Robust H_∞ Autopilot Design for Agile Missile With Time-Varying Parameters

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This paper considers two autopilot designs using H_∞ loop shaping for an agile missile that experiences high angle of attack, highly nonlinear and rapidly changing dynamics, and aerodynamic variation after launch. The main autopilot design is started with two H_∞ control designs intended to cover the low-speed and high-speed regions of the flight envelope. Then, the two control designs are combined (via Mach variation) to construct a global controller that covers the entire flight envelope. The proposed autopilots have a simple structure and require no time-consuming gain scheduling for many flight conditions, while providing satisfactory tracking and robustness over the entire flight envelope. The performance of the designed autopilots is checked via a comparison study and a challenging intercept scenario. These performance test results clearly demonstrate the merit of the proposed designs.

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I. INTRODUCTION

Agile missiles can track and effectively hit targets located in the real hemisphere of the missile launch vehicle due to high maneuverability. With these agile maneuvers, however, missiles may experience high angle-of-attack (AoA) aerodynamics, mass variation, and changes in their dynamic stability. This clearly demands a robust autopilot that allows for agile maneuvers with guaranteed performance over the required flight envelope.

The autopilot design problem for conventional missiles has been well studied, and this study can certainly be used for the initial (boost) phase and the end phase of agile missile systems. However, the autopilot design for the agile turn phase is relatively less studied, seemingly due to the undesirable phenomena mentioned previously. Among many missile autopilot design works in the literature, some representative works are listed in the following. In [1], a robust pole placement technique is used for an autopilot design. In [2], linear matrix inequalities are used to propose a systematic gain scheduling autopilot design that accommodates mass variation. In [3], the authors use a linear parameter-varying approach to design an adaptive nonlinear control for a pitch autopilot. A nonlinear control law is constructed by dynamic inversion in [4]. Note that the main criticisms about the aforementioned techniques are that 1) they do not take into account the time-varying nature of the center of gravity (CG) that plays a crucial role in stability and 2) they use conventional control surfaces, which are not useful in the high AoA domain [5]. A time-delay technique is found in [6, 7] for agile missile control, but this technique requires the exact knowledge of AoA, which is difficult to measure in flight and often requires an observer to implement this technique. This measurement issue also applies to the popular backstepping control in [8] and adaptive backstepping control in [9, 10]. These control techniques require knowledge of a large number of states and derivatives, employing many sensors to be placed over the system that increase cost and complexity.

To circumvent this measurement issue while efficiently handling the missile's time-varying nature, robust control design seems a suitable choice. Popular robust control techniques have, indeed, been applied for the missile autopilot design. In [11, 12, 13], mixed H_2/H_∞ norms are used to design a pitch autopilot. Other robust techniques, such as μ synthesis [14] and sliding mode control [15], are also employed for an autopilot design. In these robust control designs, a set of controllers (each satisfying performance and robustness requirements for a specified operating Mach number) is normally constructed to form a global gain-scheduled controller (via interpolation of the controllers' gains over the variations of AoA, Mach number, and CG). However, this gain scheduling task is often time-consuming and needs to be minimized. It is, therefore, preferred to use a minimum number of models (reflecting missile dynamics in representative flight

conditions), with controllers designed to reduce the computational burden.

In this paper, a global controller covering a large Mach variation is obtained by combining only two robust H_∞ controllers that work for the low-speed and high-speed regions, respectively. Unlike [2] and [16] (in which CG and mass variations are used), Mach variation is used in the present work for constructing linear models and control designs to accommodate the feature of high AoA aerodynamic data that vary rapidly with the Mach number. One recent work [17] can be found in which Mach variation and time-varying parameters are, indeed, used for modeling, but the operating range of present interest is much wider than the previous work. The main contributions of the present work are therefore threefold: 1) a simple autopilot (requiring only a few measurements) is proposed to effectively cater for mass, inertia, CG, and aerodynamic data that may undergo a large variation with Mach number, while providing desired performance and robustness over the entire flight envelope; 2) the proposed autopilot does not require time-consuming gain scheduling; and 3) a comparative analysis is performed to show that the proposed autopilot is much simpler to implement and yields a more feasible control input than a recently proposed nonlinear backstepping autopilot [8].

The rest of the paper is organized as follows. In Section II, agile missile dynamics and linearization against the Mach variation to construct linear models are discussed. Our focus here is on longitudinal missile dynamics, but the idea developed in this paper can also be applied to lateral or directional dynamics with little effort. In Section III, a rate feedback gain is first selected to improve the missile's transient (short-period) characteristics before the main control design. A robust H_∞-based autopilot is then designed for tracking pitch-angle commands with guaranteed performance, and some numerical results are shown. Also, a comparative study is performed to highlight the merit of the proposed autopilot design. Finally, a similar autopilot design is presented for tracking normal acceleration commands for the end phase after agile maneuvers in Section IV. Concluding remarks follow in Section V.

II. MISSILE MODELING

A. Nonlinear Model

In this paper, the AIM-9X missile [18] equipped with a thrust vectoring (TV) system is used, and its 6-degree-of-freedom nonlinear model is obtained based on [19]. The missile motion can be decoupled into longitudinal and lateral dynamics with the assumption that the agile missile is maneuvering in the vertical plane after its launch with the roll motion being stabilized. The simplified longitudinal missile dynamics is then given as follows:

$$\dot{u} = \frac{F_x}{m} - g\sin\theta - qw, \tag{1}$$

$$\dot{w} = \frac{F_z}{m} + g\cos\theta + qu, \tag{2}$$

$$\dot{\theta} = q; \quad \dot{q} = \frac{M}{I_{yy}}, \tag{3}$$

where θ is the missile pitch angle, q is the missile pitch rate, M is the pitching moment, I_{yy} is the pitching moment of inertia, u is the body frame forward velocity, w is the body frame down velocity, F_x is the force in the longitudinal direction, F_z is the force in the upward direction, m is the missile mass, and g is the gravitational acceleration. The forces are computed based on aerodynamic coefficients that typically vary nonlinearly with Mach number, α (AoA), and the missile's fin deflection. The pitching moment M and the nozzle deflection angle η for TV are given by the following relations:

$$M = QslC_m - Tx\sin\eta, \tag{4}$$

$$\dot{\eta} = (\eta_c - \eta)/\tau, \tag{5}$$

where Q is the aerodynamic pressure, s is the reference area, l is the reference length, C_m is the pitching moment coefficient, T is the thrust, x is the distance between CG and the thrust action point, τ is the TV system's time constant, and η_c is the control input.

B. State Space Model

Linear models are created from the nonlinear missile model given by (1)–(5) against the Mach variation, $\boldsymbol{M} = [0.7, 0.9, 1.1, 2.0, 3.0]$. In state space, these linear models are expressed in terms of state vector $\boldsymbol{x}$ with input vector $\boldsymbol{u}$ and output vector $\boldsymbol{y}$ as follows:

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u},$$
$$\boldsymbol{y} = C\boldsymbol{x} + D\boldsymbol{u},$$

with some constant matrices A, B, C, and D, where $\boldsymbol{x} = [u, w, q, \theta, \eta]^T$, $\boldsymbol{y} = \theta$ (for Section III), or a_n (for Section IV) and $\boldsymbol{u} = \eta_c$.

III. PITCH-ANGLE-BASED AUTOPILOT DESIGN

A. Performance Objectives

The missile of present interest often needs to make about a half turn in a very short interval (4 to 5 s) and follows a reference command for the purpose of target chasing. Thus, the following control objectives are set for the autopilot design in this section:

1) To maintain stability and reject disturbances over the flight envelope (Mach 0.7–3.0) during an agile turn, e.g., θ: $0 \rightarrow 180$ deg.

2) To provide desired tracking performance with rise time less than 0.35 s, steady-state error less than 1% and settling time less than 3 s.

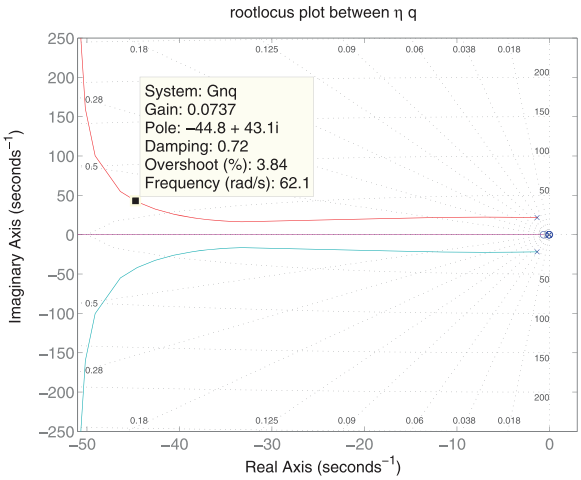

Fig. 1. Selection of rate feedback gain using root locus for $G_{\eta q}$.

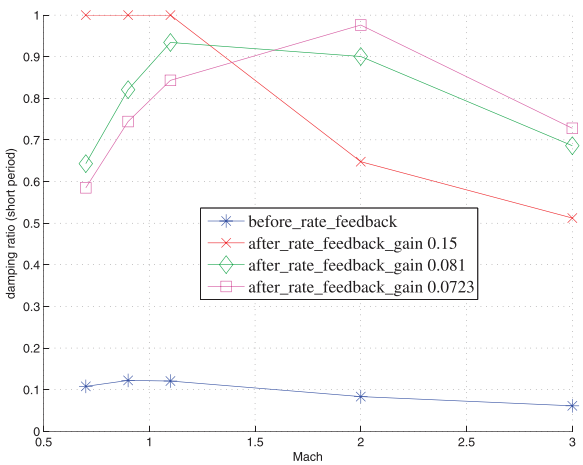

Fig. 2. Linear model's damping ratio with respect to Mach number.

3) To achieve a phase margin of more than 45 deg and bandwidth less than 10 rad/s.[1]

B. Rate Feedback Gain Selection

Pitch rate feedback is used to improve the missile's transient (short-period) characteristics. A proper rate feedback gain can be selected from the root locus (Fig. 1) and plotted for the transfer function $G_{\eta q}(s)$ between nozzle deflection η and pitch rate q.[2] This plot suggests that the gain of 0.072 can improve the short-period characteristics the most for the linear model at Mach 3.0 (at which the missile model before the rate feedback has the lowest damping ratio as indicated in Fig. 2). However, this gain of 0.072 may result in low damping ratios at low Mach numbers. For this reason, the gain of 0.081 is chosen to maximize the lowest damping ratio over the entire operational range (see Fig. 2).

[1]As shall be mentioned in Sections III.C and IV.B, the bandwidth requirement is to avoid undesirable effects (e.g., undershoot in the initial response) of a right-half complex plane (RHP) zero at $s = 33.07$.

[2]In this paper, $G_{ab}(s)$ denotes the transfer function from a to b.

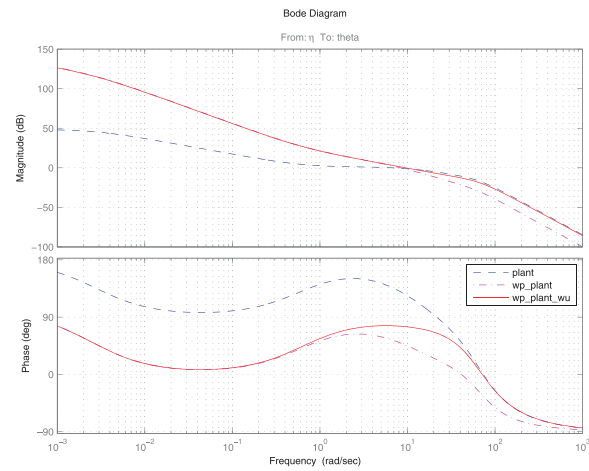

Fig. 3. Shaping $G_{\eta_c\theta}$ with pre and post compensator weights.

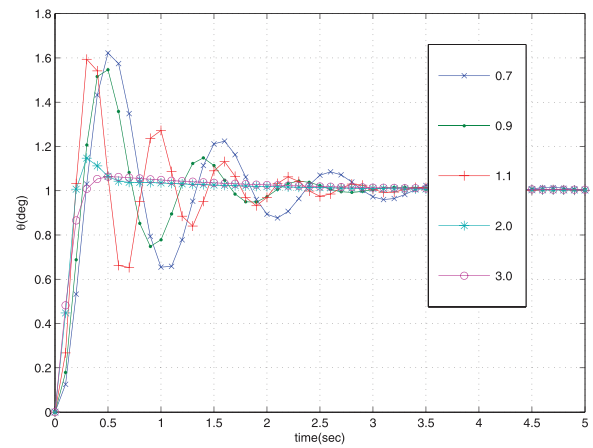

Fig. 4. Step tracking at various Mach numbers.

C. H_∞ Loop-Shaping Design

After the rate feedback, $G_{\eta_c\theta}(s)$ (linear model at Mach 3.0) is shaped with pre- and postcompensator weights, W_p and W_u, for the desired performance. These weights are selected so that $G_{\eta_c\theta}(s)$ has a high gain at low frequencies and crosses 0 dB near 10 rad/s (as stated in Section II.A) to yield good reference tracking and disturbance rejection. The crossover frequency is chosen as about 10 rad/s to avoid undesirable effects (e.g., undershoot in the initial response) of a RHP zero at $s = 33.07$ in the missile dynamics. In fact, the following choice of W_p and W_u

$$W_p = \frac{0.1764(s+50)}{s}; \quad W_u = \frac{5(s+12.5)}{(s+65)}$$

achieves the said objective and also yields a phase margin of 65 deg. Bode diagrams for the shaped plant along with the original plant are shown in Fig. 3. The standard H_∞ loop-shaping technique [20] is then employed to robustify the shaped $G_{\eta_c\theta}$. This technique leads to the controller $K_{3.0}$ in (6), and this controller yields the closed-loop system step responses at various Mach numbers, as shown in Fig. 4. As clearly seen in the figure, the controller successfully tracks the reference input (at

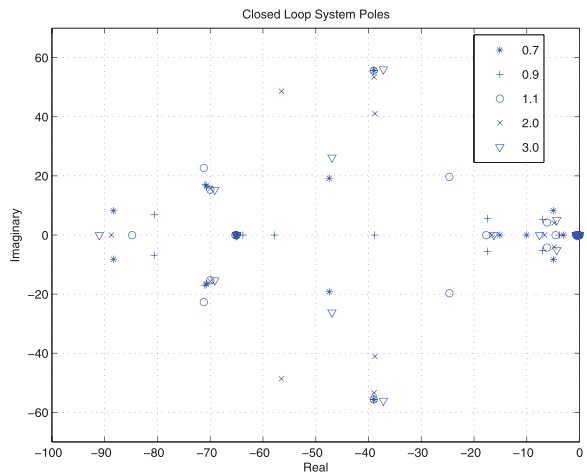

Fig. 5. Closed-loop pole locations for various Mach numbers.

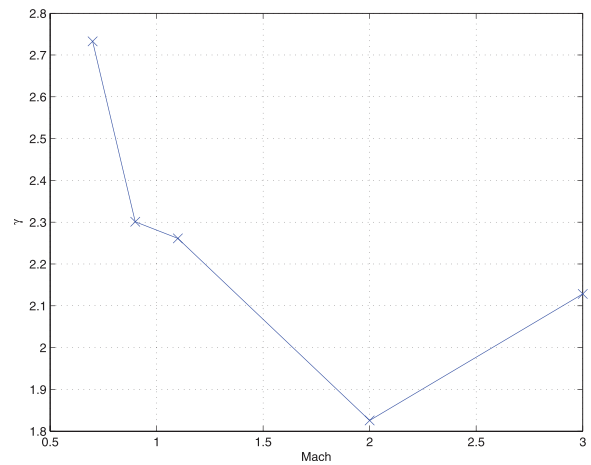

Fig. 6. Variation of γ with Mach number.

Mach 3.0) as expected, but it shows poor performance (e.g., settling time of more than 3 s) at low Mach numbers (less than Mach 0.9). This motivates the need for another controller to improve the performance in the low Mach region.

$$K_{3.0} = \frac{-56.1054(s+64.9)(s+50)(s+12.5)(s+11.67)(s+0.565)(s^2+91.36s+4402)}{(s+65)(s+81.7)(s+48.56)(s+12.35)(s+0.6379)(s+0.0001)(s^2+86.69s+5460)}, \tag{6}$$

$$K_{0.7} = \frac{-301.4488(s+10.5)(s+12.5)(s+65.05)(s+93.9)(s+0.2655)(s^2+9.122s+35.76)}{(s+104.5)(s+65)(s+0.275)(s+0.0007)(s^2+19.45s+103.4)(s^2+104.8s+3516)}. \tag{7}$$

To obtain the desired performance in the low Mach region, the linear model at Mach 0.7 is chosen for control synthesis. The same control design technique as for Mach 3.0 yields $K_{0.7}$ in (7). One may switch between $K_{3.0}$ and $K_{0.7}$, depending on the flight speed, but here these two controllers are combined for bumpless transfer in the following way:

$$K_{\boldsymbol{M}} = \frac{(3-\boldsymbol{M})}{2.3}K_{0.7} + \frac{(\boldsymbol{M}-0.7)}{2.3}K_{3.0}.$$

The natural question that arises is the stability and performance aspects of $K_{\boldsymbol{M}}$. To check the stability, close-loop poles are calculated and plotted for five representative linear models (linearized at $\boldsymbol{M}$) coupled with $K_{\boldsymbol{M}}$. Fig. 5 shows that all the closed-loop poles are in the left-half complex plane, implying that $K_{\boldsymbol{M}}$ is indeed a stabilizing controller for each of the five linear models. To check the controller's robustness, with respect to a wide class of unstructured plant variations, the normalized coprime stability margin is computed and plotted versus the Mach number. Fig. 6 implies that the closed-loop system can tolerate up to 36.5% ($= 100/\gamma_{max}$) of coprime uncertainty before reaching instability.[3] Thus, $K_{\boldsymbol{M}}$ can be regarded as a robust controller, covering the entire range of Mach number of interest.

D. Controller Performance in Nonlinear Simulation

The designed controller in Section III is now tested in a simulation environment in which the missile's nonlinear dynamics is used, instead of the linear models used for the control designs. The simulation parameters are listed in Table I. Note that the missile mass m, the moment of inertia I_{yy}, CG, and T vary with time, and aerodynamic data, such as C_m, are given as a form of table for various flight conditions. To simulate an agile turn maneuver, a step command with $\theta_c = 180$ deg is given. Also, to check the robustness of the designed controller, C_m is set to rapidly change around a nominal value by $0.35\sin(1.2\pi t)$. As shown in Fig. 7, the designed controller $K_{\boldsymbol{M}}$ renders the missile successfully tracking the command input in this nonlinear simulation with perturbed aerodynamic data.

E. Comparison Study

In this section, a comparison study is performed between the proposed autopilot and a recently proposed nonlinear backstepping autopilot [8]. The same simulation parameters as in Section III.D are used for this comparison, except that a slow-varying command

[3]MATLAB command *ncfmargin* is used to calculate the normalized coprime stability margin. See [21] for details.

TABLE I
Simulation Parameters

τ	0.01	s
I_{yy}	72.632–50.02	$kg \cdot m^2$
x	0.127	m
m	85–66	kg
g	9.81	m/s^2
CG	1.27324–1.052	m
l	3.02	m
S	$3.14x/4$	m^2
T	$30\,124–5000t$ $(0 \le t \le 6.0248\ s)$ 0 $(t > 6.0248\ s)$	N

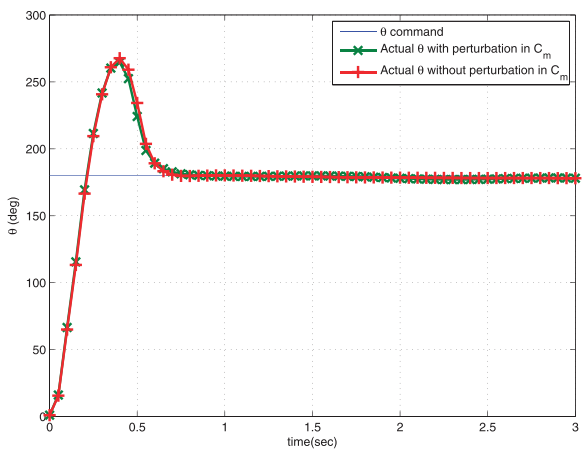

Fig. 7. Pitch angle tracking result after nonlinear simulation with perturbed aerodynamic data.

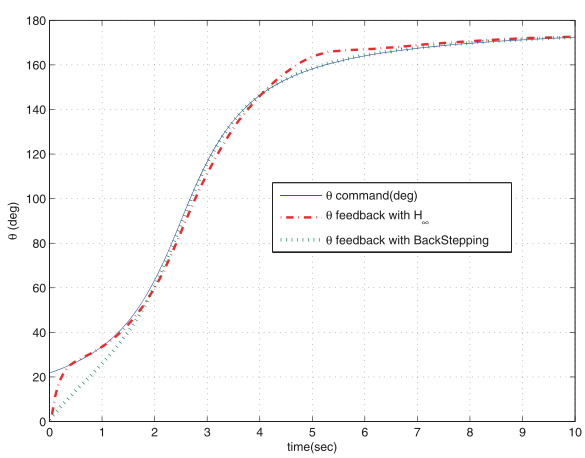

Fig. 8. Reference tracking with H_∞ and backstepping control.

$\theta_c = \tan^{-1}(t-2.5) + \pi/2$ is given.[4] Note that the equal amount of uncertainty in the aerodynamic data is used for a fair comparison. As shown in Figs. 8 and 9, the missile tracks the reference trajectory for both cases, but the nozzle deflection angle changes at high frequency for the backstepping controller.[5] Obviously, it can be a serious problem when implementing this oscillating control input using a physical actuator. Also, note that the backstepping controller requires the knowledge of a large number of states and derivatives, such as α and η, which are practically difficult to measure or use for control synthesis.

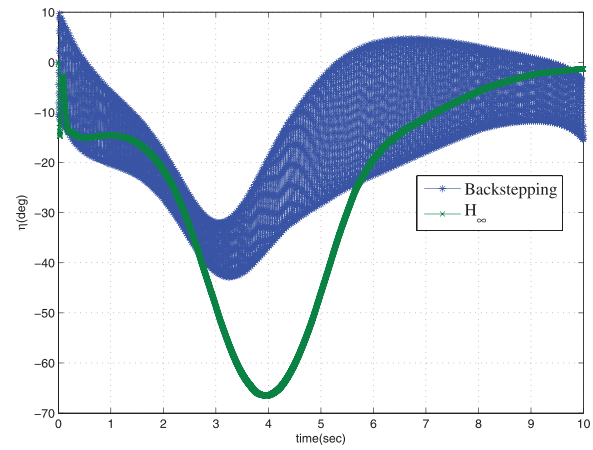

Fig. 9. Nozzle deflection for H_∞ and backstepping control.

IV. ACCELERATION BASED AUTOPILOT DESIGN

In this section, a similar H_∞-based autopilot is applied for tracking typical guidance commands, i.e., normal acceleration a_n commands. Although the present work's original objective (as stated in Section III.A) has been fulfilled, this additional design is considered for completeness to demonstrate that the proposed control design technique can easily be modified to track an actual target (normal acceleration-based command) after agile maneuvers.

A. Reduced-Order Modeling

Once the missile makes an agile turn, an acceleration-based autopilot can be used for the end phase, which involves high Mach numbers to reach the target.[6] Thus, for this acceleration-based autopilot design, only one linear model at Mach number 3.0 is chosen and subsequently reduced to a low-order (short-period) model, with three state variables $[w,q,\eta]$, one input η_c, and one output a_n. It can be shown via Bode diagrams that the low-order model

$$G_{\eta_c a_n} = \frac{3265.263(s+33.26)(s-33.07)}{(s+15.98)(s^2+86.69s+3142)} \tag{8}$$

well approximates the full-order model for short-period dynamics (associated with the high-frequency region).

[4]This slow-varying command is intentionally given because the backstepping controller requires an undesirably large control input for a fast-varying command, such as a step command.

[5]An extensive parameter tuning job was performed during the backstepping control design to achieve the best performance.

[6]Existing techniques, such as [22, 23], can be used for stable switching between two autopilots.

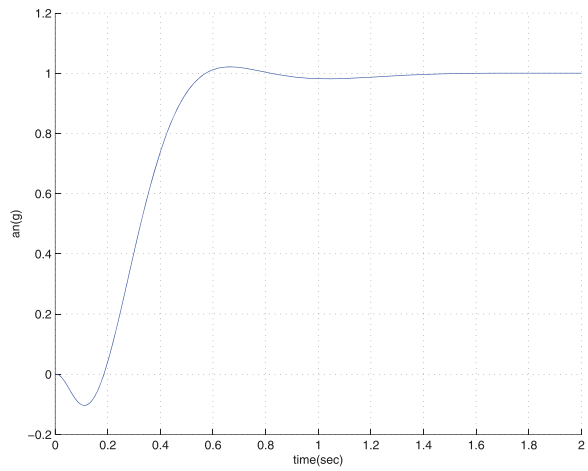

Fig. 10. Response to unit step acceleration input.

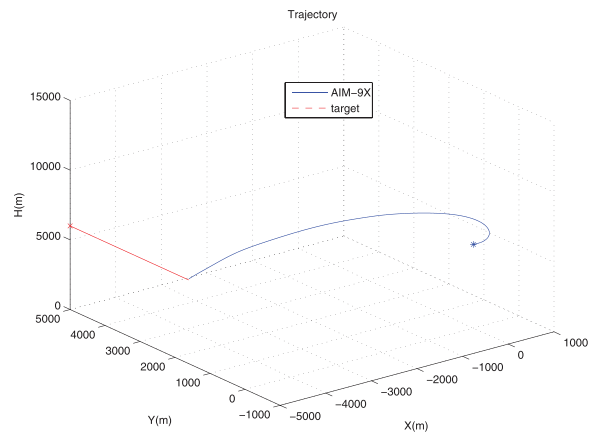

Fig. 11. An intercept scenario (solid: missile's trajectory; dotted: target's trajectory).

B. Control Design

Following a similar procedure presented in Sections III.B and III.C, a rate feedback gain and H_∞ loop-shaping controller can be designed for the low-order model (8). However, extra care must be taken to handle a real RHP zero at $s = 33.07$ in $G_{\eta_c a_n}(s)$. To address this RHP zero issue, the following weights

$$W_p = \frac{0.072218}{s}; \quad W_u = \frac{5.6738}{s + 4.95}$$

are chosen in a way that the shaped $G_{\eta_c a_n}$ has the crossover frequency much less than 33.07 rad/s to avoid undesirable effects (e.g., undershoot in the initial response) of the RHP zero. After the standard H_∞ loop-shaping design procedure, the controller shown in (9) is obtained, and the closed-loop system's step response is shown in Fig. 10. As shown in the figure, the designed controller renders the missile tracking the given acceleration command to a satisfactory level (in terms of the second performance objective in Section II.A).

$$K = \frac{-13.6236(s + 15.96)(s + 5.512)(s^2 + 86.69s + 3145)}{(s + 4.95)(s + 23.51)(s + 0.0001)(s^2 + 20.23s + 249.4)(s^2 + 87.58s + 3182)}. \tag{9}$$

C. Intercept Scenario

To demonstrate the effectiveness of the designed controller, a challenging intercept scenario is created. Suppose (X, Y, H) represent the missile position in the inertial reference frame, where the target starts from x with a constant speed and keeps moving horizontally. As depicted in Fig. 11, the missile is launched from "*" with a direction further away from the target, but it quickly makes about a half turn to hit the target.

V. CONCLUSION

In this paper, the standard H_∞ loop-shaping technique has been used to design two autopilots (pitch-angle and acceleration-based autopilots) for agile missiles, such as AIM-9X. The main autopilot design idea involved two controllers covering the low-speed and high-speed regions, respectively. These two controllers were then combined to form a global controller for the entire flight envelope. Because only two controllers were necessary to cover the entire flight envelope, time-consuming gain tuning for many flight conditions could be avoided. The proposed autopilots showed robustness against parameter variations, while providing satisfactory tracking. A challenging intercept scenario was created to demonstrate that the proposed (acceleration-based) autopilot successfully enables the missile to intercept the target. Finally, a comparison study was performed to show that the proposed (pitch-angle based) autopilot outperforms a recently proposed nonlinear backstepping autopilot controller.

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