

Robust Control System for Missiles in the Presence of Uncertainty and Disturbances: A Comprehensive Review

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Abstract

In today's warfare and defense systems, when precise and quick maneuvering is essential for mission accomplishment, missiles play a critical role. Nonetheless, the intricacy of missile dynamics by itself, combined with external disruptions and unpredictabilities in operational circumstances, provides challenging but ambitious conditions for achieving precise trajectory tracking and robust flight control. Missiles perform in highly dynamic and uncertain environments where factors such as aerodynamic disturbances, various atmospheric conditions, and sensor inaccuracies can drastically impact their trajectory and effectiveness. Robust control systems are designed to mitigate those demanding situations by means of incorporating techniques that can adapt to uncertainties and disturbances in real-time, ensuring stable and precise control all through the flight trajectory. Without robust control mechanisms, missiles may exhibit poor tracking accuracy, reduced stability, and compromised reliability, leading to diminished mission success rates and increased susceptibility to interception or countermeasures. In this paper various robust control approaches have been explored, including nonlinear disturbance observer-based control, hybrid control strategies, extended state observer-based control, backstepping control, and finite-time control methods. Each approach is analyzed in terms of its theoretical foundations, implementation details, benefits, obstacles and also discusses the realistic implications and capacity applications of these robust manipulate structures in enhancing the overall performance and reliability of missile steering and manage system.

Keywords: Autopilot, disturbance observer, backstepping control, extended state observer, ballistic missile

INTRODUCTION

Missiles play a vital position in modern warfare and defense systems, where unique and agile maneuvering is crucial for mission success. However, the inherent complexity of missile dynamics, coupled with environmental disturbances and uncertainties in operating situations, affords ambitious

demanding situations for attaining accurate trajectory tracking and strong flight control. Uncertainties in missile dynamics can arise from diverse assets, including aerodynamic variations, propulsion machine dynamics, structural flexibility, and environmental elements together with wind gusts and atmospheric disturbances. These uncertainties can extensively degrade the performance of traditional control structures, leading to suboptimal trajectory monitoring and compromised task goals. Outside disturbances, together with gusts, turbulence, and maneuvers by means of hostile targets, further exacerbate the demanding situations faced by missile steering and

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control systems. These disturbances introduce unpredictable perturbations into the gadget, necessitating robust management techniques able to mitigate their outcomes and making sure sturdy performance beneath various running situations. In response to these challenges, sturdy control methodologies have emerged as a promising approach to enhance the overall performance and resilience of missile steering and control structures. Robust management techniques provide the capability to layout controllers that hold stability and gain desired performance specifications notwithstanding uncertainties and disturbances. Additionally, robust control systems contribute to increased operational flexibility, enabling missiles to adapt swiftly to evolving threats and mission objectives while ensuring safe and reliable operation. The design and implementation of robust control systems for missiles have become increasingly vital in current defense situations, where trajectory monitoring and stable flight management are paramount for mission fulfillment.

A non-linear disturbance observer-based robust control (NDOBRC) method is designed to deal with disturbances and discontinuous uncertainties in nonlinear systems. This approach integrates a non-linear disturbance observer with a composite control law to eliminate the effects of disturbances from output channels. The existing disturbance observer-based control (DOBC) methods are used primarily when the disturbances and uncertainties meet matching conditions, entering the system in the same direction at the control inputs [1]. A robust hybrid control strategy is developed for the longitudinal autopilot system of a ballistic missile to enhance the stability and response of missile during boost phase. This method combines different control methods in a hybrid system, using their complementary strengths to effectively limit the uncertainty and disturbances in missile dynamics. Current longitudinal autopilot uses time-invariant passive resistor-inductor-capacitor (RLC) network, which does not consider time-varying dynamics of missile. This can lead to instability in closed-loop systems during large disturbances and dynamic uncertainties.

The method uses gain-scheduling adaptive control strategies which allows real-time adjustment of the controller gain based on missile performance. The proposed longitudinal controller is tested through various scenarios for the validated nonlinear dynamic flight model of the real ballistic missile system with autopilot exposed to external disturbances [2]. Extended state observer (ESO) technique is used to design robust pitch autopilot for tactical missiles to estimate and mitigate the effect of uncertainties and disturbances in the system. ESO is applied to ascertain both system states and uncertainties that allows the robustification of input-output linearization-based controller designed for the nominal system. This design does not depend on accurate plant models or uncertainty information, and thus it can estimate uncertainties effectively as well as adequately estimating states to meet specified tracking performance in real-world circumstances where there is considerable uncertainty [3]. The paper [4] discusses the development of a highly accurate height control sub-system for sea-skimming missiles and addresses the issues of sea waves as well as model inaccuracy. Sea-skimming missiles need precise height control mechanisms to operate in lower altitudes. Even in the event of rough sea conditions, the missiles need to fly closer to the surface of the sea without being detected to cause as much damage to enemy ships as possible. The system is prone to ocean waves disturbances, and if not properly treated the missile might dismount into the water.

Moreover, uncertainties connected with aerodynamic coefficients and autopilot models are additional factors which impair the quality of the flight dynamics. The ESO-based approach assists the observer to forecast changes and the system states attenuating uncertainties and external disturbances that are treated as extended states of the original system. This approach of estimating and stopping the real-time disturbances in a disturbance rejection feedback control with the main aim of the system being to meet the objectives is the best that works optimally. [5] This paper provides a complete analysis on the design of a robust nonlinear stabilizer for a highly maneuverable missile. The system is concerned with the results of the six-degree-of-freedom, nonminimum phase, uncertain, and time-varying dynamics of air-to-air tail-controlled missiles with un-modeled un-symmetric air pitches. Though the proposed model has to deal with the system's nonlinearities and uncertainty, especially in bank-to-turn and skid-to-turn

approaches, it attempts to create robust backstepping. Implementation of the detailed dynamics model of the missile is crucial for the designing of the robust controller. This model reflects the intricate dynamics of the missile, enabling a more accurate control strategy. The paper [6] introduces a new design of the Acceleration tracking pitch autopilot for a tail-controlled, skid to turn tactical missile. The control methodology amalgamates the time-scale separation, feedback linearization (FL) and extended state observer (ESO) techniques to guarantee a robust performance when uncertainties, disturbances, un-modeled dynamics, measurement noises, control input saturation, and rate saturation occur. The phenomena of pitch-plane dynamics is split into fast pitch-rate dynamics and slow acceleration dynamics by taking the time-scale separation of these phenomena as an advantage. Feedback linearizing controllers are designed and applied to each subsystem as independent units. ESOs are employed to calculate uncertainties in every individual sub-system and these uncertainties are utilized to improve the response speed of the linear controllers designed for the sub-systems in nominal conditions. One of the important benefits of this design lifestyle is that no exact model of the plant is required and no detailed information on uncertainties and disturbances is required. The paper [7] begins by presenting the problems related with conventional missile guidance and control systems, such as softness to disturbances and uncertainties.

It stresses the necessity of developing the latest control techniques to tackle these challenges and to increase the effectiveness of the missile systems. The proposed method consists of two main components: ERG (Explicit Reference Governor) and the disturbance observer. The ERG generates control commands by reference trajectory tracking while taking into account system constraints with disturbance consideration. It provides for the missile follows the given trajectory while being viable for conditions change and disturbances in real time. The role of the disturbance observer is to estimate and compensate for the disturbance effects that affect the missile's dynamics. [8] Proposes a novel method of improving accuracy of the representative of the missile acceleration autopilot. The implemented method is using an Enhanced Extended State Observer (ESO) which estimates the disturbances and uncertainties and so improves the system robustness and accuracy of the autopilot system.

The paper begins by pinpointing the challenges which are being faced by traditional missile acceleration autopilots and emphasizes the great need for reliable control processes that can reduce uncertainties and give a successful flight. It underlines the limitations of the existing control methods and therefore leads to the need for advanced techniques which will find a way to boost the performance of the acceleration autopilot. The method to be used is that of the extended state observer (ESO) which is meant to estimate both the states of the missile system and the uncertainties/disturbances which lump together representing its dynamics and response. The study [9] addresses the challenges associated with designing robust autopilots for missiles, considering time-varying parameters and uncertainties in the system. The paper proposes a novel approach based on robust backstepping control to address these issues and enhance the performance of missile autopilots and highlights the importance of robust control design for missile autopilots, particularly in the presence of time-varying parameters and uncertainties inherent in missile dynamics. It emphasizes the need for advanced control techniques to ensure accurate and stable flight control under varying operating conditions.

The proposed method revolves around the concept of robust backstepping control, which is a nonlinear control technique suitable for systems with uncertainties and disturbances. [10] Novel approach to designing robust finite-time control strategies for guidance laws, taking into account uncertainties inherent in missile dynamics. The paper emphasizes the critical importance of robust control techniques in ensuring accurate and reliable guidance for missiles, especially when facing dynamic and uncertain operating conditions. The proposed method centers on the development of robust finite-time control algorithms tailored specifically for guidance laws used in missile systems. Finite-time control aims to achieve stabilization and tracking objectives within a finite time horizon, making it particularly suitable for applications requiring rapid response and robust performance. The paper provides a detailed exposition of the mathematical framework underlying the proposed robust

finite-time control strategy. It begins by formulating the guidance law with uncertainties in missile dynamics, identifying the key challenges associated with ensuring robustness and accuracy in trajectory tracking. The proposed control approach leverages robust control techniques, such as sliding mode control and disturbance observer-based control, to address uncertainties and disturbances in the missile system effectively.

DIFFERENT ROBUST CONTROL TECHNIQUES FOR ENHANCED MISSILE PERFORMANCE AND ANALYSIS

Non-Linear Disturbance Observer-Based Robust Control (NDOBRC)

The NDOBRC method combines a nonlinear feedback controller with a disturbance compensation component. The disturbance compensation is designed primarily to prevent disturbance and the composite control law is designed to include a feedback control law without considering disturbances and a perturbation compensation gain vector is designed to account for and counteract simultaneous disturbances. The method uses a nonlinear disturbance observer (NDOB) to account for unknown disturbances in the system. An NDOB-based disturbance estimate is used in the composite control law to compensate for disturbance. The NDOB acts as a 'patch' to the existing controller, increasing disturbance mitigation and uncertainty resistance, and maintaining nominal performance in the absence of disturbance and uncertainty there. The proposed method is applied to a missile system with nonlinear dynamics, considering disturbances such as external factors and model uncertainties to demonstrate its feasibility and effectiveness under real-world conditions, and its successful application to engineering systems [1].

Hybrid Control Strategies

The robust hybrid control is obtained by designing reduced order linear quadratic regulator (LQR) in conjunction with optimal tuning-compensator. Two kinds of gain scheduling controllers are designed for the longitudinal autopilot are Gain-scheduled optimal tuning PID with actuator constraints and Gain-scheduled optimal LQ in conjunction with optimal tuning compensator. Gain-scheduled optimal tuning-PID with actuator constraints, supplies better response but requires a priori knowledge of the system dynamics. Moreover, the controller has oscillatory response in the presence of dynamic uncertainty. From the point of view of reliable flight control systems design, the purely optimal control design methodologies based on the LQR has good stability properties but may be sensitive to off-nominal conditions and the implementation requires all state variables as feedback, some of which however cannot be easily measured. If an observer is used to reconstruct the state vector from available measurements, then the optimal control system often has much less satisfactory stability property, and the system performance is very much affected by parameter variations as well as satisfactory disturbances. The use of rate gyro is recommended to solve the optimal LQR requirements [2].

Extended State Observer (ESO) Method

ESO estimates both states of the system and uncertainties, taking into account combined impacts of nonlinearities, model errors, external actions and uncertainties. By knowing the uncertainty of the whole system and states within it, robustness can be improved in control systems through disturbance rejection or compensation. The controller design follows an approach called Input-Output Linearization (IOL) where discrepancies related to aerodynamic derivatives, modeling inaccuracies, and external disturbances are lumped together as overall uncertainty to be estimated. In controller design, ESO is integrated to estimate composite uncertainty along with output derivative in a unified fashion. The design based on ESO does not need exact system models or knowledge about uncertainty characteristics, but it is still robust enough and computationally efficient. Estimated uncertainties from ESO are used to strengthen input-output linearization-based controller designed for the nominal system [3]. Functional Block Diagram of the ESO-Based Controller is shown in Figure 1.

Extended state-observer theory is proposed as an innovative method to estimate and remove sea-wave movements in real time, which helps the missile track a low skimming trajectory precisely.

and autopilot models are additional factors which impair the quality of the flight dynamics. The ESO-based approach assists the observer to forecast changes and the system states attenuating uncertainties and external disturbances that are treated as extended states of the original system. This approach of estimating and stopping the real-time disturbances in a disturbance rejection feedback control with the main aim of the system being to meet the objectives is the best that works optimally [4].

Backstepping Control

The proposed backstepping control approach offers a potent solution to the complicated dynamics of a remote guided missile with high maneuverability. The controller can exhibit top level performance in maintaining stability and tracking targets in difficult situations by using advanced control techniques and smartly dealing with uncertainties. The application of backstepping with multiple input-multiple output is the key to the successful handling of large-scale nonlinearities and complex phenomena involving a large extent of uncertainty. Therefore, it is a fundamental prerequisite for assuring stable performance in systems where the parameters are quick to vary, disturbances appear, and unmodelled dynamics occur. The uncertainties especially handled by the aerodynamic coefficients using bounding functions that are derived from the gained experience in the past and the a priori information. The robust sigmoid like control functions are applied for the zero order hold large compact filtering system to overcome uncertain terms and improve the system robustness. The controller to be implemented, ideally must be uniformly asymptotically stable, if not there will be some deviation from the specified objective within a specific level of performance in both bank-to-turn and skid-to-turn conditions [5].

The key idea behind backstepping control is to design a series of Lyapunov functions and control laws recursively to stabilize the system and reject disturbances effectively. It provides a detailed exposition of the mathematical formulation of the robust backstepping control scheme tailored specifically for missile autopilots. It elucidates the design procedure, including the derivation of Lyapunov functions, the selection of control gains, and the synthesis of control laws to account for time-varying parameters and uncertainties [9].

Finite Time Control Method

Combining linear extended state observer (LESO) and adaptive non-singular fast terminal sliding mode method, especially for dealing with existing uncertainties including time-varying parametric perturbation and nonparametric disturbances in high order line-of-sight rates and target acceleration. Sliding mode control offers robustness against uncertainties by driving the system trajectory onto a predefined sliding surface, while disturbance observer-based control estimates and compensates for external disturbances in real-time [10].

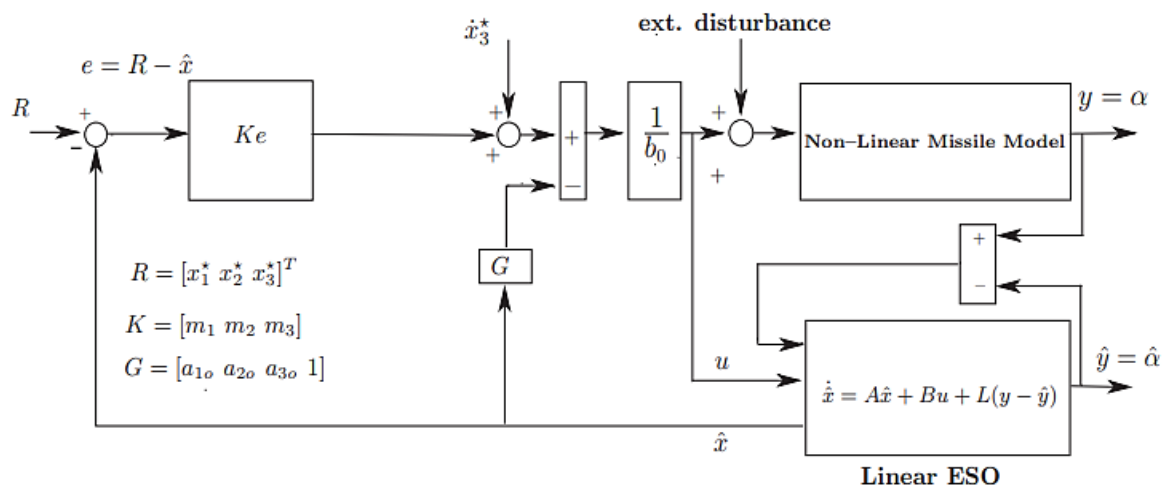


Figure 1. Functional block diagram of the ESO-based controller.

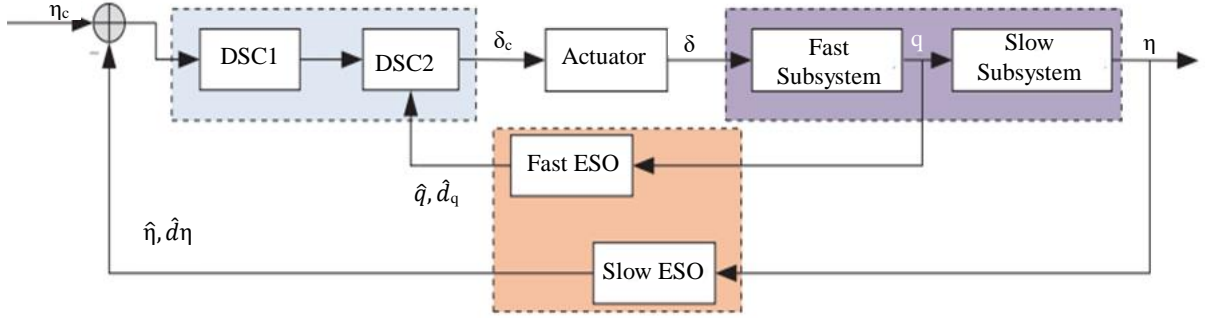


Figure 2. Functional block diagram of the ESO-based controller.

MATHEMATICAL FORMULATION AND ANALYSIS

ESO-Based Controller

The ESO can estimate the uncertainties and the states of the system, which can enable disturbance rejection or compensation. Unlike traditional observers, the ESO estimates the effect of uncertainties, unmodeled dynamics, and external disturbances acting on the system as an extended state of the original system. Therefore, in this section, an ESO-based controller is proposed to enhance the robustness of the autopilot, as shown in Figure 2.

Consider the following single-input single-output dynamic system as,

$$\dot{x}_1 = a_o x_1 + b_o \mu + d \quad (1)$$

Choosing the disturbance ‘d’ as the extended state variable, we can rewrite the extended order system as,

$$\begin{aligned} \dot{x}_1 &= a_o x_1 + x_2 + b_o \mu \\ \dot{x}_2 &= h \end{aligned} \quad (2)$$

$$y = x_1$$

where ‘h’ is the disturbance change rate and ‘y’ is the output of the system.

As shown in Figure 2, the outputs of the slow ESO and fast ESO can be used to foster the design of the DSC controller. So, we can write

$$\bar{x}_2 = \frac{1}{b_{\eta o}(\alpha)} \left(-a_{\eta o}(\alpha) \hat{\eta} - \frac{\hat{\eta} - \eta_c}{\tau_s} - B_1 \cdot \text{sgn}(\hat{\eta} - \eta_c) - d_{\hat{\eta}} + \dot{\eta}_c \right) \quad (3)$$

$$\mu = \frac{1}{b_{q o}(\delta)} \left(-a_{q o}(\alpha) - \frac{\hat{q} - q_c}{\tau_f} - B_2 \cdot \text{sgn}(\hat{q} - q_c) - d_{\hat{q}} + \dot{q}_c \right) \quad (4)$$

Closed-loop stability analysis:

Define the observation errors in the acceleration and disturbance for the slow ESO as,

$$\begin{aligned} e_{\eta o 1} &= \eta - \hat{\eta} \\ e_{\eta o 2} &= d_{\eta} - \hat{d}_{\eta} \end{aligned} \quad (5)$$

Lyapunov equation for pitch rate tracking: $V_q = \frac{1}{2} S_q^T S_q$ and the stable region of the fast subsystem can be obtained as,

$$|S_q^T| \leq \tau_f (|e_{qo2}| + |e_{LRf}| - B_2) \quad (6)$$

Lyapunov equation for the acceleration tracking: $V_\eta = \frac{1}{2} S_\eta^T S_\eta$ and the stable region of the slow subsystem can be obtained as,

$$|S_\eta^T| \leq \tau_s (|e_{\eta o2}| - B_1) \quad (7)$$

Combining (6) and (7), the stable region of the ESO-based dynamic surface controller can be obtained as,

$$\begin{aligned} B_1 &\geq |e_{\eta o2}| \\ B_2 &\geq |e_{qo2}| + |e_{LRf}| \end{aligned} \quad (8)$$

In all, the DSC controller parameters B_1 and should B_2 be selected according to the observation level of the ESO relative to the disturbance. On the other hand, the controller parameters should be as small as possible to avoid chattering of the control signals.

CONCLUSION

The review paper comprehensively analyzes the development of robust control systems for missiles in the presence of uncertainty and disturbances. Through an in-depth examination of various research articles, it is evident that researchers have made significant strides in addressing the challenges inherent in missile dynamics and operation. The reviewed papers showcase a wide range of techniques, including non-linear disturbance observer-based control, hybrid control strategies, extended state observer-based designs, and robust backstepping methods, among others. These techniques aim to enhance stability, tracking accuracy, resilience to dynamic variations, and overall performance of missile systems. By integrating advanced control methodologies and leveraging disturbance observers, researchers have demonstrated remarkable progress in mitigating the adverse effects of uncertainties and disturbances, thereby bolstering the effectiveness and reliability of missile guidance and control systems. However, further research is warranted to explore novel approaches and address emerging challenges to ensure the continued advancement of robust control systems for missiles in diverse operational environments.

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