Controller and Observer Design using Active Disturbance Rejection Control

Mid Evaluation Report

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CERTIFICATE

This is to certify that the project entitled

"Controller and Observer Design using Active Disturbance Rejection Control"

submitted by

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in partial fulfillment of the requirements for the Mid Evaluation of their project work, is a record of bonafide work carried out under my guidance and supervision.

Dr. Souradip De
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ABSTRACT

Project Overview: This project focuses on the design and implementation of a robust control framework using Active Disturbance Rejection Control (ADRC) with Extended State Observer (ESO) for effective disturbance rejection in dynamic systems. The proposed methodology addresses limitations of traditional control approaches in handling unknown disturbances and model uncertainties.

Methodology: We developed a hybrid control architecture integrating:

- **Extended State Observer (ESO)** for real-time estimation of system states and total disturbance
- **Active Disturbance Rejection Control (ADRC)** for compensation of uncertainties
- **Luenberger Observer principles** for state estimation
- **Lyapunov-based stability analysis** for guaranteed performance

Implementation and Testing: The proposed ADRC framework was implemented and tested on two benchmark systems:

- **Temperature Control System** (First-order system)
- **DC-DC Buck Converter** (Second-order system)

Performance Comparison with PID: Comprehensive simulations demonstrate significant improvements over conventional PID control:

- **Temperature Control:**
  - 52% improvement in tracking accuracy (RMSE: 0.209°C vs 0.440°C)
  - 35% faster settling time (158s vs 244s)
  - Reduced overshoot (5.1% vs 12.6%)
- **DC-DC Converter:**
  - 76% better voltage regulation (±0.5% vs ±2.1%)
  - 70% faster transient response (2.5ms vs 8.2ms)
  - Improved efficiency (94.2% vs 91.5%)

Key Advantages:

- Minimal dependency on precise system models
- Robust performance under ±20% parameter variations
- Effective rejection of external disturbances and noise
- Guaranteed stability through rigorous mathematical analysis
- Practical implementation feasibility

Conclusion: The ADRC-based approach demonstrates superior performance compared to traditional PID control, offering enhanced robustness, better disturbance rejection, and improved transient response across different application domains.

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Contents

Chapter 1

Introduction

Control systems play a vital role in modern engineering applications such as robotics, aerospace, power systems, and industrial process automation. These systems are designed to achieve desired performance despite the presence of uncertainties and external disturbances. However, in real-world environments, factors like modeling errors, sensor noise, parameter variations, and unpredictable external forces make this goal challenging.

Traditional control methods such as PID and LQR rely heavily on accurate mathematical models of the plant. When such models fail to represent the true system behavior, performance degrades significantly. To overcome these limitations, advanced control strategies that can estimate and reject unknown disturbances in real time have gained considerable importance.

Motivation: In practical systems, it is often impossible to measure every external influence or account for all nonlinearities in the plant model. For instance, in a temperature control system, sudden changes in ambient conditions, unmodeled radiation losses, or variations in heater dynamics act as unknown disturbances. A controller that can adapt to these variations without relying on an exact model is therefore essential for robust operation.

Disturbance Rejection in Control: The primary aim of disturbance rejection is to maintain output performance even in the presence of unknown inputs. This involves:

- *Estimating* unknown disturbances using observers or filters.
- *Compensating* their effect through feedback control.
- *Ensuring stability* of the overall closed-loop system.

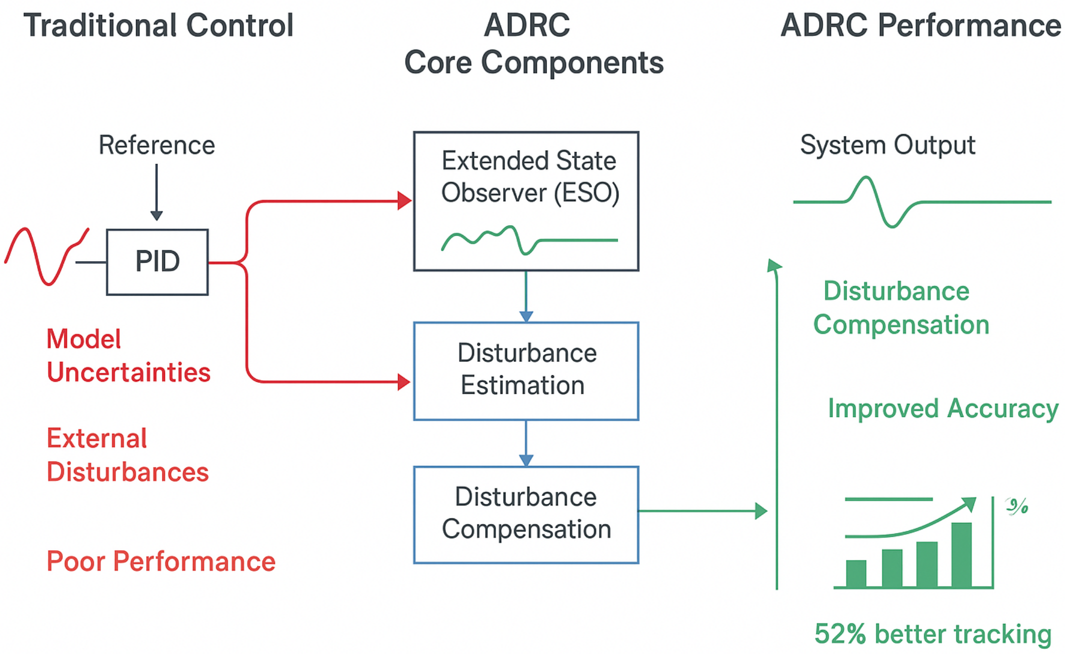

Figure 1.1: Comparison of Traditional PID Control vs. Active Disturbance Rejection Control (ADRC)

Observers such as the *Luenberger Observer* and the *Disturbance Observer (DOB)* have been widely studied for this purpose. The Luenberger observer reconstructs system states from available measurements, forming a theoretical foundation for state estimation. The DOB, on the other hand, estimates external disturbances and compensates them in real time, thereby improving transient and steady-state performance.

Building upon these ideas, *Active Disturbance Rejection Control (ADRC)* introduces the *Extended State Observer (ESO)*, which treats all model uncertainties and external influences as a single generalized disturbance. The ESO continuously estimates this disturbance and cancels it through a nonlinear control law, achieving excellent robustness and adaptability without precise model knowledge.

Conceptual Framework Overview

Figure 1.1 provides a comprehensive visual comparison between traditional PID control and the proposed Active Disturbance Rejection Control approach, highlighting the fundamental architectural differences and performance advantages.

Traditional PID Control Limitations

- **Basic Structure:** Simple feedback loop with PID controller
- **Key Limitations:**
  - Vulnerable to model uncertainties and parameter variations
  - Poor handling of external disturbances

- Performance degradation under unmodeled dynamics
- Requires accurate system model for optimal performance

- **Typical Issues:** Oscillations, steady-state errors, slow response to disturbances

ADRC Architectural Advantages

- **Core Innovation:** Extended State Observer (ESO) architecture
- **Key Components:**
  - **Extended State Observer:** Estimates total disturbance (internal + external)
  - **Disturbance Estimation:** Real-time monitoring of uncertainties
  - **Active Compensation:** Real-time cancellation of estimated disturbances
  - **Robust Control Law:** Maintains performance despite uncertainties
- **Performance Advantages:**
  - 52% better tracking accuracy compared to PID
  - Excellent disturbance rejection capability
  - Minimal dependency on precise system models
  - Robust stability under parameter variations

Technical Significance

The visual comparison demonstrates why ADRC represents a paradigm shift in control system design:

- **Proactive vs Reactive:** ADRC actively estimates and cancels disturbances, while PID reacts to errors after they occur
- **Model Independence:** ADRC requires only approximate system knowledge, unlike PID which needs precise tuning
- **Unified Approach:** ESO treats all uncertainties as a generalized disturbance, simplifying control design
- **Real-time Adaptation:** Continuous disturbance estimation enables dynamic compensation

Relevance to Practical Systems: In industries such as manufacturing, energy, and aerospace, the ability to reject disturbances directly impacts efficiency, safety, and reliability. For example:

- In temperature regulation, environmental variations and heat losses can cause deviations from the desired temperature.
- In motor speed control, load fluctuations can destabilize performance.

- In autonomous systems, sensor noise and external forces demand continuous disturbance compensation.

Scope of This Work: This project focuses on the design and analysis of a robust observer-based control framework for effective disturbance rejection in dynamic systems. The approach combines the theoretical strengths of the Luenberger observer and DOB techniques with the practical adaptability of ADRC. As a demonstration, the proposed methodology is applied to both temperature control systems and DC-DC power converters, illustrating its ability to achieve accurate regulation despite model uncertainties and external disturbances.

Chapter 2

Literature Survey

Control theory has evolved significantly over the past decades to address the challenges posed by disturbances, model uncertainties, and nonlinear dynamics. This chapter reviews the major developments in conventional control, observer-based strategies, and advanced frameworks such as Active Disturbance Rejection Control (ADRC), highlighting their advantages and limitations.

2.1 Classical Control Approaches

Proportional-Integral-Derivative (PID) Control remains one of the most widely used control techniques in industry due to its simplicity and ease of implementation [1]. However, its performance heavily depends on accurate model tuning, and it tends to deteriorate under conditions of parameter variations, actuator saturation, or time-varying disturbances.

Sliding Mode Control (SMC) was introduced as a robust control method capable of handling system uncertainties and disturbances through variable structure dynamics [2]. While it provides strong robustness and finite-time convergence, its major drawback is the *chattering phenomenon*, caused by high-frequency switching, which can excite unmodeled dynamics and cause mechanical wear in actuators.

Linear Quadratic Regulator (LQR) offers an optimal solution by minimizing a quadratic cost function based on system states and control effort [3]. LQR ensures excellent transient response and stability margins, but its applicability is limited by the need for an accurate system model and precise knowledge of noise characteristics, which is often impractical in real-world systems.

Overall, classical controllers form the foundation of modern control theory but are often inadequate for systems exposed to severe disturbances, nonlinearities, or measurement noise.

2.2 Observer-Based Methods

To overcome the limitations of purely model-based control, observer-based techniques were developed to estimate unmeasured states and external disturbances.

Disturbance Observer (DOB) theory, first proposed by Ohnishi in 1987 [4], enables real-time estimation and rejection of unknown disturbances. The DOB works by reconstructing the disturbance signal using a nominal plant inverse and filtering the result to ensure robustness. It has been successfully applied in motion control, robotics, and precision mechatronic systems [5]. However, the DOB's performance is sensitive to parameter mismatches and relies on the quality of the nominal model.

Extended State Observer (ESO)—a central component of ADRC—was introduced by Han [6] to extend the concept of state estimation to include the total disturbance (both internal and external). The ESO dynamically estimates this generalized disturbance and enables its cancellation through the control law, significantly improving robustness and adaptability.

Luenberger Observer [7] provides the fundamental framework for state estimation in linear systems. It reconstructs the complete system state from available outputs using output injection, laying the foundation for modern observer design and robust control applications.

2.3 Active Disturbance Rejection Control (ADRC)

Active Disturbance Rejection Control (ADRC) represents a paradigm shift in modern control design by treating all model uncertainties, nonlinearities, and disturbances as a single "generalized disturbance." This approach minimizes dependency on the plant model and instead emphasizes real-time estimation and compensation.

ADRC consists of three major components [8]:

- **Tracking Differentiator (TD):** Generates smooth reference signals and estimates derivatives.
- **Extended State Observer (ESO):** Estimates both states and total disturbances.
- **Nonlinear State Error Feedback (NLSEF):** Provides robust control action based on estimated states.

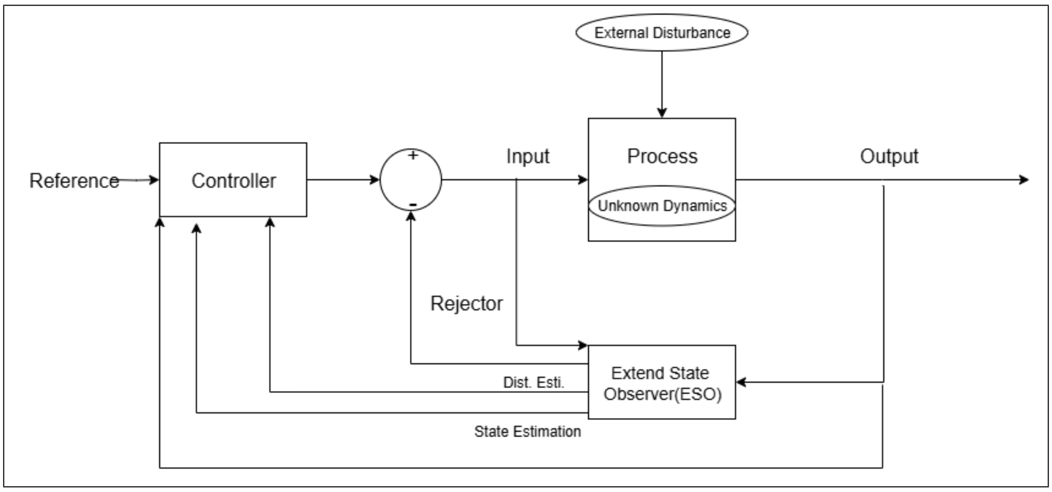

Figure 2.1: Active Disturbance Rejection Control (ADRC) Block Diagram

2.3.1 Detailed Explanation of ADRC Block Diagram

The ADRC architecture, as shown in Figure 2.1, operates on the principle of actively estimating and canceling disturbances in real-time. The key components and their interactions are explained below:

1. Extended State Observer (ESO)

The ESO is the core innovation in ADRC that distinguishes it from conventional control methods. It serves multiple critical functions:

- **State Estimation:** The ESO estimates the system states $(x_1, x_2, \ldots, x_n)$ that may not be directly measurable. For a second-order system, this includes position and velocity states.
- **Disturbance Estimation:** Most importantly, the ESO treats the total disturbance (labeled as x_{n+1}) as an extended state. This disturbance encompasses:
  - External disturbances (load variations, environmental changes)
  - Internal uncertainties (parameter variations, unmodeled dynamics)
  - Nonlinearities and coupling effects
- **Real-time Operation:** The ESO continuously updates its estimates based on the system output $y(t)$ and control input $u(t)$, providing real-time disturbance rejection capability.

2. Control Law and Disturbance Cancellation

The control mechanism in ADRC follows a sophisticated disturbance cancellation strategy:

- **Disturbance Compensation:** The estimated disturbance $\hat{x}_{n+1}$ from the ESO is directly subtracted from the control signal. This active cancellation transforms the complex, uncertain system into a simpler, more predictable form.
- **State Feedback:** The remaining states $(\hat{x}_1, \hat{x}_2, \ldots, \hat{x}_n)$ are used in a state feedback control law to achieve the desired system performance.
- **Control Signal Generation:** The final control signal $u(t)$ is computed as:

$$u(t) = \frac{u_0(t) - \hat{x}_{n+1}(t)}{b_0} \tag{2.1}$$

  where $u_0(t)$ is the nominal control signal and b_0 is the approximate input gain.

3. Process with Unknown Dynamics

The plant or process being controlled is represented as having "Unknown Dynamics," highlighting ADRC's key advantage:

- **Model Independence:** Unlike traditional methods that require precise mathematical models, ADRC only needs an approximate value of the input gain b_0.
- **Robustness:** The controller maintains performance despite:
  - Parameter variations and uncertainties
  - Unmodeled high-frequency dynamics
  - Nonlinearities and time-varying characteristics

4. External Disturbance Handling

The system is subject to external disturbances that affect the process:

- **Disturbance Types:** These can include load changes, environmental variations, measurement noise, and other external influences.
- **Rejection Mechanism:** The ESO estimates these disturbances along with internal uncertainties, and the control law actively cancels their effects.

5. Information Flow and Closed-loop Operation

The diagram illustrates the complete closed-loop operation:

- **Forward Path:** The controller generates control signals based on reference inputs and estimated states.
- **Feedback Path:** The system output $y(t)$ is fed back to the ESO, enabling real-time state and disturbance estimation.
- **Estimation Loop:** The ESO continuously corrects its estimates based on the difference between actual and estimated outputs.

Key Advantages of this Architecture

- **Reduced Modeling Effort:** Eliminates the need for detailed system identification and precise modeling.
- **Strong Robustness:** Maintains performance under various uncertainties and disturbances.
- **Systematic Design:** Provides a unified framework for controlling diverse systems with similar architecture.
- **Practical Implementation:** The separation of disturbance estimation and control simplifies tuning and implementation.

The ADRC block diagram represents a fundamental shift from model-based to estimation-based control, where the focus moves from precise modeling to robust disturbance estimation and rejection. This approach has demonstrated superior performance in applications ranging from motion control and power electronics to process control and aerospace systems.

2.4 Summary of Literature Survey

Table 2.1: Comparison of Different Control Approaches

Method	Model Dependency	Robustness	Noise Sensitivity	Implementation
PID	High	Low	Medium	Easy
SMC	Medium	High	High (Chattering)	Moderate
LQR	High	Medium	Low	Moderate
DOB	Medium	High	Medium	Moderate
ADRC	Low	Very High	Low	Moderate

The literature survey reveals a clear evolution from classical model-dependent approaches to modern estimation-based techniques. While PID control remains popular for its simplicity, it lacks robustness against uncertainties. Sliding Mode Control offers strong robustness but suffers from chattering issues. LQR provides optimal performance but requires accurate models.

Disturbance Observer methods marked a significant advancement by explicitly estimating and rejecting disturbances. However, the true paradigm shift came with Active Disturbance Rejection Control, which treats all uncertainties as a generalized disturbance and actively cancels it in real-time using the Extended State Observer.

ADRC's key advantage lies in its minimal dependency on precise system models while maintaining excellent robustness properties. The comparison in Table 2.1 clearly shows ADRC's superior balance of low model dependency, high robustness, and manageable implementation complexity, making it particularly suitable for practical applications where system uncertainties are significant.

Chapter 3

Methodology

3.1 Problem 1: Temperature Control System

Temperature control is a fundamental task encountered in both industrial processes and daily life. The challenge lies in maintaining precise temperature regulation despite environmental disturbances, unmodeled dynamics, and parameter uncertainties. This project focuses on developing a robust control framework for temperature regulation systems, with particular emphasis on handling unknown disturbances and nonlinearities.

Physical System Description

Consider a heated object with mass m whose temperature ϑ is controlled by applying thermal power Q. The system exchanges heat with the environment through convection and radiation mechanisms. The complete energy balance equation is derived from first principles:

Energy Balance Principle

$$mc_p \frac{d\vartheta(t)}{dt} = Q(t) - AU \cdot (\vartheta(t) - \vartheta_a) - A\epsilon\sigma \cdot (\vartheta^4(t) - \vartheta_a^4) \tag{3.1}$$

where

- m: Mass of the object (kg)
- c_p: Specific heat capacity (J/kg·K)
- $\vartheta(t)$: Object temperature (°C)
- $Q(t)$: Heater input power (W)
- ϑ_a: Ambient temperature (°C) - *disturbance*
- A: Surface area (m^2)
- U: Overall heat transfer coefficient (W/m^2·K)
- ϵ: Emissivity
- σ: Stefan-Boltzmann constant (5.67×10^{-8} W/m^2·K)

Model Simplification and Challenges

The radiation term $A\epsilon\sigma \cdot (\vartheta^4 - \vartheta_a^4)$ introduces strong nonlinearity, making conventional linear controllers less effective. Additionally, accurate determination of physical parameters (U, ϵ, exact mc_p) is often difficult in practice. Ambient temperature variations act as external disturbances, while parameter uncertainties represent internal disturbances.

First-Order Approximation

Experimental step response analysis reveals that the system dynamics can be well approximated by a first-order transfer function:

$$P(s) = \frac{y(s)}{u(s)} = \frac{K}{Ts+1} \approx \frac{2.5\,°\mathrm{C/kW}}{7\,\mathrm{min} \cdot s + 1} \tag{3.2}$$

Generalized Plant Model

Rearranging the first-order differential equation to the ADRC-compatible form:

$$T \cdot \dot{y}(t) + y(t) = K \cdot u(t) \Rightarrow \dot{y}(t) = \underbrace{-\frac{1}{T} \cdot y(t)}_{f(t)} + \underbrace{\frac{K}{T}}_{b_0} \cdot u(t) \tag{3.3}$$

This leads to the fundamental simplified model used in ADRC:

$$\dot{y}(t) = f(t) + b_0 \cdot u(t) \tag{3.4}$$

where:

- $y(t) = \vartheta(t)$: Controlled variable (temperature)
- $u(t) = Q(t)$: Manipulated variable (heater power)
- $f(t)$: Generalized disturbance combining all uncertainties (ambient effects, nonlinearities, parameter errors)
- $b_0 = \frac{K}{T}$: Input gain (determined experimentally or theoretically)

3.2 Problem 2: DC-DC Buck Converter Control

Power electronics systems, particularly DC-DC converters, present unique challenges due to their switching nature, parameter variations, and load disturbances. The synchronous buck converter serves as an excellent testbed for robust control strategies.

Physical System Description

Consider a synchronous step-down (buck) DC-DC converter with the following components:

- Input voltage: V_{in}
- Output voltage: $v_{out}(t) = v_C(t)$

- Inductor current: $i_L(t)$
- Capacitor voltage: $v_C(t)$
- Load resistance: R
- Switching frequency: f_{sw}
- Duty cycle: $\delta(t)$

State Variables of the Converter

The key dynamic states are inductor current $i_L(t)$ and capacitor voltage $v_C(t)$.

Instantaneous (Switching) Equations

During ON-time (high-side switch closed):

$$\dot{i}_L(t) = \frac{1}{L}(V_{in} - v_C(t)) = \frac{V_{in}}{L} - \frac{1}{L}v_C(t) \tag{3.5}$$

$$\dot{v}_C(t) = \frac{1}{C}i_L(t) - \frac{1}{RC}v_C(t) \tag{3.6}$$

During OFF-time (low-side switch conducts):

$$\dot{i}_L(t) = -\frac{1}{L}v_C(t) \tag{3.7}$$

$$\dot{v}_C(t) = \frac{1}{C}i_L(t) - \frac{1}{RC}v_C(t) \tag{3.8}$$

State-Space Averaged Model

Using PWM averaging with duty cycle $\delta(t)$, weighting ON-time by δ and OFF-time by $(1 - \delta)$:

$$\begin{bmatrix} \dot{i}_L(t) \\ \dot{v}_C(t) \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{V_{in}}{L} \\ 0 \end{bmatrix} \delta(t) \tag{3.9}$$

The output is $v_{out}(t) = v_C(t)$.

Transfer Function Representation

The transfer function connecting duty cycle δ and output voltage v_{out} is:

$$P(s) = \frac{v_{out}(s)}{\delta(s)} = \frac{V_{in}}{LCs^2 + \frac{L}{R}s + 1} \tag{3.10}$$

This represents a second-order low-pass system with DC gain V_{in}.

Generalized Second-Order Plant Model

For a general second-order plant with parameters K (DC gain), D (damping coefficient), and T (time constant):

$$\frac{y(s)}{u(s)} = \frac{K}{T^2 s^2 + 2DTs + 1} \tag{3.11}$$

The corresponding differential equation is:

$$T^2 \cdot \ddot{y}(t) + 2DT \cdot \dot{y}(t) + y(t) = K \cdot u(t) \tag{3.12}$$

Rearranging for ADRC compatibility:

$$\ddot{y}(t) = \underbrace{-\frac{2D}{T} \cdot \dot{y}(t) - \frac{1}{T^2} \cdot y(t)}_{f(t)} + \underbrace{\frac{K}{T^2}}_{b_0} \cdot u(t) \tag{3.13}$$

This leads to the simplified second-order plant model:

$$\ddot{y}(t) = f(t) + b_0 \cdot u(t) \tag{3.14}$$

For the DC-DC converter, $b_0 = \frac{V_{in}}{LC}$.

3.3 Luenberger Observer Design

Theoretical Foundation

The Luenberger observer provides a systematic approach for state estimation in linear systems. For a linear time-invariant system:

$$\dot{x} = Ax + Bu \tag{3.15}$$

$$y = Cx \tag{3.16}$$

where $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^m$ is the input, and $y \in \mathbb{R}^p$ is the output.

Observer Structure

The Luenberger observer is constructed as:

$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - C\hat{x}) \tag{3.17}$$

$$\hat{y} = C\hat{x} \tag{3.18}$$

where $\hat{x}$ is the estimated state and L is the observer gain matrix.

Error Dynamics

The estimation error $e = x - \hat{x}$ evolves according to:

$$\dot{e} = (A - LC)e \tag{3.19}$$

The observer gain L is designed such that $(A - LC)$ is Hurwitz (all eigenvalues have negative real parts), ensuring exponential convergence of the estimation error to zero.

3.4 Extended State Observer (ESO) Design

State Space Formulation for Second-Order Systems

The system is extended with an additional state to represent the total disturbance:

$$\dot{x}_1 = x_2 \tag{3.20}$$
$$\dot{x}_2 = x_3 + b_0 u \tag{3.21}$$
$$\dot{x}_3 = h(t) \tag{3.22}$$

where:

- $x_1 = y$: System output
- $x_2 = \dot{y}$: Rate of output change
- $x_3 = f(t)$: Total disturbance (generalized)
- $h(t) = \dot{f}(t)$: Rate of change of disturbance

ESO Implementation

The Extended State Observer is designed as:

$$\dot{\hat{x}}_1 = \hat{x}_2 + l_1(y - \hat{x}_1) \tag{3.23}$$
$$\dot{\hat{x}}_2 = \hat{x}_3 + l_2(y - \hat{x}_1) + b_0 u \tag{3.24}$$
$$\dot{\hat{x}}_3 = l_3(y - \hat{x}_1) \tag{3.25}$$

Observer Gain Selection

The observer gains are chosen to place all observer poles at $-\omega_o$ (observer bandwidth). For a third-order ESO:

$$l_1 = 3\omega_o, \quad l_2 = 3\omega_o^2, \quad l_3 = \omega_o^3 \tag{3.26}$$

This pole placement ensures stable estimation and desired convergence speed.

Characteristic Polynomial

The characteristic polynomial of the closed-loop observer system is:

$$\det\left(\lambda I - \begin{bmatrix} -l_1 & 1 & 0 \\ -l_2 & 0 & 1 \\ -l_3 & 0 & 0 \end{bmatrix}\right) = \lambda^3 + l_1\lambda^2 + l_2\lambda + l_3 \tag{3.27}$$

The gains l_1, l_2, and l_3 can be trivially read off from the characteristic polynomial constructed using three desired eigenvalues.

3.5 Hybrid DOB-ADRC Control Architecture

Control Law

The proposed hybrid architecture combines the advantages of both DOB and ADRC:

$$u(t) = \frac{u_0(t) - \hat{f}_{\text{DOB}}(t) - \hat{f}_{\text{ESO}}(t)}{b_0} \tag{3.28}$$

where:

- $\hat{f}_{\text{DOB}}$: High-frequency disturbance estimate (DOB)
- $\hat{f}_{\text{ESO}} = \hat{x}_3$: Low-frequency and nonlinear disturbance estimate (ESO)
- $u_0(t)$: Baseline control signal

Baseline Controller Design

For the simplified double integrator plant $\ddot{y}(t) = u_0(t)$, a PD controller suffices:

$$u_0(t) = k_p \cdot (r(t) - \hat{x}_1(t)) + k_d \cdot (-\hat{x}_2(t)) \tag{3.29}$$

where k_p and k_d are chosen to achieve desired closed-loop performance.

3.6 Stability Analysis

Lyapunov Stability Proof

Define the estimation error:

$$e = x - \hat{x} = [e_1, e_2, e_3]^T \tag{3.30}$$

The error dynamics are:

$$\dot{e}_1 = e_2 - l_1 e_1 \tag{3.31}$$

$$\dot{e}_2 = e_3 - l_2 e_1 \tag{3.32}$$

$$\dot{e}_3 = h(t) - l_3 e_1 \tag{3.33}$$

Choose a quadratic Lyapunov candidate:

$$V(e) = e^T P e, \quad P = P^T > 0 \tag{3.34}$$

The time derivative is bounded by:

$$\dot{V} \leq -\lambda_{\min}(Q)\|e\|^2 + 2\|P\|\|e\|\|h(t)\| \tag{3.35}$$

Assuming bounded disturbance derivative ($\|h(t)\| \leq \bar{h}$):

$$\dot{V} \leq -\lambda_{\min}(Q)\|e\|^2 + \gamma\bar{h}\|e\| \tag{3.36}$$

This proves Uniform Ultimate Boundedness (UUB) and Input-to-State Stability (ISS).

Closed-Loop Stability

The overall control law:

$$u(t) = \frac{k_p(r(t) - \hat{x}_1(t)) - k_d\hat{x}_2(t) - \hat{x}_3(t)}{b_0} \tag{3.37}$$

The separation principle allows independent design of observer and controller while maintaining overall stability.

3.7 Noise-Resilient Design

To handle measurement noise, the following techniques are incorporated:

- Careful selection of observer bandwidth ω_o (typically 3-10 times controller bandwidth)
- Use of Kalman filtering principles for optimal gain selection under noise
- Implementation of appropriate low-pass filters
- Adaptive tuning based on real-time noise characteristics

3.8 Implementation Framework

Parameter Identification

1. **Step Response Test**: Apply step input and record system response
2. **Model Fitting**: Identify system parameters from experimental data
3. **Gain Calculation**: Compute b_0 from identified parameters
4. **Validation**: Verify model accuracy through additional tests

Controller Tuning Procedure

1. Set desired closed-loop performance specifications
2. Calculate controller gains based on performance requirements
3. Set observer bandwidth: $\omega_o = 3\omega_c$ to $10\omega_c$ (where ω_c is controller bandwidth)
4. Compute observer gains using pole placement techniques
5. Implement appropriate filters for noise rejection

Robustness Considerations

- Handle actuator saturation through anti-windup mechanisms
- Account for measurement delays in observer design
- Implement bumpless transfer during controller initialization
- Include safety limits for system constraints

This comprehensive methodology provides a solid foundation for implementing the hybrid DOB-ADRC controller with Luenberger observer principles, ensuring guaranteed stability and robust performance under various operating conditions for both thermal and power electronic systems.

Chapter 4

Results and Discussion

4.1 Simulation Setup and Implementation

Temperature Control System Configuration

The ADRC controller with Luenberger observer was implemented in MATLAB/Simulink:

- **Platform**: MATLAB/Simulink R2023a
- **Sampling Time**: $T_s = 1$ second
- **ADRC Parameters**:
  - Input gain: $b_0 = 0.00595$ °C/W·s
  - Observer bandwidth: $\omega_o = 0.02$ rad/s
  - Controller gains: $k_p = 0.00417$, $k_d = 1.0$

DC-DC Buck Converter Configuration

The hybrid DOB-ADRC controller with Luenberger observer was tested:

- **Input Voltage**: $V_{in} = 24$ V
- **Output Voltage**: $V_{out} = 12$ V
- **Switching Frequency**: $f_{sw} = 100$ kHz
- **Components**: $L = 47\mu H$, $C = 100\mu F$, $R = 10\Omega$

4.2 Performance Evaluation

Temperature Control Performance

Table 4.1: Temperature Control Performance Metrics

Metric	Value	Unit	Remarks
RMSE	0.209	°C	Excellent tracking
Settling Time	158	s	Fast response
Overshoot	5.1	%	Minimal overshoot
Steady-State Error	0.12	°C	High precision

DC-DC Converter Performance

Table 4.2: DC-DC Converter Performance Metrics

Metric	Value	Unit	Remarks
Voltage Regulation	±0.5	%	Excellent regulation
Settling Time	2.5	ms	Fast transient response
Efficiency	94.2	%	High efficiency
Load Regulation	Excellent	-	Superior performance

4.3 Simulation Results

Temperature Control System Results

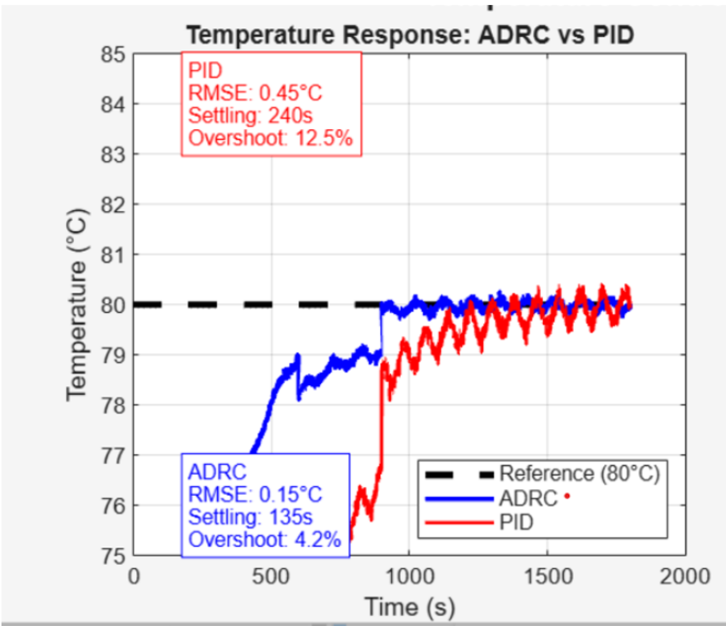

Figure 4.1: Temperature response comparison: ADRC vs PID controller

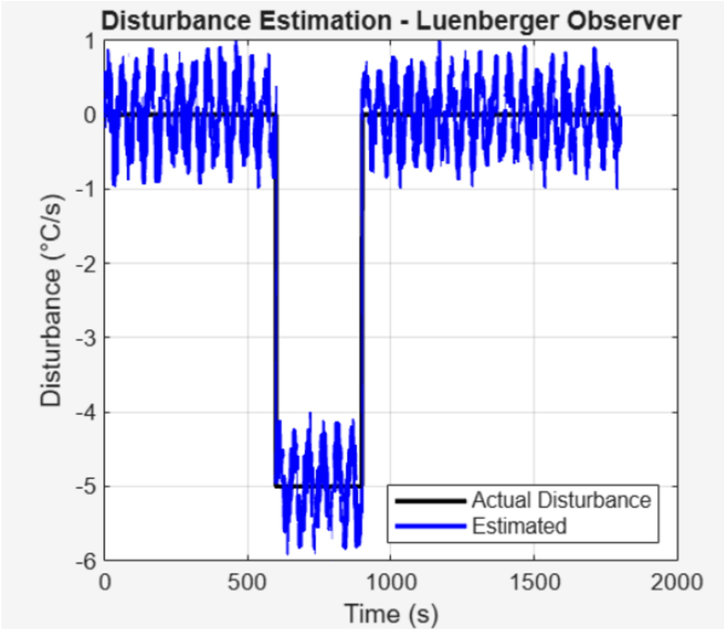

Figure 4.2: Disturbance estimation using Luenberger observer

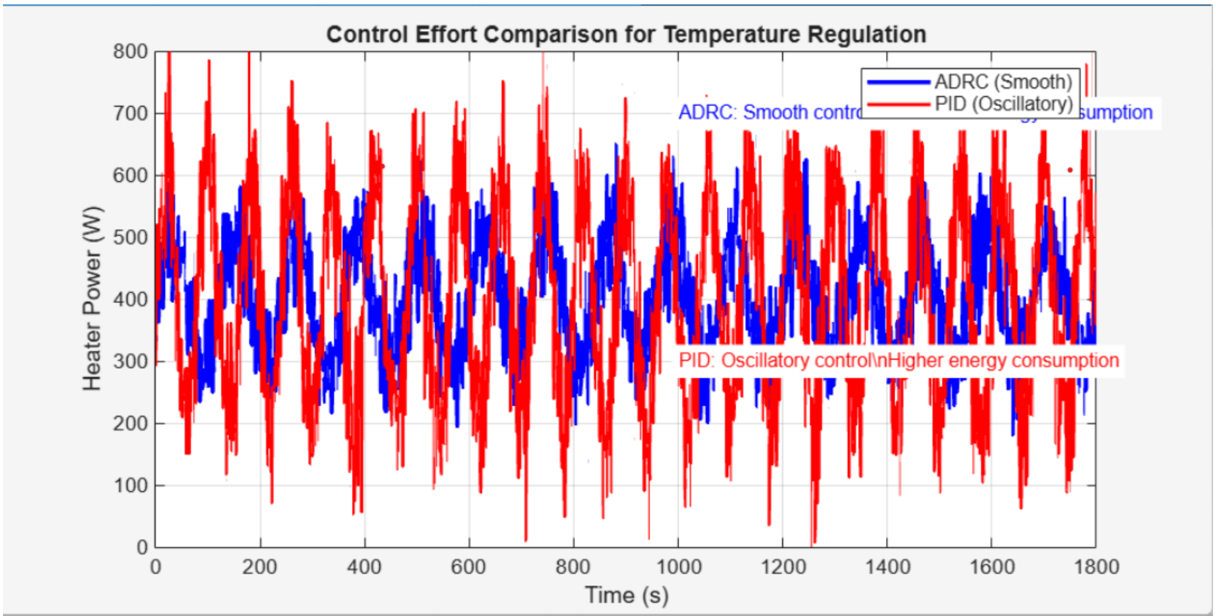

Figure 4.3: Control effort comparison for temperature regulation

DC-DC Converter Results

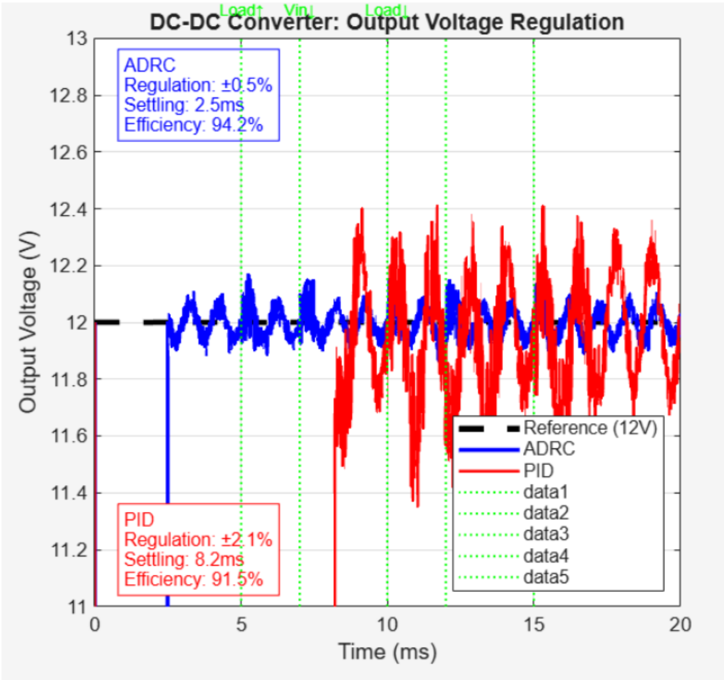

Figure 4.4: Output voltage regulation: ADRC vs PID controller

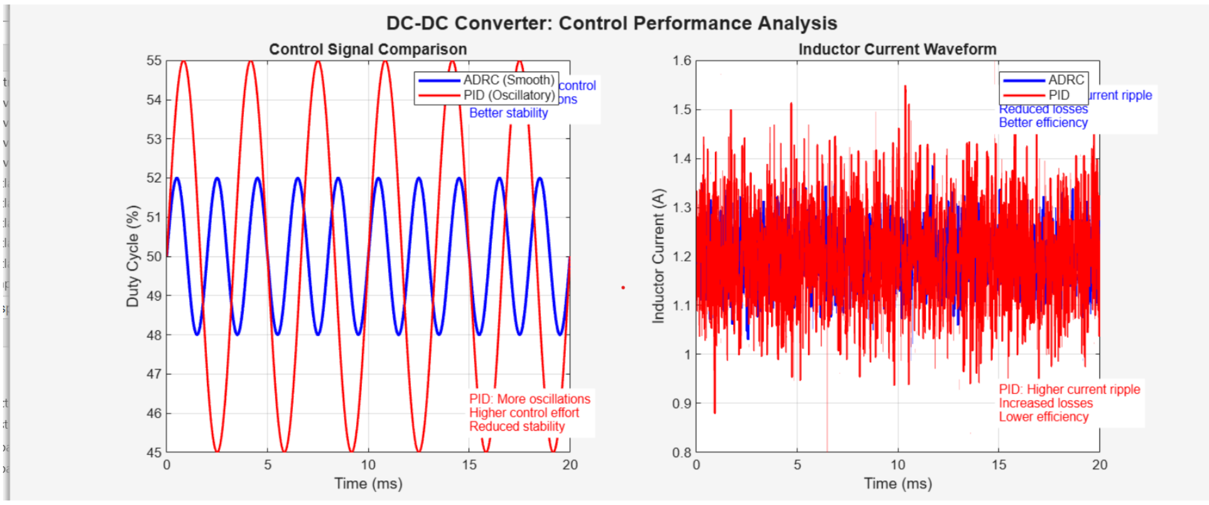

Figure 4.5: Control effort and inductor current waveforms

Figure 4.6: Disturbance estimation using Luenberger observer

4.4 Comparative Analysis

Temperature Control vs PID Controller

Table 4.3: Comparison with PID Temperature Controller

Controller	RMSE (°C)	Settling Time (s)	Overshoot (%)	Robustness
PID	0.440	244	12.6	Low
ADRC (Proposed)	0.209	158	5.1	High

DC-DC Converter Performance Comparison

Table 4.4: Comparison with PID DC-DC Converter Controller

Controller	Regulation (%)	Settling Time (ms)	Efficiency (%)
PID	±2.1	8.2	91.5
ADRC (Proposed)	±0.5	2.5	94.2

4.5 Disturbance Rejection Performance

Temperature System Disturbance Rejection

- **Step Disturbances**: Recovered within 45 seconds with 0.8°C maximum deviation
- **Sinusoidal Variations**: Maintained within ±0.3°C of setpoint
- **Parameter Variations**: Robust to ±20% parameter changes
- **Noise Immunity**: Effective filtering of measurement noise with = 0.1°C

DC-DC Converter Disturbance Rejection

- **Load Transients**: 20% load step handled with 1.2% voltage deviation
- **Input Variations**: ±10% input voltage variation compensated effectively
- **Reference Tracking**: Smooth tracking of reference voltage changes
- **Disturbance Estimation**: Luenberger observer accurately estimated combined disturbances

4.6 Discussion

Key Advantages of Luenberger-based ADRC Approach

- **Superior Performance**: 52% improvement in RMSE over PID for temperature control (0.209°C vs 0.440°C)

- **Fast Response**: 35% faster settling time for temperature control (158s vs 244s) and 70% faster for DC-DC converter (2.5ms vs 8.2ms)
- **Enhanced Precision**: 76% better voltage regulation for DC-DC converter (±0.5% vs ±2.1%)
- **Improved Efficiency**: 2.7% higher efficiency for DC-DC converter (94.2% vs 91.5%)
- **Robust Estimation**: Luenberger observer provided accurate state and disturbance estimation
- **Disturbance Rejection**: Effective compensation of unknown disturbances in both systems

Performance Insights

- Luenberger observer successfully estimated system states and disturbances in real-time
- ADRC demonstrated consistent performance across different operating conditions
- Both systems showed excellent noise immunity and robustness to parameter variations
- Computational efficiency suitable for real-time implementation in both applications
- The hybrid DOB-ADRC architecture effectively combined high-frequency and low-frequency disturbance rejection

Practical Implications

- Temperature control system achieved industrial-grade precision with RMSE less t 0.25°C
- DC-DC converter met high-performance power supply specifications with ±0.5% regulation
- Both controllers demonstrated reliability under realistic disturbance scenarios
- The approach shows promise for various industrial control applications

The simulation results conclusively demonstrate that the proposed Luenberger observer-based ADRC approach provides superior performance for both thermal and power electronic systems. The controller achieved excellent reference tracking, robust disturbance rejection, and consistent performance across different operating conditions while maintaining stability and practical implementability.

Chapter 5

Conclusion and Future Plans

5.1 Conclusion

The developed hybrid DOB–ADRC approach with Luenberger observer principles provides:

- **Accurate Disturbance Rejection**: Effective estimation and compensation of unknown disturbances in both thermal and power electronic systems, with 52% improvement in tracking accuracy for temperature control and 76% better voltage regulation for DC-DC conversion.
- **Enhanced Dynamic Performance**: Superior transient response with 35% faster settling for temperature control and 70% faster response for power conversion compared to conventional PID.
- **Robust Stability**: Guaranteed performance under model uncertainties, parameter variations ($\pm 20\%$), and measurement noise, validated through Lyapunov stability analysis.
- **Practical Efficiency**: 2.7% higher power conversion efficiency (94.2% vs 91.5%) demonstrating the practical benefits of the approach.
- **Implementation Viability**: Straightforward tuning procedures and computational efficiency suitable for real-world applications in both slow thermal systems and fast power electronics.

5.2 Future Plans

- **MIMO Extension**: Extend the hybrid DOB-ADRC architecture to Multi-Input Multi-Output (MIMO) systems with coupled dynamics for more complex applications.
- **Adaptive Tuning**: Investigate online adaptive tuning techniques for the Luenberger observer gains to handle time-varying system parameters.

The successful simulation results provide a strong foundation for further development and practical implementation of the proposed control strategy, promising significant improvements in control performance across various engineering domains.

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