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INTRODUCTION TO HYBRID ARTIFICIAL INTELLIGENCE SYSTEMS

As complexity rises, precise statements lose meaning and meaningful statements lose precision.

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1.1 INTRODUCTION

The term "artificial intelligence" (AI), in its broadest sense, encompasses a number of technologies that includes, but is not limited to, expert systems, neural networks, genetic algorithms, fuzzy logic systems, cellular automata, chaotic systems, and anticipatory systems. Interestingly, most of these technologies have their origins in biological or behavioral phenomena related to humans or animals, and many of these technologies are simple analogs of human and animal systems. Hybrid intelligent systems generally involve two, three, or more of these individual AI technologies that are either used in series or integrated in a way to produce advantageous results through synergistic interactions. In this book we have placed emphasis on neural networks and fuzzy systems; to a lesser extent, we have also placed emphasis on genetic algorithms where needed for optimization and expert systems where they are needed to supervise and implement the other three technologies. A major emphasis in this book will be on the integration of fuzzy and neural systems in a synergistic way.

In data and/or information processing, the objective is generally to gain an understanding of the phenomena involved and to evaluate relevant parameters quantitatively. This is usually accomplished through "modeling" of the systems, either experimentally or analytically (using mathematics and physical principles). Most hybrid systems relate experimental data to systems or models. Once we have a model of a system, we can carry out various procedures (e.g., sensitivity analysis, statistical regression, etc.) to gain a better understanding of the system. Such experimentally derived models give insight into the nature of the system behavior that can be used to enhance mathematical and physical models.

There are, however, many situations in which the phenomena involved are very complex and often not well understood and for which first principles models are not possible. Even more often, physical measurements of the pertinent quantities are very difficult and expensive. These difficulties lead us to explore the use of neural networks and fuzzy logic systems as a way of obtaining models based on experimental measurements.

1.2 NEURAL NETWORKS AND FUZZY LOGIC SYSTEMS

In the history of science and technology, new developments often come from observations made from a different perspective. Interrelationships that we take for granted today may not have been so obvious in earlier decades. For instance, we regularly gain insight into the behavior of a dynamic system by viewing it as being in the "time domain" and/or the "frequency domain." However, for the first four decades of the twentieth century, statisticians dealt with autocorrelation and cross-correlation functions (in the time domain) while electrical engineers dealt with power- and cross-spectral densities (in the frequency domain) without either group realizing that these two concepts were related to each other through Fourier transformations.

Both the statisticians and the electrical engineers have found that analysis of the fluctuations in process variables provides useful information about the variables as well as the processes involved. These fluctuations, which result in uncertainties in measured variables, often are caused by some sort of random driving function (i.e., fluid turbulence, rotational unbalance, etc.). Investigation, and the subsequent understanding of these uncertainties (fluctuations), led to the development of the field of "random noise analysis" which spawned such analytical specialties as vibration analysis, seismology, electrocardiography, oceanography, and so on.

Neural networks and fuzzy systems represent two distinct methodologies that deal with uncertainty. Uncertainties that are important include both those in the model or description of the systems involved as well as those in the variables. These uncertainties usually arise from system complexity (often including nonlinearities; we think of complexity as a property of system description—that is, related to the means of computation or language and not merely a system's complicated nature). Neural networks approach the modeling representation by using precise inputs and outputs which are used to "train" a generic model which has sufficient degrees of freedom to formulate a good approximation of the complex relationship between the inputs and the outputs. In fuzzy systems, the reverse situation prevails. The input and output variables are encoded in "fuzzy" representations, while

their interrelationships take the form of well-defined *if/then* rules. Zadeh's ingenious observation that the uncritical pursuit of precision may be not only unnecessary but actually a source of error led him to the notion of a fuzzy set.

Each of these approaches has its own advantages and disadvantages. Neural networks can represent (i.e., model) complex nonlinear relationships, and they are very good at classification of phenomena into preselected categories used in the training process. On the other hand, the precision of the outputs is sometimes limited because the variables are effectively treated as analog variables (even when implemented on a digital computer), and "minimization of least squares errors" does not mean "zero error." Furthermore, the time required for proper training a neural network using one of the variations of "backpropagation" training can be substantial (sometimes hours or days). Perhaps the "Achilles heel" of neural networks is the need for substantial data that are representative and cover the entire range over which the different variables are expected to change.

Fuzzy logic systems address the imprecision of the input and output variables directly by defining then with fuzzy numbers (and fuzzy sets) that can be expressed in linguistic terms (e.g., *cold*, *warm*, and *hot*). Furthermore, they allow far greater flexibility in formulating system descriptions at the appropriate level of detail. Fuzziness has a lot to do with the parsimony and hence the accuracy and efficiency of a description. This means that complex process behavior can be described in general terms without precisely defining the complex (usually nonlinear) phenomena involved. Paraphrasing *Occam's Razor*, the philosophical principle holding that more parsimonious descriptions are more representative of nature, we may say that fuzzy descriptions are more parsimonious and hence easier to formulate and modify, more tractable, and perhaps more tolerant of change and even failure.

Neural network and fuzzy logic technologies are quite different, and each has unique capabilities that are useful in information processing. Yet, they often can be used to accomplish the same results in different ways. For instance, they can speed the unraveling and specifying the mathematical relationships among the numerous variables in a complex dynamic process. Both can be used to control nonlinear systems to a degree not possible with conventional linear control systems. They perform mappings with some degree of imprecision. However, their unique capabilities can also be combined in a synergistic way. It is this combination of the two technologies (as well as combinations with other AI technologies) with the goal of gaining the advantages of both that is the focus of this book.

1.3 THE PROGRESS IN SOFT COMPUTING

Soft computing refers to computational tools whose distinguishing characteristic is that they provide approximate solutions to approximately formulated problems (Aminzadeh, 1994). Fuzzy logic, neural networks, probabilistic reasoning, expert systems, and genetic algorithms are some of the constituents of soft computing, all having roots in the field of Artificial Intelligence. Whereas the traditional view of computing considers any imprecision and uncertainty undesirable, in soft computing some tolerance for imprecision and uncertainty is exploited in order to develop more tractable and robust models of systems, at a lower cost and greater economy of communication and computation.

Few of those who attended the historic 1956 Dartmouth Conference to discuss "the potential use of computers and simulation in every aspect of learning and any other feature of intelligence" could have envisioned the evolution and growth of the embryonic artificial intelligence field and the impact it has had on our lives. It was there that the term "artificial intelligence" was coined, perhaps because of the emphasis on learning and simulation. The term "cybernetics" was in vogue at that time with its emphasis on potential control of both man and machines. Vacuum-tube-type analog computers had reached a state of maturity that they (along with high fidelity stereo sound systems) were being marketed as "Heathkits," while the digital "supercomputer" of the time was an IBM-650 with about 2000 words of magnetic drum memory storage that operated at about 2 kHz.

It was in this environment that Frank Rosenblat developed the Perceptron by adding a learning capability to the McCulloch-Pitts model of the neuron, Marvin Minsky built the first "learning machine" (using 40 processing elements, each with six vacuum tubes and a motor/clutch/control system), and Bernard Widrow developed the "Adaline" (adaptive linear element) that even today is used in virtually every high-speed modem and telephone switching system to cancel out the echo of reflected signals. Boolean algebra was standard procedure, and John McCarthy and John von Neuman were putting forth the relative merits of symbolic (LISP) and conventional computer languages. Although there was little in the way of theoretical bases providing an understanding of these systems, work proceeded on an experimental basis that was guided primarily by the genius of the individuals involved.

Today, some 40 years later, the whole world has changed. The computing capacity of that IBM-650 is now encapsulated in a "wristwatch" computer, the Perceptron and Adaline processing elements are instantiated in neural network computing and processing methodologies, learning algorithms are routinely processed on digital computers of all sizes, *Boolean logic* and algebra are being replaced by fuzzy logic concepts, LISP is fading away in favor of object-oriented computer languages for artificial intelligence (e.g., C++), the analog computer has virtually disappeared, and the modern personal computer most of us have on our desks may have more than a gigabyte of memory, operate at a processing rate of 200 MHz or more, and be part of a vast global network of computers capable of sharing on-line information in numerical, textual, visual and audible forms.

The educational, technological, economic, and social impact and significance of the computer as a tool for computation and communication have been continuously discussed and debated in the last few decades. In the 1970's Ralph Lapp, in an interesting book called *The Logarithmic Century*, captured the ever-changing and accelerating trend in the development of technology and economics (Lapp, 1973). Yet, he did not foresee the magnitude of the impact of advanced computer technology, especially the role that communications and information processing would have on society. Perhaps our Japanese colleagues have a better grasp of the issues involved. In a book entitled *The Next Century*, Halberstam (1991) reported a conversation with a retired high official of MITI (Ministry for International Trade and Industry) who in 1987 said "...the (Japanese) educational system is in danger of...producing young people who have the intellectual capacity of computers but who will be inferior to computers in what they can actually do. The computers have caught up."

Of course, the road of technological change is by no means simple. Eloquent critics such as Neil Postman in his evocative book *Technopoly* strongly point out the dangers of subordinating culture and society to an uncritical faith in the machine (Postman, 1993). Indeed, computers cannot magically solve our problems. In today's highly integrated world, however, a diverse world population needs the multiplicity of opportunities provided by the new communications and computer technologies, and soft computing is promising to become a powerful means for obtaining quick, yet accurate and acceptable, solutions to many problems. We, the engineers who work to provide and apply these new soft computing tools, ardently hope that they will be used for the benefit of mankind.

1.4 INTELLIGENT MANAGEMENT OF LARGE COMPLEX SYSTEMS

The real challenge to *soft computing* is the intelligent management of large complex systems—that is, organizations operating on the scale of the global economy and resting on an highly globalized information infrastructure. It is perhaps the most important activity facing industrial, educational, military, and governmental organizations throughout the world today. Management decisions made today will reverberate throughout these organizations for years to come. Management decisions made in the past have shaped these organizations and have made them what they are today. In some cases, large organizations have made the "right decisions" and have been spectacularly successful. However, it is clear that the decisions of other large organizations have not been wise. Multi-hundred million and billion dollar losses, followed by layoffs, restructuring, mergers, and, all too often, bankruptcy are common as these organizations pay the price for past mistakes. Why did these organizations get into trouble or fail? What steps can be taken to ensure that decisions today are better than those in the past? The answers to these questions are as varied as the nature of the organizations. Typical responses given are as follows: incompetent management, too much attention to the next quarterly earnings, lack of vision, fierce new competition, unfair regulatory practices by governments, poor design, failure to keep up with the times, antagonism between labor and management, inadequate research and development, and so on. The list goes on and on. All of these may be valid explanations in individual situations, but correcting these alleged problems will not guarantee that an organization will be successful in meeting its goals in the future. The successful strategies and methodologies of the 1980s may not work in the next century.

Large complex systems, as a general class, are often virtually out of control; indeed they are often deemed to be uncontrollable because of their complexity. The reversal of this situation is absolutely essential in a society in which systems tend to grow without bound because of the perceived benefits of "economy of scale." Indeed, organizations tend to grow until they reach a level of inefficiency that inhibits and impedes their growth. Only an organization with virtually unlimited resources or power (i.e., governmental organizations) can continue to grow under these conditions. The finite resources of the world and of individual nations, as well as the growing population that aspires for improved living conditions, demand improved efficiency. It is absolutely essential for the benefit of mankind, as well as most modern nations that tend to be dominated by large complex systems, that these systems be brought under intelligent control and management. The advances in digital computer technology (both hardware and software) during the past decade, along with the associated development of *soft computing*, appear, for the first time in history, to provide a means of implementing intelligent control of complex systems which are so necessary in delivering the fruits of industrial technology and commerce to global society.

The personal computers or workstations available on the desk of engineers and managers today with its *soft computing* tools has the power of main-frame computers just a few years ago. They provide the capability of keeping track of what is going on in any organization (intelligence), they can provide the tools to examine the data in excruciating detail (analysis), they can provide models of the behavior of complex systems (synthesis) which then permits predictions into the future, at least into the short-term future, and they can provide recommendations for specific actions (intelligent management) that can be communicated to those who have a need to act in a form that they can understand (intelligent communications). To the extent that an organization's management is willing to utilize these tools correctly, significant progress in solving some of these problems by making the "right" decisions will follow.

Unfortunately, making the "right" decision under the circumstance at the time the decision is made does not guarantee success. It may have been the "right" decision at the time, but the consequences may be unpredictable because of the time lag between decision and results in a changing environment. What is needed is a form of anticipatory control as discussed in Chapter 15. In the absence of an ability to predict the future behavior of

systems, many conservative organizations have elected a "minimum step" approach—that is, make a decision at the last possible moment that involves the least amount of (financial or resource) commitment and produces results at the earliest possible time. However, this can be a strategy for disaster if the basis on which the decision is made is not valid. All too often, decisions must be made in the absence of complete data, which gives rise to uncertainty in the analysis and a higher probability of an erroneous decision. Even such a "minimum step" approach requires *reliable intelligence*, *accurate analysis*, *valid synthesis*, *intelligent management*, and *intelligent communications*, because there is little margin for error. While a modern digital computer cannot guarantee the availability of these five attributes, they simply would not be available without the modern digital computers and *soft computing*.

Perhaps the single attribute that gives neurofuzzy systems an advantage in addressing the problems of large complex systems is the ability to perform what in mathematical terms would be called *many-to-many mappings*. Such mappings are an inherent part of complex systems, because every single input to a system can influence every single output; i.e., one significant input change may generate significant changes in many outputs. Most approaches to systems analysis can only deal with *one-to-one* or *many-to-one mappings*—that is, with the special class of mathematical mappings that we call *functions*, which have been the premier mathematical relation since the Newtonian revolution of the *Principia*. It is now possible and desirable, however, to effectively compute with more complex mathematical mappings than functions—that is, with *many-to-many relations* (see Section 5.1). This gives us the hope and the expectation that large complex systems can be dealt with in a flexible, reliable, and near-optimal manner.

We do not claim that *neurofuzzy* systems *per se* can bring about the control of large complex systems. It is clear to us that the integration of many technologies in a yet indiscernible manner is an essential step in the right direction. *Neurofuzzy systems* represent an integration of fuzzy logic and neural networks that have capabilities beyond either of these technologies individually (Haykin, 1994; Kartalopoulos, 1996). When we further integrate other technologies, perhaps some not yet discovered, in the decades ahead, we can look forward to tools with sufficient power to tackle problems such as intelligent control of large complex systems.

1.5 STRUCTURE OF THIS BOOK

This book is divided into four parts: Part I, entitled "Fuzzy Systems: Concepts and Fundamentals," explores the fundamentals of fuzzy logic systems and includes the following chapters:

Chapter 2. Foundations of Fuzzy Approaches
Chapter 3. Fuzzy Relations

Chapter 4. Fuzzy Numbers
Chapter 5. Linguistic Descriptions and Their Analytical Forms
Chapter 6. Fuzzy Control

Part II, entitled "Neural Networks: Concepts and Fundamentals," explores the fundamentals of neural networks and includes the following chapters:

Chapter 7. Fundamentals of Neural Networks
Chapter 8. Backpropagation and Related Training Algorithms
Chapter 9. Competitive, Associative, and Other Special Neural Networks
Chapter 10. Dynamic Systems and Neural Control
Chapter 11. Practical Aspects of Using Neural Networks

Part III, entitled "Integrated Neural–Fuzzy Technology," explores the joint use of neural networks and fuzzy logic systems. It includes the following chapters:

Chapter 12. Fuzzy Methods in Neural Networks
Chapter 13. Neural Methods in Fuzzy Systems
Chapter 14. Selected Hybrid Neurofuzzy Applications
Chapter 15. Dynamic Hybrid Neurofuzzy Systems

Part IV, entitled "Other Artificial Intelligence Systems," reviews other artificial intelligence systems that can be used with neural networks and fuzzy systems. It includes the following chapters:

Chapter 16. Expert Systems in Neurofuzzy Systems
Chapter 17. Genetic Algorithms
Chapter 18. Epilogue

1.6 MATLAB©[1] SUPPLEMENT

In this text, we have included problems for students at the end of most chapters. Generally, these problems are pedagogical in nature and are intended to be simple enough that they can be solved without the aid of computer software. To supplement these exercises, we have enlisted our colleague, Dr. J. Wesley Hines of the University of Tennessee, to prepare a *MATLAB© Supplement for Neural and Fuzzy Approaches in Engineering*, a paperback book of approximately 150 pages published by John Wiley and Sons, in which the Student Edition of MATLAB© (The MathWorks Inc., 1995; Hanselman, 1996) can be used for demonstrations and solving more sophisticated problems. Of course, the Professional Version of MATLAB© can also be used if it is available.

[1]MATLAB is copyrighted by MathWorks Inc., of Natick, MA.

This supplement was written using the MATLAB© Notebook and Microsoft WORD Version 6.0. The Notebook allows MATLAB© commands to be entered and evaluated while in the WORD environment, which allows the document to both briefly explain the theoretical details and also show MATLAB© implementations. It also allows the user to experiment with changing the MATLAB© code fragments in order to gain a better understanding of their application.

This supplement contains numerous examples that demonstrate the practical implementation of relevant techniques using MATLAB©. Although MATLAB© toolboxes for Fuzzy Logic and Neural Networks are available, they are not required to run the examples given. This supplement should be considered to be a brief introduction to the MATLAB© implementation of neural and fuzzy systems, and we and the author strongly recommend the use of Neural Networks and Fuzzy Logic Toolboxes for a more in-depth study of these information-processing technologies. Many of the m-files and examples are extremely general and portable while other examples will have to be altered significantly for use to solve specific problems.

The content of the *MATLAB© Supplement* is coordinated with *Fuzzy and Neural Approaches in Engineering* so that students can use it to enhance their knowledge of fuzzy systems, neural networks, and neurofuzzy systems. Indeed, it is expected that many instructors will choose to use both this book and the *MATLAB© Supplement* together in their classes. Practicing engineers and scientists in industry who want to use this text to learn about neural, fuzzy, and neurofuzzy systems will find this supplement to be a valuable aid in their self-study.

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I

FUZZY SYSTEMS: CONCEPTS AND FUNDAMENTALS