

Synthesis of an optimal backstepping controller with an adaptive extended observer for missile control systems

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ABSTRACT

The paper proposes an optimal Backstepping linear quadratic regulator (BLQR) and an Adaptive extended disturbance observer (AEDO) to enhance control performance and disturbance estimation in nonlinear, uncertain systems. The BLQR controller is employed to handle nonlinearities and uncertainties while optimizing control quality, whereas the AEDO effectively estimates and compensates for disturbances in missile control systems. The authors demonstrate system stability based on Lyapunov stability theory and conduct simulations in MatLab/Simulink. The simulation results validate the effectiveness of the proposed approach.

Keywords: Missile Control; Backstepping Control; Linear Quadratic Regulator (LQR); Adaptive Extended Disturbance Observer (AEDO).

1. INTRODUCTION

The missile dynamics and the relative motion with respect to the target during motion are described by nonlinear equations. These equations involve model uncertainties, external disturbances, varying operating conditions, and target maneuvers. These factors directly impact the missile trajectory, degrading control quality and reducing the accuracy of the guidance process. Therefore, the study of advanced control methods to enhance missile guidance and control performance remains a topic of great interest to researchers.

A modern approach to missile guidance and control design is the Integrated Guidance and Control (IGC) system, in which the guidance and control subsystems are treated as a unified system. In [1], an IGC model with uncertainties was developed to study control methods that drive the Line of Sight (LOS) angular rate to zero under various conditions. Reference [2] utilizes an adaptive fuzzy system to evaluate and compensate for parameter uncertainties in the IGC system. In [3], an observer-based approach is used to estimate target maneuvering information and disturbances, combined with Disturbance Observer and Sliding Mode Control (DSC) and Nonlinear Extended State Observer (N-ESO) to enhance disturbance rejection. In [4], a Backstepping control scheme is proposed, incorporating a reduced-order state observer and a Tracking Differentiator (TD) for control optimization. Additionally, several other studies have introduced advanced IGC control methods to improve interception performance. In [5], a novel Sliding Mode Control (SMC) algorithm is designed to enhance accuracy and disturbance rejection in IGC systems. In [6], a SMC approach integrated with an Extended Disturbance Observer (EDO) is developed to intercept highly maneuvering targets. Moreover, reference [7] introduces a nonlinear guidance strategy incorporating a virtual line-of-sight constraint, aiming to optimize the interception trajectory in complex scenarios. In [8], an impact angle constrained guidance law is proposed using a fully-actuated system approach, providing precise terminal attack angle control which is critical in modern missile engagements. Reference [9] explores an optimization-based predictive control framework for integrated missile guidance and control, demonstrating improved performance in handling constraints and uncertainties. Furthermore, studies such as [10] and [11] present significant advancements in adaptive Backstepping control and Extended State Observer (ESO) design, particularly for aerial systems like quadcopters.

However, most existing studies still have certain limitations. Specifically, the parameters of the Backstepping controller are typically fixed throughout the missile guidance process, reducing performance when operating conditions change significantly. Similarly, the ESO employs constant gains, leading to estimation errors when real-world conditions vary. Therefore, the research and development of an optimized parameter Backstepping control method (BLQR – Backstepping Linear Quadratic Regulator) combined with an Adaptive Extended Disturbance Observer (AEDO) based on system state variables is a promising direction. This approach not only enhances control effectiveness but also improves disturbance compensation and robustness against uncertainties. Optimizing the IGC system will contribute to improved guidance accuracy, optimized missile trajectories, and reduced interception time.

2. THE PROPOSED SOLUTION

2.1. Problem formulation

The mathematical model describing the motion of the missile and the target in the vertical plane is illustrated in figure 1, here OXY represents the inertial Cartesian reference frame, and M and T represent the quantities of the missile and the target, respectively.

In the model, x_m, y_m and x_T, y_T - Correspond to the current positions of the missile and the target, respectively; V_M, θ_M, a_M are the velocity, flight path angle, and normal acceleration of the missile, respectively; V_T, θ_T, a_T are the velocity, flight path angle and normal acceleration of the target, respectively; R - The relative distance between the target and missile; q - The line of sight (LOS) angle; $O_m x_b$ - The missile's body-fixed longitudinal axis; ϑ - Represents the missile pitch angle.

The missile dynamics in the vertical plane are illustrated in figure 2 [5], where the notations are defined as follows: α is the angle of attack; M_g, X_{aero}, Y_{aero} are the gravitational force, aerodynamic drag, and aerodynamic lift of the missile, respectively.

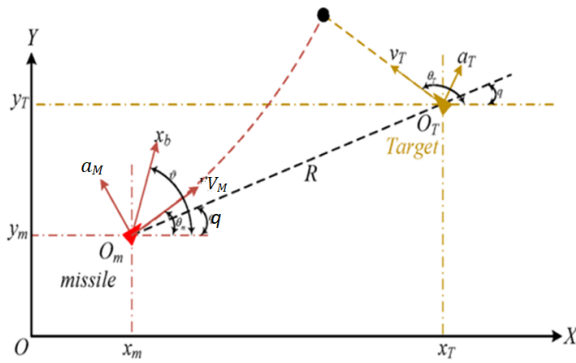


Figure 1. Relative motion of the missile and the target in the vertical plane.

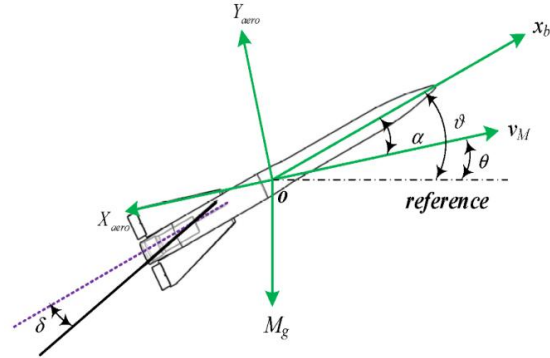


Figure 2. Missile dynamics in the vertical plane.

According to figures 1 and 2, the relative positions are defined as follows [1]:

$$\begin{cases} \dot{R} = V_T \cos(\theta_T - q) - V_M \cos(\theta_M - q) \\ R\dot{q} = V_T \sin(\theta_T - q) - V_M \sin(\theta_M - q) \\ \dot{\theta}_T = \frac{a_T}{V_T}, \quad \dot{\theta}_M = \frac{a_M}{V_M} \end{cases} \quad (1)$$

By applying an appropriate variable coordinate transformation to the system (1), we obtain:

$$\begin{aligned} \ddot{q} = & -\frac{2\dot{R}}{R}\dot{q} - \frac{\dot{V}_T}{R}\sin(q - \theta_T) + \frac{\dot{V}_M}{R}\sin(q - \theta_M) \\ & + \frac{V_T\dot{\theta}_T}{R}\cos(q - \theta_T) - \frac{V_M\dot{\theta}_M}{R}\cos(q - \theta_M) \end{aligned} \quad (2)$$

Based on the assumption that $\dot{a}_T = \dot{a}_M = 0$, equation (2) is simplified as follows:

$$\ddot{q} = \frac{2\dot{R}}{R}\dot{q} + \frac{a_T \cos(q - \theta_T)}{R} - \frac{a_M \cos(q - \theta_M)}{R} \quad (3)$$

The missile dynamics in the pitch plane are expressed as follows [1]:

$$\begin{aligned} \dot{\alpha} = & \frac{1}{mV_M}(-P \sin \alpha - Y^\alpha \alpha + mg \cos \theta_M) + \omega_z \\ J_z \dot{\omega}_z = & M_z^\alpha \alpha + M_z^{\omega_z} \omega_z + M_z^{\delta_z} \delta_z \\ \dot{\vartheta} = & \omega_z ; \alpha = \vartheta - \theta_M \end{aligned} \quad (4)$$

By transforming equation (4) under the assumption of a small α angle:

$$\dot{\alpha} = -\frac{P + Y^\alpha}{mV_M} \alpha + \frac{g \cos \theta_M}{V_M} + \omega_z = -\frac{P + 57,3QSc_y^\alpha}{mV_M} \alpha + \frac{g \cos \theta_M}{V_M} + \omega_z \quad (5)$$

Considering the system uncertainties and combining equations (3) and (4), the integrated guidance and control (IGC) equations for the missile are formulated as follows:

$$\begin{cases} \ddot{q} = \left(-\frac{2\dot{R}}{R}\dot{q} + \frac{g \cos(q - \theta_M)}{R} \cos \theta_M \right) - \left(\frac{57,3QSc_y^\alpha}{mR} \cos(q - \theta_M) \right) \alpha + d_1 \\ \dot{\alpha} = \left(-\frac{P + 57,3QSc_y^\alpha}{mV_M} \alpha + \frac{g \cos \theta_M}{V_M} \right) + \omega_z + d_2 \\ \dot{\omega}_z = \left(\frac{57,3QSlm_z^\alpha}{J_z} \alpha + \frac{QSl^2 m_z^{\omega_z}}{J_z V_M} \omega_z \right) + \frac{57,3QSlm_z^{\delta_z}}{J_z} u + d_3 \end{cases} \quad (6)$$

Where $u = \delta_z$ is the control input signal.

The system uncertainties are represented as:

$$d_1 = \frac{a_T \cos(q - \theta_T)}{R}; \quad d_2 = d_2(c_y^\alpha); \quad d_3 = d_3(m_z^\alpha, m_z^{\omega_z})$$

The first equation of (6) represents the guidance law, where the uncertainty factor d_1 is primarily due to the target's maneuverability, characterized by the target's normal acceleration a_T and flight path angle θ_T . The next two equations describe the control law: the second equation represents the angle of attack, with the uncertainty factor d_2 mainly caused by variations in the derivative of the aerodynamic lift coefficient. The third equation determines the pitch angle rate, where the dominant uncertainty factors d_3 are the derivatives of the aerodynamic moment coefficients, as well as the shifts in the center of mass and air density disturbances.

Define the state variables as follows: $x_1 = \dot{q}, x_2 = \alpha, x_3 = \omega_z, u = \delta_z$, The system of equations (4) is rewritten as follows:

$$\begin{cases} \dot{x}_1 = f_1(x_1) + g_1(x_1)x_2 + d_1 \\ \dot{x}_2 = f_2(x_1, x_2) + g_2(x_1, x_2)x_3 + d_2 \\ \dot{x}_3 = f_3(x_1, x_2, x_3) + g_3(x_1, x_2, x_3)u + d_3 \end{cases} \quad (7)$$

Where:

$$\begin{cases} f_1(x_1) = -\frac{2\dot{R}}{R}\dot{q} + \frac{g \cos(q - \theta_M)}{R} \cos \theta_M \\ f_2(x_2) = -\frac{P + 57,3QSc_y^\alpha}{mV_M} \alpha + \frac{g \cos \theta_M}{V_M} \\ f_3(x_3) = \frac{57,3QSlm_z^\alpha}{J_z} \alpha + \frac{qSl^2 m_z^\omega}{J_z V_M} \omega_z \end{cases} \begin{cases} g_1(x_1) = -\frac{57,3QSc_y^\alpha}{mR} \cos(q - \theta_M) \\ g_2(x_1, x_2) = 1 \\ g_3(x_1, x_2, x_3) = \frac{57,3QSlm_z^{\delta_z}}{J_z} \end{cases} \begin{cases} d_1 = \frac{a_T \cos(q - \theta_T)}{R} \\ d_2 = d_2(c_y^\alpha) \\ d_3 = d_3(m_z^\alpha, m_z^{\omega_z}) \end{cases}$$

2.2. Controller Design

2.2.1. Backstepping controller design

To synthesize the control law for the model (7), the Backstepping technique is utilized. The controller design task is carried out as follows:

Step 1: Define the control error: $e_1 = x_1 - x_{1d}$, Lyapunov function $V_1 = \frac{1}{2}e_1^2$

Take the derivative of V_1 with respect to time: $\dot{V}_1 = e_1 \dot{e}_1 = e_1(f_1 + g_1 x_2 + d_1 - \dot{x}_{1d})$

To ensure stability, choose the desired virtual control:

$$x_{2d} = \frac{1}{g_1}(-k_1 e_1 + \dot{x}_{1d} - f_1 - d_1) \quad (8)$$

Then, $\dot{V}_1 = -k_1 e_1^2 \leq 0$ if constant $k_1 > 0$

Step 2: Define the control error $e_2 = x_2 - x_{2d}$, Lyapunov function $V_2 = V_1 + \frac{1}{2}e_2^2$

Take the derivative of V_2 with respect to time: $\dot{V}_2 = \dot{V}_1 + e_2 \dot{e}_2 = -k_1 e_1^2 + e_2(f_2 + g_2 x_3 + d_2 - \dot{x}_{2d})$

To ensure stability, choose the desired virtual control:

$$x_{3d} = \frac{1}{g_2}(-k_2 e_2 + \dot{x}_{2d} - f_2 - d_2) \quad (9)$$

Then, $\dot{V}_2 = -k_1 e_1^2 - k_2 e_2^2 \leq 0$ if constant $k_1, k_2 > 0$.

Step 3: Define the control error $e_3 = x_3 - x_{3d}$, Lyapunov function $V_3 = V_2 + \frac{1}{2}e_3^2$

Take the derivative of V_3 with respect to time: $\dot{V}_3 = \dot{V}_2 + e_3 \dot{e}_3 = -k_1 e_1^2 - k_2 e_2^2 + e_3(f_3 + g_3 u + d_3 - \dot{x}_{3d})$

Choose the control input u to eliminate undesirable components.

$$u = \frac{1}{b_3}(-k_3 e_3 + \dot{x}_{3d} - f_3 - d_3) \quad (10)$$

Then $\dot{V}_3 = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 \leq 0$. Thus, the system will be globally asymptotically stable according to the Lyapunov criterion when the constants $k_1, k_2, k_3 > 0$.

2.2.2. Design of the AEDO

The ESO plays a crucial role in enhancing the control quality of the missile during target engagement. This observer enables the estimation and compensation of disturbances, ensuring the system operates stably and accurately even under perturbations. In this paper, an AEDO is employed to estimate the disturbance and uncertainty components d_1, d_2, d_3 present in the system equations (7).

With the known model information, the ESO for the guidance loop is designed as follows [4]:

$$\begin{cases} \dot{p}_1 = -\beta_1 p_1 - \beta_1^2 x_1 - \beta_1 (f_1 + g_1 x_2) \\ \hat{d}_1 = p_1 + \beta_1 x_1, \quad \beta_1 > 0 \end{cases} \quad (11)$$

with \hat{d}_1 is an estimate of d_1 .

Similarly, the ESO for the control loop is designed as follows. [4]:

$$\begin{cases} \dot{p}_2 = -\beta_2 p_2 - \beta_2^2 x_2 - \beta_2 (f_2 + g_2 x_3) \\ \hat{d}_2 = p_2 + \beta_2 x_2, \quad \beta_2 > 0 \end{cases} \quad (12)$$

$$\begin{cases} \dot{p}_3 = -\beta_3 p_3 - \beta_3^2 x_3 - \beta_3 (f_3 + g_3 u) \\ \hat{d}_3 = p_3 + \beta_3 x_3, \quad \beta_3 > 0 \end{cases} \quad (13)$$

Where, \hat{d}_2, \hat{d}_3 represents the estimation of d_2, d_3 .

The coefficients β_i are tuning parameters that influence the convergence rate and estimation quality of the observer. In the ESO observers (11), (12), and (13), the coefficients β_i are fixed values. When the system undergoes changes and is affected by various uncertainties and disturbances, keeping the coefficients β_i fixed may reduce the accuracy of state and disturbance estimation. To address this issue, we propose an AEDO, where the coefficients β_i are adjusted dynamically based on the error between the estimated state p_i and the actual state x_i .

$$\beta_{ai} = \beta_i + \Delta_i |x_i - p_i| \quad (14)$$

The AEDO with the adaptive parameter β_{ai} adjusted based on the error between the estimated and actual states $|x_i - p_i|$, enables the observer to dynamically respond to estimation errors. In this, the observer reacts quickly to large error variations, while β_{ai} decreases when the error is small, preventing the amplification of measurement noise and improving stability. The adaptive adjustment of β_{ai} enhances the convergence capability of the observer under rapidly changing conditions or strong disturbances. If Δ_i is appropriately chosen, the observer remains stable and converges to accurate values within a short period. By choosing suitable initial values for β_i and the adaptive gain Δ_i , and continuously updating β_{ai} in real-time, the observer can achieve high accuracy and strong adaptability to dynamic disturbance environments.

And the ESO (11), (12), (13) become AEDO observers of the following form:

$$\begin{cases} \dot{p}_1 = -\beta_{a1} p_1 - \beta_{a1}^2 x_1 - \beta_{a1} (f_1 + g_1 x_2) \\ \hat{d}_1 = p_1 + \beta_{a1} x_1, \quad \beta_{a1} > 0 \end{cases} \quad (15)$$

$$\begin{cases} \dot{p}_2 = -\beta_{a2} p_2 - \beta_{a2}^2 x_2 - \beta_{a2} (f_2 + g_2 x_3) \\ \hat{d}_2 = p_2 + \beta_{a2} x_2, \quad \beta_{a2} > 0 \end{cases} \quad (16)$$

$$\begin{cases} \dot{p}_3 = -\beta_{a3}p_3 - \beta_{a3}^2x_3 - \beta_{a3}(f_3 + g_3u) \\ \hat{d}_3 = p_3 + \beta_{a3}x_3, \quad \beta_{a3} > 0 \end{cases} \quad (17)$$

2.2.3. Design of the optimal backstepping controller (BLQR)

In the control expressions (8), (9), and (10), the initial control gains k_i are computed as fixed values to ensure system stability. However, during the control process, time-varying uncertainties and disturbances may degrade control accuracy. Using the LQR controller to modify and optimize the tuning parameters k_1, k_2, k_3 in the expressions (8), (9), and (10) instead of manual selection to achieve the highest control performance with the objective of reducing the missile interception time. This optimization ensures maximum control performance, with the primary objective of reducing missile interception time. The combination of Backstepping control and LQR results in a robust controller that ensures Lyapunov stability while simultaneously optimizing the missile trajectory and enhancing control energy efficiency.

Express the system of equations (6) in the following state-space form:

$$\dot{x} = \mathbf{A}x + \mathbf{B}u \quad (18)$$

In this formulation, the components that do not contain the control variable u in equation (18) are incorporated into the state matrix \mathbf{A} , while the coefficients related to u are placed in the control matrix \mathbf{B} . The matrices \mathbf{A} and \mathbf{B} represent the linearized dynamic model of the nonlinear system, and has the following form:

$$\mathbf{A} = \begin{bmatrix} -\frac{2\dot{R}}{R} & g_1 & 0 \\ 0 & -\frac{P + 57,3QSc_y^\alpha}{mV_M} & 1 \\ 0 & \frac{57,3QSlm_z^\alpha}{J_z} & \frac{57,3QSlm_z^{\delta_z}}{J_z} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ \frac{57,3QSlm_z^{\delta_z}}{J_z} \end{bmatrix} \quad (19)$$

The LQR method computes the matrix \mathbf{P} from the continuous-time algebraic Riccati equation:

$$\mathbf{A}^T\mathbf{P} + \mathbf{P}\mathbf{A} - \mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P} + \mathbf{Q} = 0$$

Where: \mathbf{P} is a positive definite symmetric matrix, \mathbf{Q} is a non-negative definite state weight matrix, \mathbf{R} is an input weight matrix, a non-degenerate square matrix. Matrix \mathbf{Q} determines the priority level of minimizing state errors x_1, x_2, x_3 , matrix \mathbf{R} places weight on the control signal to avoid abrupt control. After determining the matrix \mathbf{P} , the optimal values of k_1, k_2, k_3 can be computed using the LQR method as follows:

$$u = -Kx, \quad K = \mathbf{B}^T\mathbf{P} \quad (20)$$

The values k_1, k_2, k_3 optimized by the LQR algorithm will serve as the control parameters for the Backstepping controller. This approach generates the control signal u to adjust the system along an optimal trajectory, minimizing the missile interception time.

When using the LQR method, it is necessary to solve an optimization problem to determine the control signal u such that the following cost function is minimized:

$$J = \int_0^\infty (x^T\mathbf{Q}x + u^T\mathbf{R}u)dt \quad (21)$$

3. EXPERIMENT AND DISCUSSION

3.1. Simulation data

To evaluate the performance of the designed controller for the IGC model, numerical simulations are conducted for two scenarios: a target with a constant velocity and a maneuvering target with varying acceleration. A guided missile with assumed parameters is considered for the analysis [4]: The initial relative distance between the missile and the target is $R_0 = 10 \text{ km}$; The initial LOS angle is $q_0 = 30^\circ$; The constant velocity for missile is assumed to be $V_M = 500 \text{ m/s}$; The initial state angles of the missile are $\alpha_0(0) = 0$, $\delta_z(0) = 0$; The initial flight path angle of the missile is $\theta_M(0) = 45^\circ$; The constant velocity for target is assumed to be 250 m/s $V_T = 250 \text{ m/s}$; The initial flight path angle of the target is $\theta_T(0) = 120^\circ$.

The missile model parameters are as follows:

$$\frac{57,3Qsc_y^\alpha}{mV_m} = 0,3487 ; \frac{57,3Qslm_z^\alpha}{J_z} = -17,801 ; \frac{Qsl^2m_z^{w_z}}{J_zV_m} = -0,2741 ; \frac{57,3Qslm_z^{\delta_z}}{J_z} = -31,267$$

The actuator dynamics is approximated as a first-order lag system with a time constant of 0.01s and a control limit of $|\delta_z| \leq 20^\circ$.

The initial design coefficients for the proposed IGC law are as follows:

$$k_1 = 0,4 ; k_2 = 4 ; k_3 = 12 ; \beta_1 = 5, \beta_2 = 10, \beta_3 = 20 \text{ rad} / \text{s}$$

However, the control parameters k_1, k_2, k_3 are optimized by the LQR algorithm in the BLQR controller, Meanwhile, the observer parameters $\beta_1, \beta_2, \beta_3$ are determined using the adaptive algorithm in the AEDO. We conduct simulations and evaluations in the case of a maneuvering target with acceleration $a_T = 15 \sin(0,25t)(\text{m} / \text{s}^2)$, the missile's aerodynamic coefficients vary by $\pm 25\%$, and the typical external disturbances are $d_2 = 0,5 \text{ sint}$ and $d_3 = 0,2 \text{ sint}$.

3.2. Simulation results and analysis

The simulation results are presented in the figures 3 – 8. The simulation results in the guidance loop include the missile and target trajectories (figure 3); the distance between the missile and the target; the LOS angular rate; and the missile acceleration when using the optimal Backstepping controller with the AEDO, as presented in figure 4.

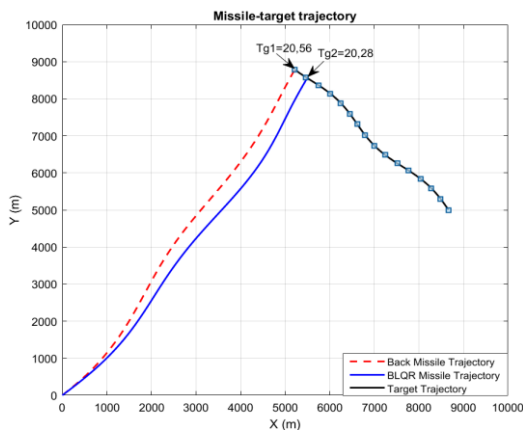


Figure 3. Missile and target trajectories when combining the optimal Backstepping controller with the AEDO.

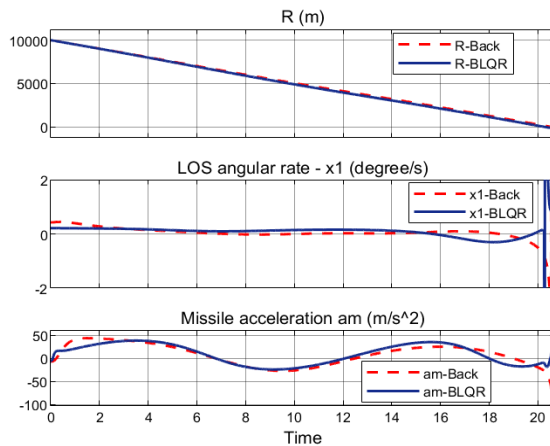


Figure 4. The simulation results in the guidance loop when using the optimal Backstepping control combined with the AEDO.

The simulation results of the missile states in the control loop when using the optimal Backstepping controller with the AEDO are presented in figures 5 – 6.

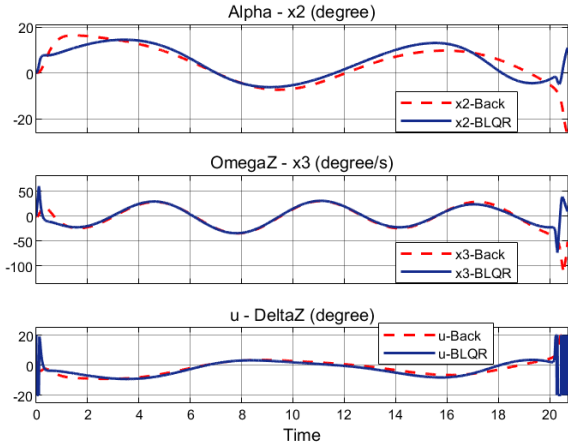


Figure 5. System states in the control loop.

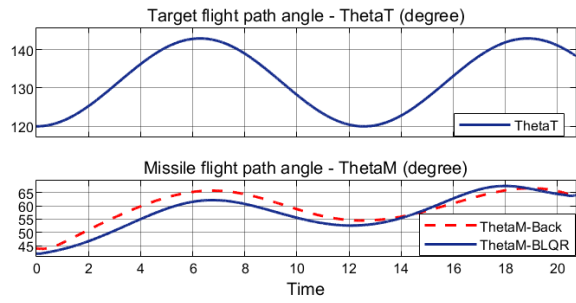


Figure 6. Missile and target trajectory parameters.

The disturbance estimation results using the ESO and the AEDO are presented in figures 7 - 8:

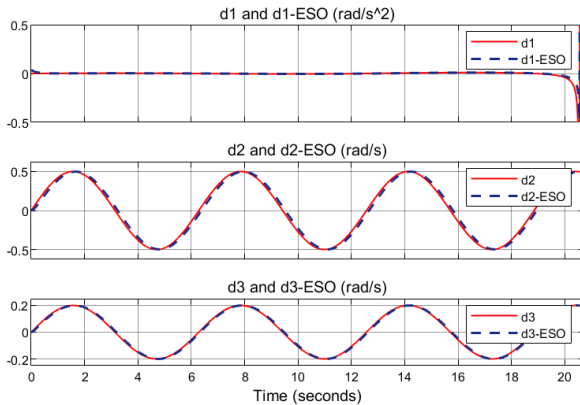


Figure 7. Disturbance and estimated disturbance using the ESO.

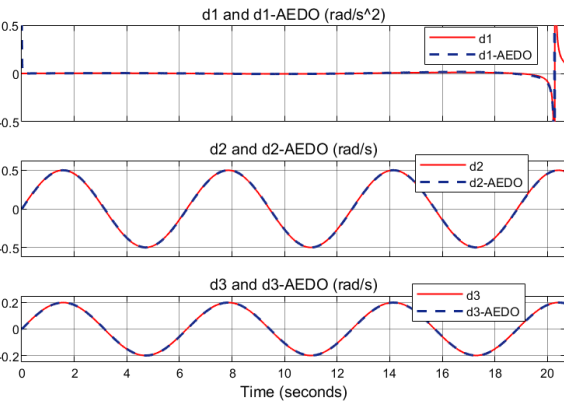


Figure 8. Disturbance and estimated disturbance using the AEDO.

Discussion:

Figure 3 illustrates the missile interception trajectories for two cases: using the optimal Backstepping controller combined with the AEDO and using the conventional Backstepping controller with the ESO. In the proposed approach, the missile trajectory remains smooth without sudden changes, achieving a smaller sliding deviation. Additionally, the engagement time ($T_2=20.28$ s) is shorter compared to the conventional method ($T_1=20.56$ s).

The LOS angular rate exhibits variations in the final phase; however, it still converges toward zero (figure 4). The angle of attack α changes while remaining within the permissible range (figure 5). The missile trajectory angle adjusts correspondingly to the target's motion trajectory.

The AEDO features self-tuning parameters, the estimated disturbance values closely track the actual values, even at points with significant fluctuations. The adaptive observer improves estimation accuracy and minimizes deviations compared to the conventional extended method, especially in the presence of strong and rapidly varying disturbances.

4. CONCLUSIONS

The paper presents a control law design method for integrated missile guidance and control based on the optimal Backstepping control method and an AEDO. The control law is synthesized using the Backstepping approach, ensuring the global stability of the system. By integrating the LQR technique with the AEDO, the method achieves more accurate disturbance estimation and effective disturbance compensation. As a result, the system's performance is enhanced, which leads to reduced tracking errors and a shorter time for the missile to reach the target. Simulation results and analysis confirm the validity of the proposed method in reducing response time and improving accuracy when intercepting maneuvering targets.

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TÓM TẮT

Tổng hợp bộ điều khiển Backstepping tối ưu với bộ quan sát mở rộng thích nghi cho hệ thống điều khiển tên lửa

Bài báo trình bày thiết kế điều khiển Backstepping tối ưu (BLQR) và bộ quan sát nhiễu mở rộng thích nghi (AEDO) nhằm cải thiện chất lượng điều khiển và khả năng ước lượng nhiễu trong các hệ thống phi tuyến, bất định. Bộ điều khiển BLQR được sử dụng để xử lý các yếu tố phi tuyến, bất định và tối ưu hóa chất lượng điều khiển, trong khi bộ quan sát AEDO giúp ước lượng và bù nhiễu hiệu quả trong hệ thống điều khiển tên lửa. Các tác giả chứng minh tính ổn định của hệ thống dựa trên lý thuyết ổn định Lyapunov và thực hiện các mô phỏng trên MatLab/Simulink. Các kết quả mô phỏng đã khẳng định tính đúng đắn của phương pháp đề xuất.

Từ khóa: Điều khiển tên lửa; Điều khiển Backstepping; LQR; Bộ quan sát nhiễu mở rộng thích nghi.