1, x_2, x_3, \bar{p}) + g_2(x_1, x_2, x_3, \bar{p})u + \Delta_2 \\
\dot{x}_3 &= f_3(x_1, x_3, \bar{p}) + \Delta_3
\end{aligned} \tag{6}
$$

where $\Delta_1 = \Delta f_1$, $\Delta_2 = \Delta f_2 + \Delta g_2 u$, $\Delta_3 = \Delta f_3$ are lumped uncertainties consisting of the parametric uncertainties as well as the un-modeled dynamics. The uncertainties are expressed as follows:

$$
\begin{aligned}
\Delta_1 &= \frac{1}{V}\begin{bmatrix} -\frac{\sin\alpha}{\cos\beta} & 0 & \frac{\cos\alpha}{\cos\beta} \\ -\cos\alpha\sin\beta & \cos\beta & -\sin\alpha\sin\beta \\ a_{11} & a_{12} & a_{13} \end{bmatrix}\begin{bmatrix} \Delta a_x \\ \Delta a_y \\ \Delta a_z \end{bmatrix} \\
\Delta_2 &= \begin{bmatrix} \Delta\left\{\left(\frac{QSd}{I_{xx}}\right)C_l\right\} \\ \Delta\left\{\frac{(I_{zz}-I_{xx})}{I_{yy}}pr + \frac{QSd}{I_{yy}}C_m\right\} \\ \Delta\left\{\frac{(I_{xx}-I_{yy})}{I_{zz}}pq + \frac{QSd}{I_{zz}}C_n\right\} \end{bmatrix} \\
\Delta_3 &= \frac{1}{a}\left[\cos\alpha\cos\beta\;\; \sin\beta\;\; \sin\alpha\cos\beta\right]\begin{bmatrix} \Delta a_x \\ \Delta a_y \\ \Delta a_z \end{bmatrix}
\end{aligned} \tag{7}
$$

To express the lumped uncertainties in Eq. (7) as parametric uncertainties, define unknown parameter vectors, θ_1 and θ_2 as:

$$
\begin{aligned}
\theta_{\mathbf{1}} &= \left[\; \frac{\Delta C_x}{C_x} \;\; \frac{\Delta C_y}{C_y} \;\; \frac{\Delta C_z}{C_z} \;\; \frac{\Delta m}{m} \;\right]^T \\
\theta_{\mathbf{2}} &= \left[\; \frac{\Delta I_{xx}}{I_{xx}} \;\; \frac{\Delta I_{yy}}{I_{yy}} \;\; \frac{\Delta I_{zz}}{I_{zz}} \;\; \frac{\Delta C_l}{C_l} \;\; \frac{\Delta C_m}{C_m} \;\; \frac{\Delta C_n}{C_n} \;\right]^T
\end{aligned} \tag{8}
$$