CONTROLLER DESIGN

FOR INDUSTRIAL APPLICATIONS

Edited By
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Preface

Industrial processes are often complex and dynamic, making it challenging to design controllers that can maintain stable and optimal operation. Traditional controllers, such as PID controllers, have been widely used in industrial applications but have limitations in handling non-linear and uncertain systems. Intelligent controllers offer an alternative solution that can adapt to changing system dynamics and disturbances.

Intelligent controllers utilize advanced control theory and techniques, such as fuzzy logic control, neural network control, and model predictive control, to achieve optimal control performance. They are capable of learning from data and experience, making them suitable for handling non-linear and uncertain systems. Furthermore, they can improve the robustness and flexibility of the control system and enhance the overall performance.

The use of intelligent controllers in industrial applications has gained increasing attention in recent years, with numerous successful implementations in various fields, such as process control, robotics control, HVAC control, power systems control, and autonomous vehicles control. However, the design and implementation of intelligent controllers require careful consideration of hardware and software requirements, as well as simulation and testing procedures to ensure reliable and safe operation.

In recent years, there has been a growing interest in the development and implementation of intelligent controllers for industrial applications. Intelligent controllers are capable of adapting to changing system dynamics and disturbances, resulting in improved performance and robustness. In the rapidly evolving industrial landscape, it is essential to develop advanced control techniques to enhance productivity, minimize costs, and ensure safety. Traditional control methods often struggle to handle complex systems and unpredictable environments.

However, with the emergence of intelligent control techniques, there is a great opportunity to improve industrial automation and control systems. This book aims to provide a comprehensive understanding of intelligent controller design for industrial applications, from theoretical concepts to practical implementation. It will cover the fundamental concepts of intelligent control theory and techniques, their application in various industrial fields, and the practical implementation and design considerations. It is suitable for researchers, engineers, and students in the field of control engineering and industrial automation.

Chapter 1 deals with the practical applications of Fuzzy Logic Control (FLC) in various industries, highlighting its ability to manage imprecise and uncertain data effectively. It underscores the adaptability of FLC to dynamic and complex systems, illustrating its utilization in automotive, consumer electronics, robotics, and other sectors.

Chapter 2 discusses the application of Artificial Neural Networks (ANNs) in various industrial contexts, emphasizing their capacity to handle complex data and improve decision-making processes. It also explains the basic structure of ANNs, including different types like multilayer perceptron and recurrent networks, and how they are used in sectors such as manufacturing, energy management, and process control. Moreover, the chapter highlights the role of ANN in enhancing productivity and cost-efficiency through examples like predictive maintenance and quality control, demonstrating the technology's broad applicability and effectiveness across different industries.

Chapter 3 deliberates an innovative approach that combines an Artificial Neural Network (ANN) based observer with a Sliding Mode Controller (SMC) to enhance control over non-linear systems. This integration aims to utilize the capability of ANN to accurately estimate unknown system states and disturbances, improving the robustness and performance of the SMC. The effectiveness of this combined strategy is demonstrated through simulations, particularly using a single-link robot dynamical model, showing significant improvement in handling system uncertainties and disturbances.

Chapter 4 presents a comprehensive examination of the Finite Control Set Model Predictive Control (FCSMPC) approach for Permanent Magnet Synchronous Motor (PMSM) drives, focusing on the application in electric vehicles (EVs) and its integration with renewable energy sources. It covers the evolution from traditional motor control strategies like Field-Oriented Control and Direct Torque Control to the advanced FCSMPC, detailing its advantages in handling complex, dynamic performance requirements. The chapter also elaborates on the mathematical models and the real-time implementation challenges of FCSMPC, underscoring its effectiveness in reducing computational complexity and improving system responsiveness and efficiency.

Chapter 5 explores the kinematic and dynamic modeling of walking robots, focusing on creating accurate simulations using MATLAB to better understand the complexities of robotic locomotion. It also emphasizes the importance of integrating mechanical, electrical, and control systems to develop robots capable of handling real-world tasks. The chapter further highlights the potential applications of walking robots in various fields such as healthcare, manufacturing, and service industries, underscoring the ongoing innovations and challenges in the field of robotics.

Chapter 6 discusses the design and implementation of a hybrid FUZZY-(1+PD)-FOPID controller for a two-area power system, integrating thermal, nuclear, and non-conventional energy sources. It highlights the use of the Tree-Seed Algorithm (TSA) for optimizing controller parameters to enhance system stability and response characteristics, such as settling time and overshoot. The effectiveness of this controller is demonstrated through MATLAB simulations, showing superior performance over traditional PID controllers in managing frequency and tie-bar power deviations within the power system.

Chapter 7 explores the implementation of the Tree Seed Algorithm (TSA) for tuning a Model Predictive Control (MPC) system aimed at enhancing the performance of a two-area interconnected hybrid power system. This hybrid system incorporates both conventional (thermal and nuclear) and non-conventional (ocean thermal and solar) energy sources. The TSA optimizes the MPC parameters to minimize power system oscillations, effectively improving stability and response times in the face of load changes and system uncertainties, as demonstrated through MATLAB simulations.

Chapter 8 outlines the development and implementation of Wide Area Monitoring, Protection, Automation, and Control (WAMPAC) systems in response to the integration of renewable energy sources and the risks of power outages. It further emphasizes the role of Phasor Measurement Units (PMUs) and Intelligent Electronic Devices (IEDs) in enhancing grid visibility and control by providing real-time data, which aids in maintaining system stability and efficiency. The chapter also discusses various phasor estimation techniques and the critical use of communication protocols like DNP3, IEC61850, and others to ensure seamless data flow and reliable grid operation.

Chapter 9 discusses the design and implementation of a smart prepaid interface for power distribution in industrial settings, focusing on the integration of microgrid technology with prepaid systems. This approach enhances consumer empowerment by allowing them to purchase electricity efficiently from the closest available power station, thereby optimizing the electricity flow and improving cost-effectiveness. The system also utilizes a dynamic fusion of centralized and decentralized features to streamline user experiences and tailor electricity distribution based on location and priority, ultimately promising a more resilient and consumer-centric future in energy distribution.

Chapter 10 presents a study on the implementation of the Grey Wolf Optimization (GWO) algorithm for maximum power point tracking (MPPT) in photovoltaic (PV) systems under partial shading conditions. It contrasts the GWO method with the traditional Perturb and Observe (P&O) method, highlighting the effectiveness of GWO in avoiding local maxima and efficiently tracking the global maximum power point, even with variable irradiance. The analysis includes simulation results validating the enhanced performance and reliability of the GWO algorithm, which optimizes the output of the PV system by adapting dynamically to changes in environmental conditions.

Chapter 11 introduces an efficient optimization approach for solving the Relay Coordination Problem (RCP) in power distribution systems, emphasizing the need for precise configuration of over-current relays (OCRs) to handle real-time fault mitigation. It discusses the optimization of relay settings to achieve minimal fault clearance times while maintaining system integrity, using Particle Swarm Optimization (PSO) among other techniques. The chapter further details various strategies and algorithms used historically and currently, providing a comprehensive look at advancements in relay coordination to enhance the reliability and efficiency of power systems.

Chapter 12 focuses on the advanced control strategies for energy-efficient HVAC systems, particularly the integration of intelligent control techniques using machine learning and artificial intelligence. It discusses the complexities of modeling HVAC systems due to dynamic, interconnected components and external influences like weather changes and occupancy variations. The chapter also emphasizes the enhancement of HVAC control through predictive models and adaptive algorithms that improve energy efficiency, occupant comfort, and system responsiveness. Case studies are presented to demonstrate the significant impacts of these intelligent control systems in reducing energy consumption and maintaining optimal indoor environmental quality in various settings.

Chapter 13 introduces the Closest Obstacle Avoidance and A* (COAA*) Algorithm, a robust and efficient obstacle avoidance and navigation solution tested on the Heavy Lift Experimental (HLX) unmanned aerial vehicles, effectively combining the strengths of both offline and online methods while ensuring optimal performance in both simulations and real-world applications.

Chapter 14 develops a novel control scheme called Steady-State Integral Proportional Integral Controller (SIPIC) for racing-grade multi-rotors, designed to optimize system actuation with minimal overshoot and oscillations, and evaluates its performance using a nonlinear dynamic model simulator. Additionally, it employs a Robust and Perfect Tracking (RPT) controller for accurate tracking of position, velocity, and acceleration setpoints, demonstrating remarkable robustness and performance with a straightforward tuning process.

Chapter 15 introduces a novel cascaded fuzzy logic-based approach for path planning and collision avoidance in autonomous vehicles, utilizing multiple fuzzy inference systems (FIS) to enhance navigation and safety. The approach employs LiDAR sensor data to dynamically adjust vehicle movement, aiming to effectively manage real-time navigation challenges due to sensor inaccuracies and environmental unpredictability. The techniques are further validated through MATLAB simulations, emphasizing their potential in improving autonomous vehicle control systems.

Chapter 16 delves with the integration of artificial intelligence (AI) in optimizing electric vehicle (EV) charging systems to address the increased demand on power grids and improve charging infrastructure. It explores how AI can dynamically manage charging schedules, balance demand, and provide predictive maintenance to enhance efficiency and reliability. Additionally, the chapter also considers the implications of AI-driven systems on data privacy, interoperability, and regulatory challenges, aiming to provide a robust framework for sustainable electric vehicle integration.

Chapter 17 discusses the various wireless power transfer (WPT) methods for electric vehicles (EVs), focusing on dynamic wireless charging systems that operate through electromagnetic induction. It reviews three types of WPT—inductive, capacitive, and resonant inductive—detailing their operational principles, efficiencies, and system designs. The chapter emphasizes the advantages of dynamic, contactless EV charging stations that integrate renewable energy sources, aiming to enhance charging infrastructure and address electric vehicles' range and energy storage challenges.

1

Fuzzy Logic Control for Industrial Applications

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Abstract
Fuzzy control has emerged as the most important and practical field of study in fuzzy set theory, particularly for industrial developments that do not use conventional control techniques due to the lack of readily available, precise data on input-output relationships. The foundation of the fuzzy control system is fuzzy logic. Basically, this logical system is considerably more analogous to how people think and speak. A linguistic control approach built on expert knowledge can be transformed into an automatic control strategy using the fuzzy logic–based controller, which is based on the fuzzy logic concept. The understanding of membership functions, in particular, is well-known and plays a significant role in a variety of applications such as industry, traffic, and medical science. While probability theory deals with randomness, the main objective of fuzzy set theory is to provide a technique for the analysis of uncertainty originating in human subjectivity. The fuzzy logic system focuses primarily on decision-making and fuzzy inference systems. It includes fuzzification and defuzzification strategies, fuzzy control rules, fuzzy implication, and an analysis of fuzzy reasoning appliances. There are multiple applications of fuzzy logic controls observed in the industrial process. Without the operator having any prior knowledge of the system to be controlled, the industrial controller's hardware aids in fine-tuning a PID controller. Fuzzy logic supervisory control is utilized in software in the process industry to enhance the functioning of the sintering oven through an advanced integration of priority management and deviation-controlled timing. It can also be utilized in intelligent control modeling, and programmable logic controller (PLC), where programmed to function in a cost-effective manner. Additionally, it can be used

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in a fuzzy image processing scheme, medical engineering vessel segmentation, the development of fuzzy controllers for maintaining an inter-vehicle safety headway, and knowledge-based gear-position decision, among other applications. All these industrial applications are discussed in this chapter.

***Keywords*:** Fuzzy set theory, fuzzy logic control, programmable logic controller (PLC), fuzzy image processing

1.1 Introduction

In the field of modern industrial automation, the search for improved control techniques capable of managing intricate and unpredictable systems has resulted in the development of novel methodologies. Fuzzy logic control (FLC) is an effective and adaptable technique that has actually attracted considerable passion. Unclear reasoning stems from human reasoning together with assumption efficiently dealing with vague and unclear information, making it a very ideal choice for a large range of useful applications.

Proportional-integral-derivative (PID) controllers have actually been typically utilized in commercial setups for control objectives. Although these methods have actually shown efficiency in numerous circumstances, they regularly come across problems when faced with nonlinear, uncertain, and vibration-based systems. The fundamental restrictions of conventional controllers mandated the growth of advanced and also smart approaches, leading to the appearance of FLC.

Lotfi A. Zadeh created fuzzy logic in the 1960s as a mathematical device rooted in the concept of unclear collections [1]. Unclear collections vary from traditional collection concepts because they permit partial subscription, whereas, in traditional collection concepts, a component either completely comes from a collection or does not belong in any way. Unclear reasoning makes it possible for the depiction and control of obscurity as well as vagueness in a way that carefully mirrors human cognitive procedures. FLC might efficiently imitate human decision-making by using etymological variables as well as unclear guidelines to replicate fancy communications between inputs as well as outcomes.

FLC features by utilizing a collection of language guidelines that express the professional understanding relating to the system under control. FLC is thus an efficient knowledge-based control technique that is created from the experience of the specialists and also domain-specific understanding. The control technique uses certain if-then regulations in which inputs as well as outcomes are related to fuzzy linguistic principles like "low," "medium," and "high" [2]. The FLC (fuzzy logic control) procedure includes three important actions: fuzzification, rule assessment, and defuzzification. Throughout the fuzzification stage, exact input worths are changed right into unclear collections and connected to appropriate language principles. After this, the rule assessment phase gauges the degree of fulfillment for each and every regulation by taking into consideration the fuzzy input values. Lastly, the defuzzification treatment incorporates the fuzzy outcomes to acquire exact control activities.

Meanwhile, FLC has proven its worth through its ability to handle uncertainty and disturbances effectively. The traditional control approaches typically require an exact mathematical model of the system which in turn makes these approaches susceptible to errors when implemented in real life. In contrast, FLC possesses the ability to handle imprecision adequately and as such is of great importance in cases when the system's performance or unfavorable behavior is unknown or cannot be predicted accurately. These modifications make FLC adaptable in such a way that it can respond to dynamic situations while ensuring optimal performance online and so on and so forth. This characteristic has given rise to the use of PID as a satisfactory controller in complex industrial systems especially where they experience variable operating conditions [3].

Control techniques available for linear systems face insurmountable complexities when it comes to nonlinearities. The underlying nonlinear nature of FLC makes it an effective tool in solving complicated control problems. It can represent complex interactions between inputs and outputs which are hardly accounted for by the usual linear control methodologies. It has the advantage of being intuitive, enabling its prompt application and understanding of control rules. By including language variables and rules, the control logic becomes more easily understandable for specialists in the subject, thereby allowing them to actively participate in designing and refining processes. The transparency of FLC promotes a clear understanding and examination of the decision-making process while enhancing confidence and facilitating problem-solving within industrial applications.

FLC has widely been applied in many industrial sectors including process control, robotics, energy management, and intelligent transport systems. FLC is a very successful method for controlling various parameters in industrial processes such as temperature, pressure, humidity, and flow rate; it can handle uncertainties and nonlinearities that make it suitable for chemical plants, oil refineries, and power generation facilities. It plays a fundamental role in robotics and automation fields where accuracy of control and adaptability are vital. It is used to control robot motion, identify objects, plan paths or trajectories, and avoid collisions so that robots can operate safely and efficiently in changing environments. FLC has the capability to enhance energy efficiency in industrial facilities through the regulation of equipment operation and load management. This makes it easier to distribute energy effectively thus promoting the economical utilization of energy in different applications including smart grids, renewable energy systems; HVAC (heating ventilation air-conditioning) control. In traffic control systems, FLC has proven itself by effectively regulating traffic flow as well as timing of signals. To mitigate congestion and enhance collective traffic efficiency, the system can change signal timings quickly depending on the traffic state. FLC is a tough control strategy whose applications in various industries are very promising. It is an attractive alternative for guiding complex systems as it can handle unpredictability, nonlinearity, and adaptiveness. The intuitive nature of FLC, its transparency, and robustness make it suitable for professionals and easily understood by them for practical use [4].

1.2 The Evaluation of Fuzzy Logic Control: From Theory to Industrial Applications

1.2.1 The Origin of Fuzzy Logic: A Paradigm Shift in Control Theory

Fuzzy logic dates back to 1965 when Lotfi A. Zadeh developed the concept of fuzzy sets [1]. The scholar argued that the binary definition of set membership was not suitable for real-life cases and should be substituted with partial membership based on the degree of truthfulness. The consideration above revolutionized control theory by introducing a new paradigm that could accurately work with vague and uncertain information.

1.2.2 Mamdani's Fuzzy Logic Control: The First Practical Implementation

In the early 1970s, Mamdani and Assilian implemented the first practical application of fuzzy logic control based on fuzzy logic controllers, known as the Mamdani model [5]. They demonstrated the successful employment of FLC for the control of a steam engine, illustrating its potential for solving complicated control problems in the real world. The Mamdani model relied on linguistic variables, fuzzy rules, and membership functions to create a relationship between the inputs and outputs, creating a system that is interpretable.

1.2.3 Takagi-Sugeno-Kang (TSK) Fuzzy Models: Advancing the Practicality of FLC

In the late 1980s, Takagi, Sugeno, and Kang proposed the TSK fuzzy model, which enhanced the applicability and computational efficiency of FLC [6]. The TSK model is distinguished from the Mamdani model because it uses a weighted linear summation of input variables to generate output. This introduced the opportunity for a reduced rule base with less complicated computation and eased the practical implementation of real-time control systems.

1.2.4 Hybrid and Adaptive Fuzzy Logic Control: Addressing Complexity and Uncertainty

With the rising popularity of FLC, researchers have started investigating hybrid and adaptive methods to cope with the difficulties put forward by complex and unpredictable systems.

1.2.4.1 Hybrid Fuzzy Logic Control

Hybrid FLC combines fuzzy logic with other control methods to allow them to cooperate with their best abilities [7]. The best example is integrating the fuzzy logic controller with neural networks, allowing neuro-fuzzy systems to appear. Such systems combine the ability to learn presented by neural networks with the ability to interpret and illuminate operations of fuzzy logic. It enables enhanced control and increased flexibility.

1.2.4.2 Adaptive Fuzzy Logic Control

Adaptive FLC implies the ability to independently change the fuzzy rules and membership functions concerning the development of the system's dynamics or environmental conditions. The FLC system changes and refines the control system through adaptive procedures, including fuzzy rule interpolation, fuzzy clustering, and genetic algorithms, among others. In scenarios where the system parameters change or are unknown, this system is more effective [8].

1.3 Basics of Fuzzy Logic Control: A Comprehensive Overview

FLC is a versatile and resilient control method that has attracted attention for its ability to handle unpredictable systems effectively. Fuzzy logic, which mirrors cognition and understanding, is also employed to manage data that lacks precision or clarity. This summary will explore the core components of FLC, such as its principles, ideas, and the sequential steps involved in the control procedure.

1.3.1 Fuzzy Sets and Linguistic Variables

The core concept of FLC is centered on the idea of sets. Unlike set theory, fuzzy sets permit membership rather than strict binary classification of elements as fully belonging or not belonging to a set. Fuzzy sets excel at handling uncertainty and vagueness, making them ideal for modeling real-world systems. In a set, membership is determined by a boundary, whereas, in a fuzzy set, membership can exist to a certain degree.

Fuzzy logic uses linguistic variables to denote the input and output variables in a control system. Linguistic variables allow the use of human-like linguistic expressions to describe the states of the system. For example, in controlling the speed of a car, language such as "low," "medium," and "high" can be used to describe the speed values.

1.3.2 Membership Functions

The membership functions do play a critical role in the FLC by demarking the degree of membership of an element in a fuzzy set. A membership function maps the crisp input/output values to their corresponding degrees of membership in a fuzzy set. A fuzzy set usually allows a member to have a partial degree of membership, which can be mapped into a universe of membership values. Let us assume that we have a fuzzy set B, and if an element x is a member of this fuzzy set, the mapping can be represented as

$$\mu_B(x) \in \left[0,\ 1\right] (\mathrm{B} = (\mathrm{x}, \mu_B(x)\big|\ x \in \mathrm{X}) \tag{1.1}$$

A fuzzy subset B with an element x has a membership function of $\mu_B(x)$. In the situation when the universe of discourse X is discrete and finite, this mapping can be denoted by Equation 1.2.

$$B = \frac{\mu_B(x_1)}{x_1} + \frac{\mu_B(x_2)}{x_2} + \ldots\ldots = \sum_i \frac{\mu_B(x_i)}{x_i} \tag{1.2}$$

In the situation when universe X is continuous and infinite, at that situation, fuzzy set B can be written as

$$B = \int \frac{\mu_B(x)}{x} \tag{1.3}$$

There are several shapes of membership functions that can be used, such as triangular, trapezoidal, Gaussian, or sigmoidal, depending on the nature of the variables and the desired representation.

1.3.3 Fuzzy Rule Base

The fuzzy rule base represents the knowledge and expertise of human operators or domain experts. It is composed of several instances of fuzzy if-then rules that connect the fuzzy input and fuzzy output variables. Each rule consists of an antecedent (if-part) and a consequent (then-part). The antecedent uses fuzzy logic operators (e.g., AND, OR) to evaluate the degree of satisfaction of the rule based on the input variables' membership values. The outcome depicts the fuzzy output variables and their corresponding membership functions.

For example, a fuzzy rule that describes a situation when it is necessary to control the speed of a vehicle is: IF the distance to an obstacle is large AND the speed of the vehicle is slow THEN increase the speed. Here, the antecedent checks the level of satisfaction using the membership degree of "far" and "low." The consequent, in turn, defines the action to be taken, which is increasing the speed for this particular case.

1.3.4 Fuzzification

This stage involves transforming the crisp input values into fuzzy sets by applying the membership functions of each of them. Translation to linguistic phrases is conducted based on the membership degrees. The process of fuzzification is characterized by the need to determine the values of membership of each linguistic term dependent on the input values [10].

1.3.5 Rule Evaluation

Fuzzy paradigm thinking relies on fundamental information derived from fuzzy IF-THEN rules. After the input variables have been fuzzified, the rule evaluation step calculates the level of satisfaction for each rule by considering the fuzzy input values. The process involves the utilization of fuzzy logic operators (AND, OR) to merge the membership degrees linked to the antecedent linguistic phrases of each rule. The outcome is a level of activation for each rule, denoting the intensity or significance of the rule in the specific circumstance [11].

1.3.6 Rule Aggregation

The rule aggregation procedure combines the activated rules to determine the overall fuzzy output, after evaluating the degree of satisfaction for each rule. Multiple aggregation techniques, such as maximum, average, or weighted average, can be employed based on the particular application and control criteria.

1.3.7 Defuzzification

Defuzzification is the last phase in FLC when the fuzzy outcome received from rule aggregation is changed right into an accurate control activity. Defuzzification is the procedure of transforming the subscription levels of the fuzzy outcome back right into the crisp outcome room. Defuzzification can be achieved by making use of various methods consisting of centroid defuzzification. This method involves calculating the center of gravity of the fuzzy output and using it as the precise output value. Below are the enumerated defuzzification procedures.

- Center of sums method (COS)
- Center of gravity (COG)/centroid of area (COA) method
- Center of area/bisector of area method (BOA)
- Weighted average method
- Maxima methods
    - First of maxima method (FOM)
    - Last of maxima method (LOM)
    - Mean of maxima method (MOM)