STUDIES IN *FUZZINESS* AND *SOFT COMPUTING*

Oscar Castillo
Patricia Melin

Soft Computing for Control of Non-Linear Dynamical Systems

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With 112 Figures
and 13 Tables

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Preface

This book presents a unified view of modelling, simulation, and control of non-linear dynamical systems using soft computing techniques and fractal theory. Our particular point of view is that modelling, simulation, and control are problems that cannot be considered apart, because they are intrinsically related in real world applications. Control of non-linear dynamical systems cannot be achieved if we don't have the appropriate model for the system. On the other hand, we know that complex non-linear dynamical systems can exhibit a wide range of dynamic behaviors (ranging from simple periodic orbits to chaotic strange attractors), so the problem of simulation and behavior identification is a very important one. Also, we want to automate each of these tasks because in this way it is more easy to solve a particular problem. A real world problem may require that we use modelling, simulation, and control, to achieve the desired level of performance needed for the particular application.

Soft computing consists of several computing paradigms, including fuzzy logic, neural networks, evolutionary computation, and chaos theory, which can be used to produce powerful hybrid intelligent systems. We believe that to really be able to automate modelling, simulation, and control of dynamical systems, we require the use of hybrid combinations of soft computing techniques. In this way, we can exploit the advantages that each technique offers for solving these difficult problems. On the other hand, fractal theory provides us with powerful mathematical tools that can be used to understand the geometrical complexity of natural or computational objects. We believe that, in many cases, it is necessary to use fractal techniques to understand the geometry of the problem at hand.

This book is intended to be a major reference for scientists and engineers interested in applying new computational and mathematical tools to modelling, simulation, and control of non-linear dynamical systems. This book can also be used as a textbook or major reference for graduate courses like: soft computing, control of dynamical systems, applied artificial intelligence, and similar ones. We consider that this book can also be used to get novel ideas for new lines of research, or to continue the lines of research proposed by the authors of the book.

In Chapter one, we begin by giving a brief introduction to the problems of modelling, simulation, and control of non-linear dynamical systems. We discuss the importance of solving these problems for real-world applications. We motivate the reasons for automating modelling, simulation, and control using computational techniques. We also outline the importance of using soft computing techniques and fractal theory to really achieve automated modelling, simulation, and adaptive control of non-linear dynamical systems.

We describe in Chapter 2 the main ideas underlying fuzzy logic, and the application of this powerful computational theory to the problems of modelling and control of dynamical systems. We discuss in some detail fuzzy set theory, fuzzy reasoning, and fuzzy inference systems. We also describe briefly the generalization of conventional (type-1) fuzzy logic to what is now known as type-2 fuzzy logic. At the end, we also give some general guidelines for the process of fuzzy modelling and control. The importance of fuzzy logic as a basis for developing intelligent systems for control has been recognized in several areas of application. For this reason, we consider this chapter essential to understand the new methods for modelling, simulation, and control that are described in subsequent chapters.

We describe in Chapter 3 the basic concepts, notation, and the learning algorithms for neural networks. We discuss in some detail feedforward networks, adaptive neuro-fuzzy inference systems, neuro-fuzzy control, and adaptive neuro-control. First, we give a brief review of the basic concepts of neural networks and the backpropagation learning algorithm. We then continue with a general description of adaptive neuro-fuzzy systems. Finally, we end the chapter with a review of the most important current methods for neuro-control, and some general remarks about adaptive control and model-based control. The importance of neural networks as a computational tool to achieve "intelligence" for software systems has been well recognized in the literature of the area. For this reason, neural networks have been applied for solving complex problems of modelling, identification and control.

We describe in Chapter 4 the basic concepts and notation of genetic algorithms, and simulated annealing. We also describe the application of genetic algorithms for evolving neural networks, and fuzzy systems. Both genetic algorithms and simulated annealing are basic search methodologies that can be used for modelling and simulation of complex non-linear dynamical systems. Since both techniques can be considered as general purpose optimization methodologies, we can use any of them to find the model which minimizes the fitting error for a specific problem. Also, genetic algorithms can be used to automate the simulation of dynamical systems, because it can be used to produce the best set of parameter values for a model of the system. As genetic algorithms are based on the ideas of natural evolution, we can use this methodology to try evolving a neural network or fuzzy system for a particular application. The problem of finding the best architecture of a neural network is very important because there are no theoretical results on this, and in many cases we are forced to trial and error unless we use a genetic algorithm to automate this process. A similar thing occurs in the determining the optimum number of rules and membership functions of a fuzzy system for a particular application, here a genetic algorithm can also help us avoid time consuming trial and error.

We describe in Chapter 5 the basic concepts of dynamical systems and fractal theory, which are two powerful mathematical theories that enable the understanding of complex non-linear phenomena. We also describe the general mathematical methods for controlling chaos in dynamical systems. Dynamical systems theory gives us the general framework for studying non-linear systems. It can also be used to for behavior identification in complex non-linear dynamical systems. On the other hand, fractal theory gives us powerful concepts and techniques that can be used to measure the complexity of geometrical objects. In particular, the concept of the fractal dimension is very useful in classifying the complexity for time series of measured data for a problem. We discuss at the end of the chapter the problem of controlling chaotic behavior in non-linear dynamical systems. We review several methods for chaos control based on different ideas of how to move from a chaotic orbit of the dynamical system to a periodic stable orbit. This is very important in real world applications, because in many cases we need to control chaos to avoid physical damage to the system.

We describe in Chapter 6 our new method for time series analysis and prediction. This method is based on a new hybrid fuzzy-fractal approach, that combines the advantages of the fractal dimension for measuring the complexity of the time series, and of fuzzy logic for constructing a set of fuzzy rules to model the problem. We also define a new concept, which we have called the fuzzy fractal dimension, to generalize the mathematical definition of the capacity dimension. We show results of the application of our new method to real time series and measure the efficiency of our new hybrid approach for modelling. This new approach for time series prediction can be very useful for forecasting the behavior of complex non-linear dynamical systems.

We describe in Chapter 7 a new method for modelling complex dynamical systems using multiple differential equations. This method is a new fuzzy reasoning procedure that can be considered as a generalization of Sugeno's original fuzzy inference system. Our method uses a set of fuzzy rules, which have as consequents non-linear differential equations. Each equation is viewed as local model, for each region of the domain of definition for a complex non-linear dynamical system. The general idea of the approach is to simplify the task of modelling complex dynamical systems, by dividing the domain in smaller regions in which a simpler model can be formulated. We show the application of our new approach to the problems of modelling complex robotic dynamic systems, and aircraft systems. Modelling these dynamical systems can be used in controlling their complex non-linear dynamic behavior.

We describe in Chapter 8 a new method for automated simulation of non-linear dynamical systems with a hybrid fuzzy-genetic approach. Genetic algorithms are used, in this case, to generate the parameter values for the mathematical models of the dynamical systems. Fuzzy logic is used to model the uncertainty in behavior identification for a particular dynamical system. A set of fuzzy rules can be developed as a classification scheme of the dynamic behaviors using as information the fractal dimension or the Lyapunov exponents of the system. We also present a new concept, which we have called fuzzy chaos, to generalize the mathematical definition of chaos. In many cases, due to uncertainty it is more appropriate to find fuzzy regions of specific dynamic behaviors, even more for the complex chaotic behavior. We show results of the application of this hybrid fuzzy-genetic approach to the problem of automated simulation for robotic dynamic systems.

We present in Chapter 9 a new method for adaptive model-based control of robotic dynamic systems. This method combines the use of neural networks, fuzzy logic, and fractal theory to achieve real time control of robotic systems. Our neuro-fuzzy-fractal approach uses neural networks for identification and control, fuzzy logic for modelling, and fractal theory for time series analysis. We show results of our hybrid approach for several types of robot manipulators. Robotic systems are highly non-linear dynamical systems with a wide range of dynamic behaviors going from simple periodic behavior to the completely unstable chaotic behavior. In this case, chaotic behavior has to be avoided to prevent physical damage to the robot, and also other types of unstable behavior could be dangerous for the system. For this reason, the control of these systems is very important in real world applications. Our hybrid neuro-fuzzy-fractal approach exploits the advantages that each technique has for achieving the ultimate goal of controlling robotic dynamic systems in an efficient way.

We present in Chapter 10 the application of our new method for adaptive model-based control to the case of controlling biochemical reactors in the food industry. We use our hybrid neuro-fuzzy-fractal approach for controlling the complex behavior of biochemical reactors during production. Bioreactors are used in food production plants to produce the food with the required characteristics and level of quality. In this case, we need to control the reactor to optimize the production and the quality of the food product. Biochemical reactors use specific bacteria to produce chemical compounds that needed to obtain particular food products. The behavior of these reactors is highly non-linear and requires complex control strategies. For this reason, the application of soft computing techniques can help in achieving the goal of adaptive control of this type of reactors. In this case, neural networks are used for identification and control, fuzzy logic for modelling, and fractal theory for identifying bacteria during the production process.

We describe in Chapter 11 the application of soft computing techniques to the problem of controlling complex electrochemical processes. Electrochemical processes, like the ones used in battery formation, are highly non-linear and difficult to control. Also, mathematical models of these processes are difficult to obtain. The ultimate goal, in this case, is to control the process to optimize the manufactured product, avoiding at the same time going over the limiting temperature value for the electrochemical reaction. We use a hybrid neuro-fuzzy-genetic approach to control the electrochemical process during battery formation in a manufacturing plant. Neural networks are used for modelling the electrochemical reaction, fuzzy logic is used for controlling the process, and genetic algorithms are used to optimize the membership functions for the fuzzy systems using as input the measured data for the process.

We describe in Chapter 12 the application of soft computing techniques to the problem of controlling aircraft dynamic systems. Aircraft systems, are very complicated non-linear dynamical systems that show a wide range of dynamic behaviors even chaos. For this reason, controlling these systems is a very difficult task. We use a hybrid neuro-fuzzy-fractal approach for controlling the aircraft dynamics during flight. Neural networks are used for identification and control of the system, fuzzy logic for modelling, and fractal theory to measure the complexity of dynamic situation. We use our new fuzzy reasoning procedure for multiple differential equations to model the complex dynamical system. Our hybrid neuro-fuzzy-fractal approach enables on-line real time control of these type of dynamical systems.

Finally, we present in Chapter 13 the application of soft computing techniques to the problem of controlling dynamic economic systems. We consider the complex situation of the competing economies of three countries with international trade. This economic system is highly non-linear and coupled, and for this reason has a wide range of dynamic behaviors going from simple stable periodic orbits to the very unstable chaotic behavior. The ultimate goal, in this case, is to control international trade so as achieve stable economic growth and optimize the national income. We can use mathematical models of this economic system to simulate different kinds of behaviors and analyze the possible routes for control. We can then use a fuzzy system with rules having as consequents differential equations, to completely model the economic dynamic system. We can also use neural networks to control the economic system. The neural networks can be trained with historical data or using a genetic algorithm and simulations. Our hybrid approach can enable the control of this complex economic dynamic system, and illustrates that computing techniques can also be applied to problems in economics.

Contents

Chapter 1

Introduction to Control of Non-Linear Dynamical Systems

We describe in this book, new methods for modelling, simulation, and control of dynamical systems using soft computing techniques and fractal theory. Soft Computing (SC) consists of several computing paradigms, including fuzzy logic, neural networks, and genetic algorithms, which can be used to produce powerful hybrid intelligent systems. Fractal theory provides us with the mathematical tools to understand the geometrical complexity of natural objects and can be used for identification and modelling purposes. Combining SC techniques with fractal theory, we can take advantage of the "intelligence" provided by the computer methods and also take advantage of the descriptive power of fractal mathematical tools. Non-linear dynamical systems can exhibit extremely complex dynamic behavior, and for this reason, it is of great importance to develop intelligent computational tools that will enable the identification of the best model for a particular dynamical system, then obtaining the best simulations for the system, and also achieving the goal of controlling the dynamical system in a desired manner.

As a prelude, we provide a brief overview of the existing methodologies for modelling, simulation, and control of dynamical systems. We then show our own approach in dealing with these problems. Our particular point of view is that modelling, simulation and control are problems that can not be considered apart because they are intrinsically related in real-world applications. We think that in many cases control of non-linear dynamical systems can not be achieved if we don't have proper mathematical models for the systems. Also, useful simulations of a model, that can give us numerical insights into the behavior of a dynamical system, can not be obtained if we don't have the appropriate model.

Traditionally, mathematical models of dynamical systems have been obtained by statistical methods, which lack the accuracy needed in real-world applications. We instead of the traditional approach, consider a general modelling