

Preface

Modeling and simulation of dynamical systems has been taught all around the globe with many methods, including standard modeling techniques of differential equations. These differential equation models are later transformed into frequency domain for analysis. In the latter part of the last century, time domain analysis began to be taught at undergraduate and graduate levels. Many books are currently serving the purpose of introducing modeling and simulation of linear time invariant systems. In the current scenario, new degrees are evolving such as systems engineering, mechatronics engineering, and biomedical engineering, where concepts of different conventional degrees (electrical, mechanical, etc.) merge together. Students are always curious in taking elective courses which widen their depth of knowledge. Accordingly, the courses and relevant text are being introduced continuously for meeting this demand. A modeling technique that covers the interdisciplinary modeling problems in a much better way than any other technique is the “bond graph method.” This scheme has been taught since the mid-1970s, and the best available text is *System Dynamics: Modeling, Simulation, and Control of Mechatronic Systems* by Dean C. Karnopp, Donald L. Margolis, and Ronald C. Rosenberg, now in its fifth edition. Most of the literature or lectures are drawn from this book, as all respectable authors themselves were students of Prof. H. M. Paynter, who introduced bond graph techniques in the late 1960s. Recent developments, especially software in modeling and toolboxes in MATLAB as well as Maple, allow students to use different modeling paradigms interchangeably. In addition, a modeling software 20-Sim originally used for bond graph now also provides other modeling techniques as well. A simple course only on bond graph modeling may interest students from different backgrounds. The purpose of this book is to introduce modeling, simulation, and control perspectives to mixed-background students of different undergraduate degrees at final (senior) year or as a first/elementary course at graduate level. This book introduces state space modeling derived from two modeling techniques, namely, Lagrangian formulation and bond graph method, followed by analysis of system and usage of model in control system design. This is a one-semester text derived into eight chapters for lectures

and other texts as case studies in different applications. I myself taught this course five times at the graduate level and improved the text accordingly in order to meet the requirements of students from various engineering disciplines and concentration areas. This book in no capacity is a replacement of *System Dynamics*, which is always the unique reference book for students and teachers in terms of examples, exercises, and descriptions of problems. I myself prefer that students should attempt the examples and problems of this book for better understanding and practice to get a good grip on the subject.

The book presented here, *Real Time Modeling, Simulation and Control of Dynamical Systems*, provides a better and comprehensive study text to cover over one semester. The focus is to introduce state space modeling and Lagrangian and bond graph techniques such that students can work on advanced problems easily after this course. The book also introduces MATLAB commands and most of the examples and problems are developed in 20-Sim software. Analysis and simulation chapters use MATLAB and Simulink in order to broaden students' knowledge of various software utilities. Real-time modeling means covering the system in differential equations or equivalently state space formulation. The analysis of the state space model is presented in time domain with concepts of eigenvalues and gains mainly. Frequency-based analysis is briefly discussed. The input-based responses are also simulated in time domain with state space and not with frequency domain. The present control techniques are well understood with pole placement rather than frequency domain-based analysis; hence the focus of time-based responses are given as compared to frequency-based responses, which are mostly popular in current textbooks. The chapters are organized systematically in the natural way so students keep on building from previous knowledge. There are no recommended prerequisites for engineering students as they already cover engineering mathematics in detail before taking these electives. However, universities that offer graduate-level engineering programs to non-engineering graduates should check for engineering mathematics knowledge before recommending this course or make an "advanced engineering mathematics" course as a prerequisite to it. The chapter descriptions are given as follows.

Chapter 1: The first chapter is very important in this text in order to explain details of any system, its dynamics, what a model is, and why to model. This chapter discusses in detail the model types and classifications of models in engineering practices. Furthermore, state space formulation is introduced from ordinary differential equations for nonlinear as well as linear time varying and invariant systems. Concepts of linearization and transfer function realizations are also discussed. The state space realization developed in this chapter will further be used in Lagrangian and bond graph techniques in the following chapters.

Chapter 2: Lagrangian modeling is discussed in this chapter from basic to advance level. A single-point rigid body model in Cartesian coordinates is initially discussed and converted into polar coordinates. Later the same model is expanded in vector notation for any generalized coordinates (Cartesian, spherical, cylindrical, etc.). The basic physics behind work-energy relationship is discussed with

conservative and nonconservative forces. At the end of the chapter, state space formulation is obtained and elaborated with a few examples.

Chapter 3: This chapter introduces preliminary concepts of bond graph modeling techniques by drawing analogies of different energy systems. Concepts of power and energy variables, word bond graphs, causality, and flow of power are introduced with arguments building toward elements of bond graphs.

Chapter 4: Elements of bond graphs, which are 1-port, 2-port, and junctions, are discussed with their causality assignments and the governing or constitutive laws and examples of different energy systems. Examples within different energy systems with corresponding analogy are described. Junctions are discussed with signs of power flow as well as effort/flow equations. Modulated transformer and gyrator (2-port elements) are discussed in text, and modulated sources (1-port) are introduced in the problem section. It is assumed that students are well versed in basic knowledge of physics for electrical, mechanical, translational, and rotational systems.

Chapter 5: Writing analytical equations in state space formulation using constitutive laws is explained with different examples of electrical, mechanical, and mechatronics systems. As per existing literature, a generalized rule for all kinds of systems is not available. A simplified procedure for all kinds of systems is to be evolved into a basic methodology of bond graph as independent energy systems (electrical, mechanical, hydraulics, etc.) must not be violated. This procedure is emphasized and discussed to develop bond graph of multidisciplinary energy systems. This chapter develops capability in students to fully model different systems in bond graph and write its equations.

Chapter 6: Different concepts of advance bond graph modeling are summarized and combined in this chapter in a logical sequence so the reader can understand why specific advancement or extra elements are needed. It covers algebraic loops, derivative causality, and fields, as well as some advanced mixed system with partial bond graph portions. A further combination of elements in different requirements is discussed, and, at the end, the topic of vector bond graph is touched. This chapter helps to develop a significant grasp on the bond graphs method by exploring different key concepts so students can utilize them in their projects. This is the last of four chapters covering specific bond graph techniques.

Chapter 7: Analysis and simulation of state space systems are discussed with details in time domain and some analysis in frequency domain. Most engineering students are familiar with responses in transfer function approach, and in this chapter, these responses are discussed with state space method. Generalized solutions of state space equations followed by free and forced responses are discussed as homogenous and non-homogenous solutions. Concepts of internal and external stabilities are explained with free and forced responses, thus discussing damped and amplified systems. Forced responses are studied with impulse, step, sinusoidal, and decaying sinusoidal signals in order to elaborate the bounded input and bounded output of control system designs with stability planes and resonance.

Chapter 8: A complete paradigm of control system design based upon state space model is discussed in this chapter. It introduces a detailed simulation diagram

for control system design followed by its simplification based upon design requirements. Open- and closed-loop observers are also discussed with complete compensator design. Performance parameters and tuning of PID and control gains are also discussed with the help of MATLAB tuning and constraint optimization blocks, which help to understand the requirement of control design. The basic idea is to familiarize the readers with different types of control systems, keeping the design scope for advance courses.

Chapter 9: This chapter consists of different projects and research work for multidisciplinary energy systems with special focus on bioengineering systems. Recent advances in bond graph allows the research in the area of biomedical and bio-mechatronics systems. Bond graph models of biomechanics systems are discussed briefly in order to introduce their applications in this field. The selected projects of this part can also be taught in the classroom for description, analysis, or assessment purposes depending upon the time of the semester.

The book is written for a semester workload in real-time modeling, simulation, and control system design. This can serve as a beginning course for control system specialization and may be taken with linear system theory during the same semester. I prefer and teach this course with a semester project requiring students to develop and simulate a model of any electromechanical or mechatronics system by utilizing bond graph technique. It is highly recommended that the book *System Dynamics* should be employed as a reference book and guideline for the semester project from students. The lecture-wise breakdown is given in the table below for a 16-week semester for a 3-credit-hour course.

Content	Duration (weeks)
Chapter 1: Dynamical Systems and Modeling	1
Chapter 2: Lagrangian Modeling	2
Chapter 3: Introduction to Bond Graph Modeling	1
Chapter 4: Elements of Bond Graph	1
Chapter 5: Analytical Formulation by Bond Graph Modeling	2
Chapter 6: Advance Bond Graph Modeling	2
Chapter 7: Simulation and Analysis of State Space Systems	2
Chapter 8: Introduction to Control Systems	2
Chapter 9: Recent Applications of Bond Graph Modeling	1.5
<i>Assessments, Review, and Project Presentations</i>	<i>1.5</i>

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