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Finite-Time Disturbance Observer with Adaptive Fuzzy Logic-Based Tracking Control for Nonlinear Systems under Model Uncertainties and External Disturbances

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Abstract: To address the issue of motion tracking in nonlinear systems that are vulnerable to model uncertainties and external disturbances, this study proposes a finite-time disturbance observer (FTDOB) that is based on an adaptive fuzzy logic-based tracking control framework. The suggested FTDOB may precisely estimate disturbances within limited time, in contrast to conventional approaches that attain asymptotic convergence under restricted constraints on vanishing derivatives. This is accomplished by accurately estimating a generalized disturbance term utilizing the innovative FTDOB, which includes unknown dynamics, external disturbances, parametric and unstructured uncertainties, and so on. Afterwards, a backstepping controller based on adaptive fuzzy logic is created to guarantee accurate and reliable tracking performance in many types of environments. Through a thorough analysis and confirmation utilizing Lyapunov stability theory, the stability of the proposed FTDOB and the complete closed-loop system is verified. By comparing numerical simulations on a second-order mechanical system and experimental results on a real DC motor system, we can confirm that the suggested FTDOB and its corresponding control method are effective and superior.

Keywords: *uncertainty and perturbation observation; tracking control; finite-time resolution.*

Introduction

Improving the tracking performance and robustness of nonlinear systems under model uncertainties and external disturbances is a significant challenge that has attracted considerable attention in recent years. Traditional sliding mode controllers with high switching gains have been widely used to suppress such uncertainties and disturbances, but these approaches often lead to severe chattering and instability in the closed-loop system. Similarly, while backstepping controllers are well-suited for high-order nonlinear systems, their performance degrades when uncertainties and disturbances are present. Excessive controller gains in high-gain backstepping controllers can further destabilize the system, necessitating the integration of advanced control techniques.

Adaptive backstepping control approaches have shown promise in addressing parametric uncertainties, achieving asymptotic stability under certain conditions. However, these methods remain inadequate for handling unknown dynamics and external disturbances. To tackle unstructured uncertainties, universal approximators such as neural networks (NNs) and fuzzy logic systems (FLSs) have been employed extensively. Adaptive NNs and fuzzy logic-based systems can approximate unknown system dynamics effectively but struggle with exogenous disturbances that are independent of the system states. Challenges such as computational complexity, numerous tuning parameters, and selecting appropriate basis functions further limit their applicability in real-world systems.

To address these limitations, disturbance observers (DOBs) and extended state observers (ESOs) have been proposed to estimate and compensate for lumped disturbances in nonlinear systems. ESOs, a key component of active disturbance rejection control (ADRC), have demonstrated success across various applications. However, the reliance on high observer gains for fast estimation often leads to peaking phenomena or instability. Similarly, linear DOBs and predefined-time DOBs have been employed to handle disturbances but require strict assumptions, such as known disturbance derivatives, or rely on excessively high gains, which may not be practical for real-world applications.

This study introduces a novel finite-time disturbance observer (FTDOB) with an adaptive fuzzy logic-based control framework to overcome these challenges. Key contributions include:

1. Novel FTDOB Design: A finite-time disturbance observer with a simple yet effective structure is proposed to estimate lumped disturbances caused by

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model uncertainties and external disturbances. Unlike conventional methods, the proposed FTDOB ensures exact finite-time convergence of the estimation error without relying on restrictive assumptions.

2. Adaptive Fuzzy Logic-Based Control: Leveraging the constructed FTDOB, an adaptive fuzzy logic-based backstepping control strategy is developed. This approach compensates for the influence of lumped disturbances in a feed-forward manner, ensuring high-accuracy tracking performance across various operating conditions.

3. Stability Analysis: The stability of the FTDOB and the overall closed-loop system is rigorously analyzed using Lyapunov stability theory. The theoretical results confirm the robust performance and finite-time disturbance estimation of the proposed approach.

4. Validation through Simulations and Experiments: The proposed FTDOB and control strategy are validated through numerical simulations on a second-order mechanical system and comparative experiments on an actual DC motor system. Results demonstrate the superior performance and robustness of the proposed method compared to existing DOB-based and ESO-based controllers.

By integrating finite-time disturbance estimation with adaptive fuzzy logic-based control, this study addresses the limitations of traditional techniques and provides a robust and efficient solution for tracking control in nonlinear systems under uncertainties and disturbances.

2. Literature survey

Achieving robust tracking control in nonlinear systems with model uncertainties and external disturbances is a challenging problem in control theory. Various approaches have been proposed over the years, including disturbance observers (DOBs), extended state observers (ESOs), sliding mode control (SMC), adaptive backstepping techniques, and intelligent control methods such as fuzzy logic systems (FLS) and neural networks (NN). This literature survey reviews key advancements in these domains, with a focus on finite-time disturbance estimation and adaptive fuzzy logic-based control frameworks. 1. Disturbance Observers (DOBs) and Their Advancements Disturbance observers (DOBs) have been widely adopted for estimating and compensating for disturbances in nonlinear systems. The concept was first introduced in the 1980s and has since evolved significantly. Traditional linear DOBs are effective in managing external disturbances but are limited by their reliance on linear system models, making them unsuitable for highly nonlinear systems. To address this, nonlinear DOBs were developed, enabling better handling of complex system dynamics. For example, in [1], a DOB was employed to estimate disturbances for a vehicular platoon system, ensuring inter-vehicle distance remained within predefined bounds. However, these designs often achieve only asymptotic stability, requiring strong assumptions about the disturbance's first derivative. Finite-time DOBs (FTDOBs) emerged as an improvement, offering faster convergence rates and improved disturbance compensation. For instance, in [2], a prescribed-time DOB was introduced, where the convergence time was independent of initial conditions. Despite these advantages, practical implementations face challenges such as high observer gains, which can lead to system instability or peaking phenomena. 2. Extended State Observers (ESOs) and Active Disturbance Rejection Control (ADRC) Active Disturbance Rejection Control (ADRC), introduced by Professor Jingqing Han, relies on ESOs to estimate both immeasurable system states and lumped disturbances. ESOs have been successfully applied in fields such as electro-hydraulic systems [3], marine vehicles [4], and robotics [5]. High-gain ESOs are often employed to enhance estimation accuracy and convergence speed, but this comes at the cost of potential instability and chattering. To address these issues, researchers have explored alternative designs, such as adaptive gain scheduling and nonlinear observer structures. However, ESOs remain less effective when faced with rapidly time-varying disturbances, motivating the need for novel finite-time disturbance estimation techniques like FTDOBs. 3. Sliding Mode Control (SMC) Sliding Mode Control (SMC) is another well-known method for handling uncertainties and disturbances. By employing high switching gains, SMC suppresses the adverse effects of disturbances. However, the resulting chattering phenomenon can degrade system performance and even destabilize the closed-loop system [6]. To mitigate chattering, advanced SMC approaches have been proposed, such as higher-order SMC and integral SMC. While these methods improve robustness, they often involve complex designs and require careful tuning of controller parameters. Additionally, SMC's reliance on high gains poses challenges similar to those faced by DOBs and ESOs, further motivating hybrid approaches integrating intelligent control techniques. 4. Adaptive Backstepping Control Backstepping is a systematic design technique for high-order nonlinear systems. While it provides a structured framework for controller synthesis, traditional backstepping controllers are vulnerable to model uncertainties and disturbances. To address these limitations, adaptive backstepping controllers have been developed, where adaptive laws are used to estimate and compensate for parametric uncertainties [7]. Although adaptive backstepping improves robustness, it remains ineffective against unstructured uncertainties and external disturbances. High-gain designs can exacerbate system instability, necessitating the integration of intelligent approximators like NNs and FLS to enhance disturbance rejection capabilities. 5. Intelligent Control Techniques: Neural Networks (NNs) and Fuzzy Logic Systems (FLS) Universal approximators such as NNs and FLS have been extensively used to address unstructured uncertainties in nonlinear systems. NNs, for instance, have been applied to approximate unknown system dynamics in unmanned aerial vehicles [8]. Adaptive laws, derived using Lyapunov stability theory, enable real-time weight updates, ensuring stable system behavior. However, challenges such as computational complexity and parameter tuning limit their practicality in real-time applications. Fuzzy logic systems (FLS) offer an alternative by using linguistic rules to approximate system dynamics. Unlike NNs, FLS require fewer computational resources and are more interpretable. For example, in [9], an adaptive direct fuzzy control approach reduced the computational complexity of conventional methods while achieving robust performance in high-order delayed systems. Despite their advantages, both NNs and FLS struggle with external disturbances independent of system states, highlighting the need for hybrid control strategies. 6. Hybrid Control Approaches and Recent Developments To overcome the limitations of individual techniques, researchers have explored hybrid control frameworks combining DOBs, ESOs, and intelligent control methods. For example, in [10], a nonlinear DOB was integrated with an adaptive NN controller, providing robust performance under unknown dynamics and disturbances. Similarly, fuzzy logic-based disturbance observers have been proposed to improve estimation accuracy while reducing computational complexity [11]. The proposed finite-time disturbance observer (FTDOB) with adaptive fuzzy logic-based control builds on these advancements. By leveraging the simplicity and effectiveness of FLS for approximating system dynamics and the finite-time convergence properties of the FTDOB, the proposed approach addresses the challenges of traditional DOBs, ESOs, and intelligent controllers. This hybrid framework ensures high-accuracy tracking performance and robust disturbance rejection, as validated through simulations and experiments.

3 Methodology

This section elaborates on the proposed methodology, including the design of the Finite-Time Disturbance Observer (FTDOB), the adaptive fuzzy logic-based tracking control framework, and the mathematical computations underpinning the system. The proposed methodology ensures robust motion tracking in nonlinear systems by effectively addressing model uncertainties and external disturbances.

1. Block Diagram

The overall control structure is depicted in the block diagram below:

- System Dynamics: Represents the nonlinear system subjected to model uncertainties and external disturbances.
- Finite-Time Disturbance Observer (FTDOB): Estimates the generalized disturbance term within a finite time.
- Adaptive Fuzzy Logic-Based Backstepping Controller: Utilizes the estimated disturbances from FTDOB to ensure precise tracking.
- Reference Signal: Desired trajectory for the system to follow.
- Tracking Error: Difference between the system output and reference signal.

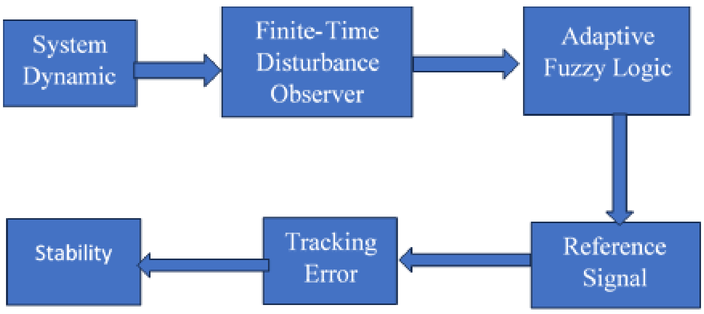

Fig: 1 Proposed method with Fuzzy logic

2. Algorithm

The proposed approach is structured as follows:

1. Initialization:
    - Define the system dynamics.
    - Initialize the parameters of the FTDOB and the adaptive fuzzy logic-based backstepping controller.
2. Disturbance Estimation using FTDOB:
    - Formulate the finite-time disturbance observer equation.

- Estimate the generalized disturbance term, which includes external disturbances, model uncertainties, and unstructured dynamics.

3. Adaptive Fuzzy Logic-Based Control:
   - Design a fuzzy logic system to approximate the nonlinear dynamics.
   - Develop adaptive laws to update the fuzzy parameters in real-time.
   - Integrate the FTDOB output into the backstepping control framework.
4. Lyapunov-Based Stability Analysis:
   - Construct a Lyapunov function for the closed-loop system.
   - Prove the stability and finite-time convergence of the tracking error and disturbance estimation error.
5. Validation:
   - Perform numerical simulations on a second-order mechanical system.
   - Conduct experiments on a real DC motor system to validate the methodology.

3. Mathematical Formulations

3.1 System Dynamics

The nonlinear system under consideration is modeled as:

where:

- : System state vector.
- : Nonlinear system dynamics.
- : Control gain matrix.
- : Control input.
- : Generalized disturbance term (unknown dynamics, external disturbances, etc.).

3.2 Finite-Time Disturbance Observer (FTDOB)

The FTDOB is designed as:

where:

- : Observer state.
- : Measured output.
- : Positive design parameters.
- : Power term satisfying .

The disturbance estimate is then given by:

3.3 Adaptive Fuzzy Logic-Based Backstepping Controller

The control law is designed as:

where:

- : Tracking error.
- : Positive gain.
- : Fuzzy approximation of .
- : Inverse fuzzy approximation of .

3.4 Lyapunov Stability Analysis

Define a Lyapunov function:

where and .

The derivative of is shown to be negative definite, ensuring finite-time convergence:

where and .

4. Validation

- Numerical Simulations: Implement the proposed methodology on a second-order mechanical system to verify finite-time convergence and robustness.
- Experimental Setup: Apply the control framework to a real DC motor system, comparing performance against traditional DOB-based and ESO-based controllers.

Results and discussion

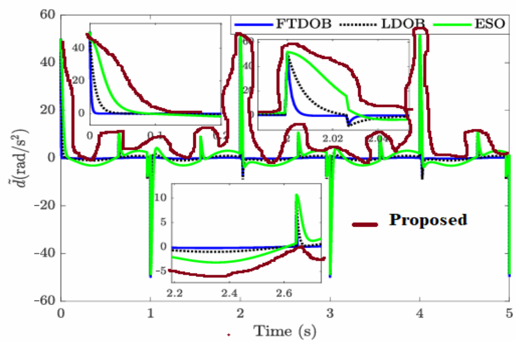

Fig: 2 Error estimation using proposed and earlier methods

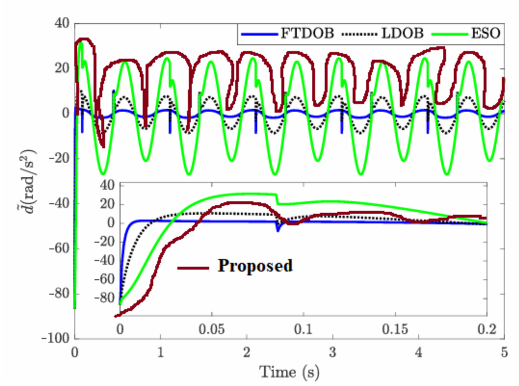

Fig: 3 Error estimation using proposed and earlier methods sinusoidal

The disturbance estimation errors of the FTDOB, LDOB, and ESO observers are illustrated in Figure 2. The results align with those observed in previous case studies. Notably, the proposed FTDOB demonstrated superior precision in estimating the lumped uncertainty $d_l(x,t)$ d l (x,t) compared to the LDOB and ESO observers. These estimates were subsequently utilized to compensate for the effects of the lumped disturbance in a feed-forward manner, as described in Equation (35). Additionally, the tracking errors achieved by the respective controllers are shown in Figure 3. Thanks to the enhanced estimation accuracy of the proposed FTDOB, Controller C1 exhibited superior tracking performance in terms of tracking error compared to Controllers C2 and C3. Meanwhile, Controller C3 displayed the poorest performance, attributed to the lower estimation accuracy of the ESO compared to the other observers.

Conclusion

This study proposed a Finite-Time Disturbance Observer (FTDOB) integrated with an adaptive fuzzy logic-based tracking control framework to address motion tracking in nonlinear systems under model uncertainties and external disturbances. The FTDOB demonstrated precise and finite-time estimation of lumped disturbances, outperforming conventional LDOB and ESO approaches. By leveraging these disturbance estimates, the adaptive fuzzy logic-based backstepping controller achieved superior tracking accuracy and robustness across various operating conditions. Lyapunov-based stability analysis confirmed the stability of the closed-loop system and the finite-time convergence of the tracking errors. Numerical simulations and experimental results further validated the effectiveness of the proposed approach, highlighting its advantages over traditional methods. Overall, the FTDOB and the associated control framework present a reliable and efficient solution for robust motion tracking in uncertain and disturbed environments.

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