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Fuzzy Logic Technology and Applications

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IEEE Technology Update Series

Fuzzy Logic Technology and Applications

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PREFACE BY
Lotfi A. Zadeh

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FOREWORD

Fuzzy systems and neural networks have emerged as important new technologies for consumer and industrial applications. In recognition of the growing volume of research and interest in this field, the IEEE Technical Activities Board (TAB) and the TAB Book Broker Committee selected fuzzy logic as the topic of the second volume in the IEEE Technology Update Series. This Series was developed to furnish readers with up-to-date research and practical applications information in specific fields of interest. "Fuzzy Logic: Technology and Applications" contains applications-oriented material from IEEE conferences and journals for electrotechnology professionals around the world.

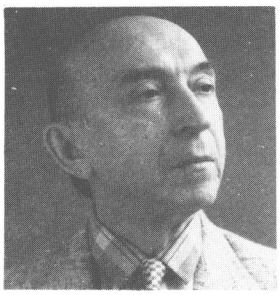
For bringing this book to fruition, my thanks go to Robert J. Marks II for serving as Editor-in-Chief and for gathering an outstanding group of Associate Editors and papers in the field of fuzzy logic. Prof. Marks served as the first President of the IEEE Neural Networks Council and continues to be a leader in the field. Conferences sponsored and co-sponsored by the Neural Networks Council provided much of the material for this reprint book.

I am indebted to Prof. Donald M. Bolle, IEEE Vice President-Technical Activities, and Dr. Jan Brown, Chair of the TAB Book Broker Committee, for their guidance in this venture.

I would also like to recognize the diligence and time expended by my staff in fulfilling the task of bringing this book to print. Thanks go to Tania Skrinnikov, Harry Strickholm, John Vitale, Mark A. Vasquez-Jorge, Lois Pannella, Patricia Thompson and Jayne F. Cerone for their editorial input. The production assistance of Ann H. Burgmeyer, Production Editor, and Art Director Janet Romano completed the task.

Robert T. Wangemann
Staff Director - IEEE Technical Activities

PREFACE



Lotfi A. Zadeh

The past few years have witnessed an explosive growth in the number and variety of papers dealing with the applications of fuzzy logic. A consequence of the wide variety of applications is a wide dispersal of the sources of publication. By assembling and structuring a representative collection of applications in a single volume, Professor Robert Marks II, the Editor, and the Associate Editors of "Fuzzy Logic: Technology and Applications" have performed a valuable service.

Although some of the earlier controversies regarding the applicability of fuzzy logic have abated, there are still influential voices which are critical and/or skeptical. Some take the position that anything that can be done with fuzzy logic can be done equally well without it. Some are trying to prove that fuzzy logic is wrong. And some are bothered by what they perceive to be exaggerated expectations. That may well be the case but, as Jules Verne had noted at the turn of the century, scientific progress is driven by exaggerated expectations.

To view the claims and the counterclaims in a proper perspective, it is necessary, first, to clarify what is meant by fuzzy logic. There is a need for such a clarification because the label fuzzy logic is used in two different senses.

In a narrow sense, fuzzy logic, FLn, is a logical system which aims at a formalization of approximate reasoning. In this sense, FLn is an extension of multivalued logic. However, the agenda of FLn is quite different from that of traditional multivalued logics. In particular, such key concepts in FLn as the concept of a linguistic variable, canonical form, fuzzy if-then rule, fuzzy quantification, fuzzification and defuzzification, predicate modification, truth qualification, the extension principle, the compositional rule of inference and interpolative reasoning, among others, are not addressed in traditional systems. This is the reason why FLn has a much wider range of applications than traditional logical systems.

In its wide sense, fuzzy logic, FLw, is fuzzily synonymous with fuzzy set theory, FST, which is the theory of classes with unsharp boundaries. FST is much broader than FLn and includes the latter as one of its branches. What is important to realize is that any field X can be fuzzified -- resulting in fuzzy X -- by replacing the concept of a crisp set in X by a fuzzy set. This is the genesis for fuzzy arithmetic, fuzzy mathematical programming, fuzzy probability theory, fuzzy decision analysis, fuzzy control, fuzzy neural network theory, fuzzy topology, etc. The question is: What is accomplished by fuzzifying X? The answer is (a) greater generality; and (b) enhanced ability to deal with real-world problems, especially in the realms of control, probability theory, decision analysis and, more generally, those fields in which crisp models are unrealistic or there is an opportunity to exploit the tolerance for imprecision to achieve higher MIQ (Machine Intelligence Quotient) and/or lower cost.

In arguing about fuzzy logic, it is necessary to recognize that, at this juncture, the label fuzzy logic, FL, is used most frequently in its wide sense, mainly because as a label fuzzy logic is more euphonious and self-explanatory than fuzzy set theory. This is the perspective in which the contents of "Fuzzy Logic: Technology and Applications" should be viewed.

Today, most of the applications of fuzzy logic are based -- implicitly rather than explicitly -- on the use of a subset of FL which might be called the calculus of fuzzy rules (CFR). As its name suggests, CFR is concerned with the generation and processing of fuzzy if-then rules. The importance of CFR derives from the fact that it is basically a language which serves to describe and analyze imprecise dependencies -- dependencies which do not lend themselves to representation via differential equations, difference equations, algebraic equations or other conventional techniques. What is important to recognize is that CFR does not replace the conventional

techniques. Rather, it adds to them a body of concepts and techniques which can be used effectively in the conception, analysis, design and construction of systems which in their entirety or in part involve imprecisely defined or imprecisely known dependencies or commands. The wide range of applications covered in this volume suggest that such systems are ubiquitous. The controversies surrounding fuzzy logic will fade away when this becomes a widely accepted view.

"Fuzzy Logic: Technology and Applications" is certain to find an appreciative audience and contribute importantly to the awareness of ways in which fuzzy logic can be applied in the solution of real-world problems. The editors of the volume deserve our thanks and congratulations.

INTRODUCTION

Lord Kelvin argued in 1885 that "Heavier than air flying machines are impossible." In 1923, Nobel Laureate Robert Milikin claimed, "There is no likelihood man can ever tap the power of an atom." Henry M. Warner of Warner Brothers fell victim to his own thinking inertia in 1927 when he muttered "Who the hell wants to hear actors talk?" Today, a US President quoted saying "Sensible and responsible women do not want to vote" as Grover Cleveland did in 1905 would be committing political suicide. These are but a few examples of resistance to a paradigm shift -- a revolutionary alteration in a way of thinking.

The term 'fuzzy', first introduced by Lotfi Zadeh in 1965 [1], invokes similar responses. Consider the following recently published comment.

"The image of (fuzzy control) which is portrayed is of the ability to perform magically well by the incorporation of 'new age' technologies of fuzzy logic, neural networks, expert systems, approximate reasoning, and self organization in the dismal failure of traditional methods. This is pure, unsupported claptrap which is pretentious and idolatrous in the extreme, and has no place in the scientific literature" [2].

Mamdani [3] counters that statements such as this emanate from a *'cult of analyticity'*. What is the truth? Are fuzzy systems 'claptrap' or are they, as others claim, a revolutionary technology? Can't other technology be used to do the same thing fuzzy systems do [4]? Isn't the lack of stability assurance a hindrance to the use of fuzzy control [5]? Doesn't a dimensional explosion of rules prohibit the use of fuzzy control of multivariate systems? These questions are examples of concerns over fuzzy systems that largely remain unanswered. Nevertheless, these and other open questions have not been a hindrance in attempts to apply fuzzy technology to certain problems. One of the purposes of this book is to address the utility of fuzzy systems by looking at the evidence, i.e., the applications, of fuzzy systems. One indisputable fact is that fuzzy systems have been applied to a wide spectrum of engineering applications and, in certain important cases, work quite well.

The research and development activity in fuzzy systems have been increasing rapidly. The vitality of the field can be seen in the recent increase in publication and patent activity [6]. Figure 1 shows the publication activity in fuzzy systems over the last few years. In 1991, over 1400 papers dealt with the topic. A better gauge of fuzzy system application and implementation is in the United States patent activity shown in Figure 2. The number of fuzzy patents issued in 1992 exceeds the sum total of all previously issued fuzzy system patents.

The papers in this volume were chosen from hundreds of fuzzy papers published in IEEE conference records over the last few years. Except for overview manuscripts, each paper deals with an application of fuzzy systems. The papers were chosen by a distinguished pool of Associate Editors. In general, the Associate Editors are neither specialists nor advocates of fuzzy systems. They are, rather, disinterested practitioners in an applications area where fuzzy systems can be used. Papers were thus chosen in accordance to the worth of their proposed application.

Robert J. Marks II
Editor

SCANNING THE BOOK

Engineering specialties are either problems looking for solutions (e.g. robotics, power engineering, industrial applications, vehicular technology) or solutions looking for problems (e.g. signal processing, neural networks, computer science). Fuzzy systems fall into the latter category. The section titles in this book fall into the former. Indeed, most of the section titles are the names of IEEE Societies wherein problems seek solutions. Section 2, for example, contains papers appropriate for the IEEE Vehicular Technology Society, Section 3 the IEEE Robotics and Automation Society, Section 5 the IEEE Power Engineering Society, etc. The proposed applications across numerous IEEE specialties is evidence of the widespread utility of and interest in fuzzy systems.

The first section of this volume contains surveys and *Overviews* of various areas of fuzzy systems. The first paper, by James C. Bezdek, is reprinted from the inaugural issue of the *IEEE Transactions on Fuzzy Systems*. Bezdek directly addresses many of the misconceptions about fuzzy logic using fundamental examples. His 'evolution of new technology' curve nicely describes the perception of fuzzy logic throughout the last three decades. It is a curve traveled by the evolution of a number of technologies, including information theory in the 1950's, optical computing in the 1970's, neural networks in the 1980's and virtual reality in the 1990's.

Takagi provides an overview of the application of fuzzy logic to appliances including washing machines, air conditioners, vacuum cleaners, microwave ovens, clothes dryers, electric fans, refrigerators and rice cookers. The vast majority of these products are produced by Japanese corporations who, historically, are singularly responsible for the reduction of fuzzy logic to practice. Fuzzy logic has also found an important place in the Intelligent Highway System. Bosacchi and Masaki provide a broad overview. One of the most popular applications of fuzzy logic is to control. Mamdami, who pioneered fuzzy control, reflects on two decades of its development. Finally, Krishnapuram and Keller present an overview of fuzzy computer vision and Pal reviews fuzzy image processing and recognition. Both of these papers contain extensive bibliographies.

The papers in the *Vehicular Technology* section explore applications of fuzzy systems to such diverse vehicular technology applications such as speed and cruise control, guidance, automatic transmission control, traffic signal control, carburetor control and suspension design. Anti-lock braking is both a nonlinear and time variant problem. Madau, Yuan, Davis and Feldkamp show that fuzzy systems provide a viable approach to the problem.

Fuzzy systems offers solutions to many of the control problems encountered in *Robotics* both in arm manipulation and navigation. Control of nonlinear time variant *Motors, Servos and Drives* can be quite difficult. Fuzzy approaches are shown through experimentation and prototyping to be a solution. In *Power Systems*, fuzzy expert systems for forecasting and fault isolation are tested with actual power system data. Power system stabilization using fuzzy methods is both simulated and applied to a four machine study system. Papers in *Industry Applications* deal with application of fuzzy systems to diverse problems, including tank level control, sewer overflow control, air pollution monitoring, semiconductor manufacturing, built-in testing, welding control, natural gas system design, machining, and photo-voltaic energy conversion.

In *Electronics*, Pin & Watanabe discuss the use of a custom-designed VLSI chip in the control of a car. Franssila & Koivo control a robot using fuzzy transputer circuitry. Use of fuzzy logic in VLSI circuit design and adaptive multiprocessor arbitration protocol is also presented. Fuzzy systems are used to increase the performance of certain *Sensors*. Improved performance is verified through a series of extensive experiments.

In the *Aeronautics* section, Berenji et.al. contrast conventional and fuzzy control of the Space Shuttle. Fuzzy control and automatic carrier landing of flying vehicles is also addressed. *Communications* applications of fuzzy logic include HDTV, vector quantization and nonlinear channel equalization.

Bioengineering has potentially a number of interesting fuzzy applications, including blood pressure control, hospital stay forecasting and heart rate trend classification. LaPlante, Sinha and Giardina present an interesting technique of fuzzy *Pattern Recognition* where coin quality is graded. Region extraction and scene understanding are also discussed

in this section. *In Image Recognition,* facial expressions, documents, spelling, handwriting, thermal infrared images and vowels are recognized using fuzzy systems.

The uncertainties of *Management* suggest application of fuzzy logic. A fuzzy model is proposed to simulate the activities of a group. Fuzzy models are also proposed for human decision-making and personnel evaluation.

The last section is entitled *General and Multidisciplinary.* It contains papers who belong in a section of their own. Egusa et.al. discuss the operation of video camera stabilization based on fuzzy reasoning. Banknote transfer control by fuzzy methods is proposed by Sato et.al. Fuzzy solutions are also proposed for electrophotography process control, virtual reality intent amplification, database security clouding, and simulation of the motions of an orchestra conductor.

FOR FURTHER INFORMATION:

There are a number of resources available on fuzzy systems.

• Videos:

A number of videos covering fuzzy systems are available from the *IEEE Educational Activities Board* (800 678-IEEE). A wonderful video conference proceedings covering the *1993 International Conference on Fuzzy Systems* (FUZZ-IEEE) and the *1993 IEEE International Conference on Neural Networks* is **Fuzzy Logic and Neural Networks: Clips from the Field (FUZZ-IEEE '93)**, San Francisco, March 1993.

It nicely covers a number of fascinating applications of fuzzy systems including self tuning fuzzy systems, and helicopter and robotics control.

Also available from EAB is a series of topical tutorials. Each runs about two hours.

- **Introduction to Fuzzy Set Theory and Fuzzy Logic: Basic Concepts and Structures** by Enrique Ruspini, SRI
- **International Fuzzy Logic: Advanced Concepts and Structures,** Lotfi Zadeh, UC/Berkeley
- **Information Processing With Fuzzy Logic,** Pierro Bonissone, General Electric
- **Fuzzy Logic and Neural Networks for Control Systems,** Hamid R. Berenji, NASA Ames Research Center
- **Fuzzy Logic and Neural Networks for Pattern Recognition,** James C. Bezdek, University of West Florida
- **Fuzzy Logic for Neural Networks for Computer Vision,** James Keller, University of Missouri

All of these tapes are sponsored by the *IEEE Neural Networks Council.*

• Journals:

Journals devoted primarily to fuzzy logic include

- *IEEE Transactions on Fuzzy Systems* , IEEE
- *Fuzzy Sets and Systems*, North Holland
- *International Journal of Approximate Reasoning* , Elsevier

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- SOFT (Society of Fuzzy Technology) Journal, Japan

Papers dealing with fuzzy systems also commonly appear in

- *IEEE Transactions on Neural Networks*
- *IEEE Transactions on Systems, Man and Cybernetics*

• Books:

As in any new field, a plethora of books on fuzzy systems are available. Below is a partial list. The first few chapters of the book by Klir and Folger provide a particularly good introduction to fuzzy logic. Advanced concepts are built from fundamental axioms. The IEEE Press book by Bezdek contains classical papers in the development of fuzzy pattern recognition. Included are seminal papers by Zadeh and Ruspini. A nice survey of fuzzy systems applications is in Terano, Asai and Sugeno.

- J.C. Bezdek, **Pattern Recognition with Fuzzy Objective Function Algorithms**, Plenum Press, New York, (1981).
- J.C. Bezdek, **Analysis of Fuzzy Information**, CRC Press, Boca Raton, Fla, (1985).
- J.C. Bezdek, editor, **Fuzzy Models for Pattern Recognition**, IEEE Press, (1992).
- D.Dubois and H. Prade, **Fuzzy Sets and Systems, Theory and Application**, Academic Press, New York, (1979).
- A. Kandel, **Fuzzy Mathematical Techniques with Applications**, Addison Wesley, Reading, Mass (1982).
- A. Kaufmann, **Introduction to the Theory of Fuzzy Subsets**, Academic Press, New York, (1975).
- A. Kaufmann and M.M. Gupta, **Introduction to Fuzzy Arithmetic: Theory and Applications,** Von Nostrand Reinholt, New York.
- G.J. Klir & T.A. Folger, **Fuzzy Sets: Uncertainty, and Information**, Prentice Hall, (1988).
- B. Kosko, **Neural Networks and Fuzzy Systems: A Dynamical Systems Approach to Machine Intelligence,** Prentice Hall, (1992).
- D.K.D. Majumder, **Fuzzy Mathematical Approach to Pattern Recognition**, John Wiley, New York, (1968).
- C.V. Negoita, **Expert Systems and Fuzzy Systems,** Benjamin/Cummings, Menlo Park, CA (1985).
- W. Pedrycz, **Fuzzy Control and Fuzzy Systems, 2nd extended ed.,** New York : Wiley, (1993).
- K.J. Schmucker, **Fuzzy Sets, Natural Language Computations, and Risk Analysis,** Computer Science Press, Rockville, MD (1983).
- T. Terano, K. Asai and M. Sugeno, **Fuzzy Systems Theory and its Applications,** Academic Press, (1992).
- H.J. Zimmermann, **Fuzzy Set Theory and Its Applications,** Second Edition, Kluwer Academic Publishers, (1991).

• Societies and Conferences:

Fuzzy activities in IEEE are under the *IEEE Neural Networks Council* (NNC). The NNC has, as members, a number of IEEE Societies. Other international fuzzy professional organizations include the *International Fuzzy Systems Association* (IFSA) and the *North American Informations Processing Society* (NAFIPS). Each sponsors a fuzzy conference.

The largest conference devoted solely to fuzzy systems is *The International Conference on Fuzzy Systems* (a.k.a. FUZZ-IEEE). Dates and location of this annual conference are listed in the *IEEE Technical Activities Guide* (TAG) and in the *IEEE Spectrum.*

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° 1. L.A. Zadeh, "Fuzzy Sets", Information and Control, Vol. 8, pp. 338-353 (1965); reprinted in J.C. Bezdek, editor, **Fuzzy Models for Pattern Recognition,** IEEE Press, 1992.

° 2. "On fuzzy control ... and fuzzy reviewing", ***IEEE Control Systems,*** Vol. 13, no. 3, pp. 5-7 (June 1993).

° 3. E.H. Mamdani, "Twenty Years of Fuzzy Control: Experiences Gained and Lessons Learnt", **IEEE International Conference on Fuzzy Systems** (FUZZ-IEEE) 1993, p. 339-reprinted in this volume.

° 4. Possibly, but one can also unwisely analyze the frequency response of linear time-invariant circuits without the use of complex numbers. Fuzzy logic has the advantage of providing a match between technology design and the way we think and, in this sense, is a technology choice. A more proper question might be, 'can other technology more simply be used to do the same thing fuzzy systems do?' An example was voiced to the author by Enrique Ruspini.

° 5. There is currently much attention being focused on the question of fuzzy system stability. Some recent results can be found in

L.X. Wang, "Stable adaptive fuzzy control of nonlinear systems", **IEEE Transactions on Fuzzy Systems,** vol. 1, pp. 146-155, (1993).

H. Kang, "Stability and control of fuzzy dynamic systems via cell-state transitions in fuzzy hypercubes", **IEEE Transactions on Fuzzy Systems,** vol. 1, pp. 267-279, (1993).

° 6. R.J.. Marks II, "Intelligence: Artificial Versus Computational", **IEEE Transactions on Neural Networks** (September, 1993).

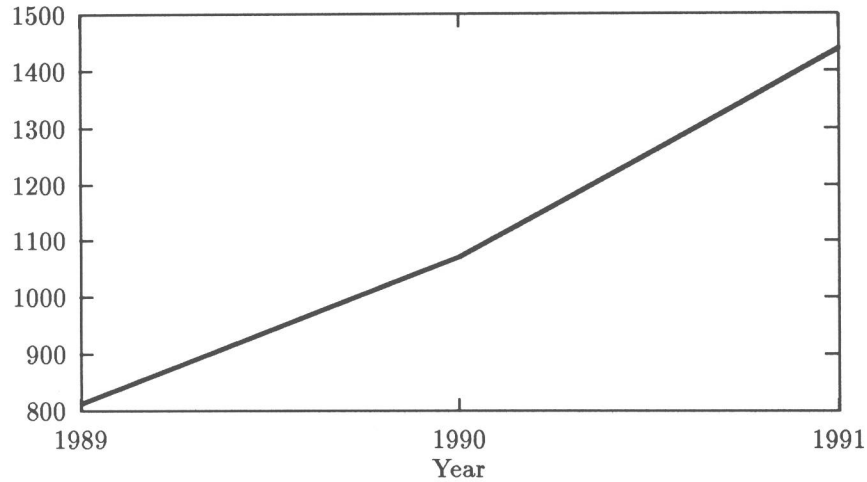

Figure 1: This data was obtained from the INSPEC *(Information Service for Physics and Engineering Communities)* data base compiled by the IEE and the IEEE. The INSPEC data base contains titles, authors and abstracts from over 4000 journals and is augmented with entries of books, reports and conference records. It is focused on the fields of physics, electrical engineering, computer science and electronics. Over one million entries have been logged into INSPEC since 1989. Contents are updated monthly. Searches for key words are performed over titles, authors, journal titles, and abstracts. At this printing, the data base for 1992 was not complete.

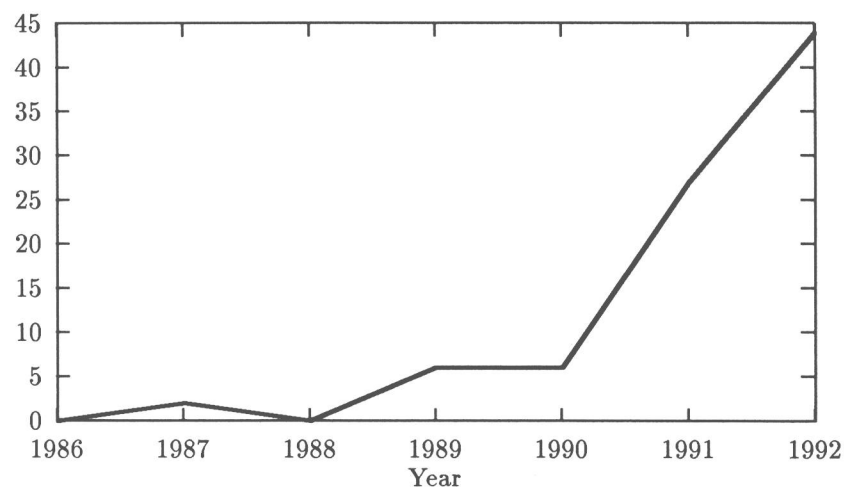

Figure 2: US Patent data was obtained from CASSIS (*Classification for Search Support Information System*). Searches are also performed over titles and abstracts.

CONTENTS

Section II: Applications

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