Introduction to Intelligent Systems, Control, and Machine Learning using MATLAB

Dive into the foundations of intelligent systems, machine learning, and control with this hands-on, project-based introductory textbook, featuring:

- Precise, clear introductions to core topics in fuzzy logic, neural networks, optimization, deep learning, and machine learning, avoiding the use of complex mathematical proofs, and supported by over 70 examples.
- Modular chapters built around a consistent learning framework, enabling tailored course offerings in intelligent systems, controls, and machine learning.
- Over 180 open-ended review questions to support self-review and class discussion, and over 120 end-of-chapter problems to cement student understanding.
- Over 20 hands-on Arduino assignments connecting theory to practice, supported by downloadable MATLAB and Simulink code.
- Comprehensive appendices reviewing the fundamentals of modern control, and practical information for implementing hands-on assignments using MATLAB, Simulink, and Arduino.

Accompanied by solutions for instructors, this is the ideal guide for senior undergraduate and graduate engineering students, and professional engineers, looking for an engaging and practical introduction to the field.

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This book is dedicated to
my mother and father,
Georgette and Friedrich Schoen,
who always inspired and supported me
&
my family,
Renata, Mathias, and Natalie Schoen,
who made this book project possible

Contents

Preface

This book is for engineering students and practicing engineers interested in intelligent systems, machine learning, and their application to controls and modeling. It offers insight into the underlying mathematics and presents solutions in terms of programming using MATLAB and Simulink. As the fields of machine learning and controls are vast and continuously expanding, the book provides for the understanding of the key concepts along with practice material to allow for learning and mastery of many of these data-driven methods and algorithms. The individual chapters are constructed such that the depth of the material is modularly built with the progression of the chapter, allowing the reader or course instructor to include or leave out certain topics toward the end of a chapter if necessary. In addition, courses in intelligent systems and controls can be constructed by assembling different chapters from the book to provide emphasis and nuances that allow for tailoring the course to the audience. Examples throughout each chapter are presented with solutions as well as MATLAB and Simulink code and programs. The reader is also challenged by a set of review questions and end-of-chapter problems.

At first glance we may not be aware of the presence of automatic control when engaging with everyday activities such as driving a car, cooking dinner, or surfing the internet. The comportment of controls is only possible through its capability of perceiving and reacting to changes in the world around our activities. Despite its inconspicuous presence, control has been a major factor in improving efficiency, reliability, and safety in our daily lives. For much of its history, the development of automatic control algorithms has relied on rather precise mathematical formulations of the environment it is supposed to control. The derivation of these descriptions often depends on a first-principles approach: utilizing the underlying physics along with the mathematical relations that characterize these processes and expressing these relations as compact dynamical models. Much of the corresponding analysis, in particular the investigations into the resulting stability of the controlled system, has been based on these derived mathematical models. A competing approach to building controllers based on derived dynamic models is the "model-free" approach. *Model-free* refers to the fact that we neglect to consider some or all of the underlying physical principles when developing the characterization of the process or system we control. There are a number of model-free approaches, both statistical and deterministic. However, neural networks and machine learning approaches have garnered much popularity in recent years as alternative model-free modeling tools. The

popularity is partially due to some of the recent advancements made in deep learning, along with the availability of increased computational resources and computational capabilities. The progress in the development of these intelligent methods manifests itself in a plethora of available computer code, often using the Python programming language.

IT departments, academia, and data and computer scientists alike are not only served by this infrastructure, but actively built on it to allow the steady advancement in intelligent systems to permeate into a broad field of applications. Nonetheless, we have yet to see these model-free data-driven intelligent systems conquer a number of applications that are under the supervision of regulatory committees, such as specific flight, medical, and food safety applications. Proven and reliable methods such as PID and model predictive controllers are still the standard in many of these industries. Engineers are trained to develop, design, tune, and implement these standard controller architectures using common tools and skills acquired during their educational journey. Although Python programming has made its way into some of the current engineering curricula, control and control design is still very much done using MATLAB and Simulink. One of the reasons for the adherence to these programs is the very rich set of control design and analysis tools, including machine learning and deep learning apps, that they provide.

Is This Book for Me?

This book is primarily for engineering students in all disciplines at the advanced undergraduate or graduate level who are taking courses on intelligent control systems, machine learning, and advanced control systems. It is also suitable for information science, business, and psychology majors, among others. Each topic included in this book is clearly derived, explained, and presented in a gentle way while refraining from the use of mathematical proofs. Prior exposure to MATLAB and Simulink is a plus, but is not considered necessary. Special appendices provide tutorials on both the program environments of MATLAB and Simulink and their general use beyond control-related applications. For readers lacking a formal controls background, Appendix A details a tutorial on modern control systems, including a brief introduction and review of the major topics that a traditional controls course would cover. The use of MATLAB is emphasized in this tutorial in preparation for the primary chapters in this book.

Each topic in each chapter provides examples how to implement the concepts presented using MATLAB and Simulink. There is no emphasis on using or generating an efficient and compact MATLAB code due to the aim to remain generally readable to novice users of these programming environments. Many routines and programs in MATLAB presented in the book do not require more than a few toolboxes. However, the later chapters benefit from having access to

MATLAB apps such as the Deep Network Designer, Reinforcement Learning Designer, Classification Learner, Fuzzy Logic Designer, and Regression Learner App.

How Is the Book Structured?

The book introduces fuzzy logic-based methods and algorithms first, followed by neural networks and their use in modeling. Both topics are presented in a way that consideration of controls can be included or left out. As optimization is an integral part of many of the data-driven learning methods, heuristic as well as iterative optimization methods are detailed in separate chapters prior to their use in the respective discussions of machine learning algorithms. The later chapters emphasize deep learning concepts as well as pure machine learning algorithms. A project-based and hands-on class, or even laboratory section accompanying a traditional class, can be offered by making use of the project information as well as the microcontroller programming material described in the appendices.

How Can I Use This Book for Teaching a Class in Intelligent Systems and Controls?

The organization of this book is kept deliberately so that one can construct different types of courses. Hence, the book can be used to offer courses serving diverse interests and a range of student demographics, including graduate and undergraduate courses, as well as different disciplines in engineering and other science programs. In the following, some sample topic outlines are provided with different course emphases.

An undergraduate course in controls and intelligent systems may include:

- Appendix A – overview of modern control systems using MATLAB;
- Chapter 1 – introduction to intelligent systems, controls, and machine learning;
- Chapter 2 – principles of fuzzy logic;
- Chapter 3 – fuzzy inference systems, leaving out Section 3.4;
- Chapter 4 – optimization;
- Chapter 6 – fundamentals of neural networks;
- Chapter 7 – control design using neuro-fuzzy systems;
- Chapter 9 – introduction to machine learning concepts.

A graduate course in controls and intelligent systems can be offered by selecting the following chapters as part of the list of topics for the course:

- Chapter 2 – principles of fuzzy logic;
- Chapter 3 – fuzzy inference systems;
- Chapter 5 – intelligent optimization algorithms;
- Chapter 6 – fundamentals of neural networks;
- Chapter 7 – control design using neuro-fuzzy systems;
- Chapter 8 – deep learning;
- Chapter 9 – introduction to machine learning and reinforcement learning.

An undergraduate course that is more focused on intelligent systems than controls can be constructed by addressing the topics of the following chapters:

- Chapter 1 – introduction to intelligent systems, controls, and machine learning;
- Chapter 2 – principles of fuzzy logic;
- Chapter 3 – fuzzy inference systems, leaving out Section 3.5;
- Chapter 4 – optimization;
- Chapter 5 – intelligent optimization algorithms;
- Chapter 6 – fundamentals of neural networks;
- Chapter 8 – deep learning;
- Chapter 9 – introduction to machine learning concepts.

In addition to the various combinations of chapters to construct a course for a specific target audience, the book also includes a project for implementing some of the controls topics on an embedded system using simple components for physical demonstration and testing. The appendices provide for the necessary details on the project realization, including specifics on Arduino microcontrollers and how to program these devices using Simulink. Implementing a laboratory section for hands-on work that accompanies the lecture material is possible with the given project descriptions and implementation instructions.

What Are the Features of This Book?

Having taught intelligent control systems for a number of years, I have found that current resources that cover the range of topics entailed in the present book are usually distributed across many different books and separate tutorials, as well as online articles. Many methods and algorithms are also available online as Python code. One of the goals of this book is to combine systematically the various intelligent systems topics into one volume. In addition, an emphasis is placed on providing MATLAB-based solutions throughout the different chapters.

Having seen the benefits of incorporating hands-on projects into courses, this book allows for practicing the theoretical material on assignments that are based on a simple physical setup. These projects only involve simple physical systems and employ readily available embedded system platforms. Hands-on or

project-based components in a class or laboratory setting not only allow for a "reinforcement" learning environment, but may also provide for inspiration to expand on the material covered and to include other domain-specific projects and topics. Some of the other features of this book are:

- A consistent presentation of theory and practice: All topics are developed in a precise and clear manner, supported by examples throughout the book, supplemented with end-of-chapter problems, questionnaires, and summaries.
- The book is composed in a modular fashion, allowing for tailored course offerings in intelligent systems, controls, and machine learning.
- Many chapters include assignments that involve the practical implementation of the theory covered using a simple physical setup, a common microcontroller, and Simulink.
- The book provides for a solid introduction to machine learning using MATLAB. Included in this introduction are common classification and regression methods, as well as image processing algorithms for object identification and guidance and control applications.
- A section detailing the concept of reinforcement learning is included in Chapter 9. Although this chapter builds on prior chapters in the book, it presents a clear and easy introduction to reinforcement learning and reinforcement learning control using the appropriate MATLAB app.
- Instructors will have access to a set of PowerPoint slides covering all the images in the book. In addition, instructors can utilize full-length syllabi for some versions detailed above of a course in intelligent control systems and machine learning.
- Instructors will have access to a solutions manual. Students and instructors will have access to a companion webpage that holds a repository of all the MATLAB and Simulink code used throughout the book, as well as many of the appendices.
- For courses that build on a curriculum missing the traditional modern controls course, or students who need a review of modern controls, the book includes an entire appendix with the main concept of modern controls using MATLAB.
- Students and practitioners who are new or need a refresher in the use of MATLAB and/or Simulink have separate appendices covering a range of topics to allow them to become sufficient in the use of MATLAB and MATLAB programming, as well as Simulink programming.