Preface

Uncertainty[2] is the fabric that makes life interesting. For millennia human beings have developed strategies to cope with a plethora of uncertainties, never absolutely sure what the consequences would be, but hopeful that the deleterious effects of those uncertainties could be minimized. This book presents a complete methodology for accomplishing this within the framework of fuzzy sets and systems. This is not the original fuzzy sets and systems, but is an expanded and richer fuzzy sets and systems, one that contains the original fuzzy sets and systems within it.

The original fuzzy sets, founded by Prof. Lotfi Zadeh, have been around for more than 50 years, as of the year 2017, and yet the fuzzy systems that use them are unable to handle uncertainties. By *handle*, I mean *to model and minimize the effect of*. That the original fuzzy sets—type-1 fuzzy sets—and the fuzzy systems that use them—type-1 fuzzy systems—cannot do this sounds paradoxical because the word *fuzzy* has the connotation of uncertainty. The expanded fuzzy sets—type-2 fuzzy sets—and the fuzzy systems that use them—type-2 fuzzy systems—are able to handle uncertainties because they can model them and minimize their effects. And, if all uncertainties disappear, type-2 fuzzy sets and systems reduce to their type-1 counterparts, in much the same way that, if randomness disappears, probability and the systems that use it reduce to determinism and deterministic systems.

Although many applications have been found for type-1 fuzzy sets and systems, it is arguably their application to *rule-based systems* that has most significantly demonstrated their importance as a powerful design methodology. Such rule-based systems, both type-1 and type-2, are what this book is about. It explains and shows how to use fuzzy sets and systems in new ways and how to effectively solve problems that are awash in uncertainties.

When the first edition of this book was published in 2001 (Mendel 2001), most of its contents about type-2 fuzzy sets and systems were based on the works of my former Ph.D. students, Nilesh Karnik and Qilian Liang, and mine. Since 2001,

[2]Some of this Preface is taken from or paraphrased from the Preface to the first edition of this book (Mendel 2001).

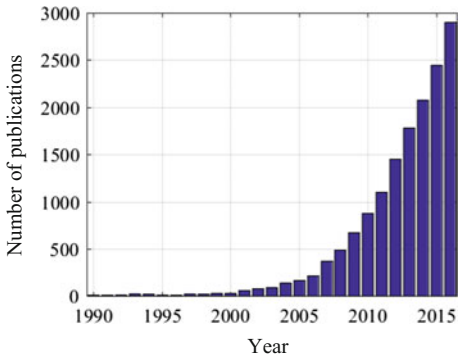

Fig. 1 The number of publications per year, when searched in Google Scholar using the exact phrase "type-2 fuzzy" excluding citations and patents.[3] The *last bar* is for 2016, up to December 31

thousands of journal and conference articles (Wu and Mendel 2014), as well as some other books, have been published about type-2 fuzzy sets and systems (Fig. 1). Consequently, this new edition is more diverse and presents results developed by many people. As a result of such a large literature, it took me more than seven months just to assemble the materials for this new edition of the book.

One measure of the importance of a field is the number of its publications as well as the citations to them. In addition to these measures, another measure is the number of journal and conference Outstanding Paper Awards that have been given to such papers. The *IEEE Trans. on Fuzzy Systems* has made five such awards to papers that have "Type-2" in their titles (Karnik et al. 1999; Hagras 2004; Coupland and John 2007; Wagner and Hagras 2010; Wu and Mendel 2011). In addition, at least eight other awards have been given to conference or workshop papers about type-2 fuzzy sets and systems between 2005 and 2016.

Fuzzy sets and systems have already been applied in numerous fields, in many of which uncertainties are present (e.g., control, signal processing, digital communications, computer and communication networks, diagnostic medicine, operations research, financial investing, etc.). Hence, the results in this book can immediately be used in all of these fields. To demonstrate the performance advantages for type-2 systems over their type-1 counterparts, when uncertainties are present, I describe and provide results for the following applications in this book: forecasting of time series, knowledge mining using surveys, control, classification of video data working directly with compressed data, and equalization of time-varying nonlinear digital communication channels.

The following major changes have been made from the first to this second edition:

- Mamdani and TSK fuzzy systems are unified.
- Singleton and non-singleton fuzzy systems are also unified.

[3]This figure was prepared by Dongrui Wu, and does not count the number of publications about interval-valued sets and systems.

- α-cuts and their related topics are included because of their importance to general type-2 fuzzy sets and systems.
- Notations about type-2 fuzzy sets are cleaned up.
- Four different and valuable mathematical representations of a general type-2 fuzzy set are explained and used.
- General type-2 fuzzy sets and systems are given much greater prominence.
- A unified approach to type-reduction is presented, one that builds upon a weighted average called the interval-weighted average.
- Mathematical explanations about many aspects of the optimization problems that are associated with type-reduction are included.
- Practical alternatives to type-reduction + defuzzification, called *direct defuzzification*, are presented.
- A case study on fuzzy logic control is included.
- Tables that let the reader know what choices have to be made for the designs of type-1, interval type-2 and general type-2 fuzzy systems are included and illustrated.
- Comprehensive numerical examples are included for type-1, interval type-2 and general type-2 fuzzy systems that illustrate all of their computations.
- Materials that appeared in appendixes at the rear of the first edition are now attached to their respective chapters.
- The appendix in the first edition about Computation has been removed. In its place, Sect. 1.9 refers the reader to sources for downloadable software that will let them implement much of what is in this book.
- Richer and more diverse exercises are included at the end of each chapter.

This book can be read by someone who has an undergraduate BS degree, and should be of great interest to computer scientists and engineers who already use or want to use rule-based systems and are concerned with how to handle uncertainties about such systems. Many worked-out examples are included in the text, and homework exercises are included at the end of Chaps. 2–11 so that the book can be used in a classroom setting as well as a technical reference.

This book can be used for either a one-semester course or a two-semester course. For a *one-semester course*, I would cover:

- Chapter 1: Sects. 1.1 and 1.2
- Chapter 2: All of it except for Sects. 2.11–2.13
- Chapter 3: All of it
- Chapter 6: All of it except for Sects. 6.7.3, 6.7.4 and 6.9
- Chapter 7: Focus only on interval type-2 fuzzy sets and systems. See Sect. 7.1 for a guide on how to do this.
- Chapter 8: Sects. 8.1–8.3.
- Chapter 9: Focus on singleton fuzzification for one kind of interval type-2 fuzzy system, e.g., COS type-reduction + defuzzification for an IT2 Mamdani fuzzy system, Sects. 9.4.1, 9.4.2.1, 9.4.2.4, 9.5, 9.6.3, 9.7, 9.9–9.13
- Design: Sects. 4.1, some of 4.2, 10.1 and some of 10.2

- Application: Choose one of the case studies (forecasting of time series, knowledge mining using surveys or fuzzy logic control)

For a two-semester course, I would cover:

- Semester 1: Chaps. 1–6
- Semester 2: Chaps. 7–11

Portions of this book are an amalgamation of the research of some of my past Ph.D. students who have worked with me during the past 25 years on fuzzy sets and systems. I, therefore, want to give each of them the credit here that they so richly deserve.

Li-Xin Wang studied singleton type-1 fuzzy sets and systems.[4] He developed many concepts about them including the WM method for extracting rules from data, fuzzy basis functions and expansions, tuning the membership function parameters using training data, interpreting a fuzzy system as a layered architecture, and arguably was the first to prove that a certain kind of type-1 fuzzy system is a universal approximator. Many of the topics that are covered in Chap. 3 are due to him.

George Mouzouris extended Li-Xin's works to non-singleton fuzzification, which represented our first attempt at handling one kind of uncertainty (uncertain measurements of the inputs to a fuzzy system) totally within the framework of a fuzzy system. The topics in Chap. 3 about non-singleton fuzzification and fuzzy systems are due to him. He also showed how rule reduction can be achieved by using the SVD algorithm. The material that is in Sect. 4.2.4 is due to him.

Nilesh Karnik provided the entire foundation and framework for singleton type-2 fuzzy systems, including[5] type-reduction and two very widely used algorithms for computing the type-reduced set (the KM algorithms), as well as algorithms for computing the join and meet of general type-2 fuzzy sets, and the extended sup-star composition. Many of the topics that are in Chaps. 6–8 and Sect. 9.4.1 are due to him.

Qilian Liang made type-2 fuzzy systems practical by focusing on how to design such systems when the uncertainties about type-1 fuzzy sets are modeled as type-1 interval fuzzy numbers, the results being interval type-2 Mamdani and TSK fuzzy systems [this was done for singleton and two kinds of non-singleton fuzzification (type-1 and interval type-2)]. Many of the topics that are in Chap. 9 are due to him. He also showed how rule reduction can be achieved in an interval type-2 fuzzy system by using the SVD algorithm (covered in Sect. 10.2). The simulations in this book about time series forecasting of the Mackey–Glass chaotic time series

[4]Why I now prefer to call such systems "fuzzy systems" rather than "fuzzy logic systems," as was done in Mendel (2001), is explained in Sect. 1.2.

[5]Although Lotfi Zadeh introduced the concept of a type-2 fuzzy set in 1975, and after that date a very small number of other papers were published about type-2 fuzzy sets, no one prior to our work had developed a type-2 fuzzy system.

(Sects. 4.3 and 10.3), forecasting of compressed video traffic using Mamdani and TSK fuzzy systems (Sects. 4.5 and 10.5), rule-based classification of video traffic (Sects. 4.6 and 10.6), and equalization of time-varying nonlinear digital communication channels (Sect. 10.7), all appeared in the first edition of this book, and were performed by him. I wish to express my sincere appreciation to him for helping me in this way.

Hongwei Wu developed the uncertainty bounds for type-reduced sets. The material that is in Sect. 9.8 is due to her. She also proved a very important result about the switch points of the centroid (covered in Property 8.13).

Feilong Liu developed the α–plane representation of a general type-2 fuzzy set (covered in Sect. 6.7.3) and showed how it can be used to compute the centroid of a general type-2 fuzzy set (covered in Sect. 8.4.1). He also established and proved the properties of the interval-weighted average that are covered in Appendix B.1 in Chap. 8.

Dongrui Wu improved the KM algorithms (the EKM algorithms) and provided many very important insights and theoretical results about fuzzy systems, including continuity of type-1 and interval type-2 fuzzy systems, and fundamental differences between type-1 and interval type-2 fuzzy systems. The topics that are in Sects. 3.9.3, 8.2.4, 9.7, 9.13.2 and 9.13.4 are due to him.

Mohammad Biglarbegian, along with Prof. William Melek, developed the direct defuzzification method known as the BMM method and showed how it can be used in rigorous studies of stability and robustness of a control system. This method is covered in Sect. 9.9.2.

Daoyuan Zhai examined many aspects of general type-2 fuzzy sets, including the connections between endpoints and average of endpoints defuzzification in a general type-2 fuzzy system (covered in Theorem 11.3) and centroid (and enhanced centroid) flow algorithms for speeding up the computations of the centroid of a general type-2 fuzzy set (discussed in Sect. 8.4.1).

Other students who worked on many aspects of type-1 or interval type-2 fuzzy sets and systems that fell outside the scope of this book but that influenced the writing of this book, are Minshen Hao, Mohammad Reza Rajati and Mohammad Mehdi Korjani.

Professor Tufan Kumbasar made very valuable contributions to this book about fuzzy logic control, in Sects. 4.7, 10.8 and 11.16. He wrote much of what is in those three sections, and generated all the simulations. I wish to express my sincere appreciation to him for helping me in this extraordinary way.

I have also had the privilege of working with the Prof. Robert John (the wavy-slice representation of a general type-2 fuzzy set, that is covered in Sect. 6.7.2, is a result of our joint collaboration), Prof. Xinwang Liu (the continuous KM algorithms for the centroid of an interval type-2 fuzzy set and its properties, that are covered in Appendix B.2 of Chap. 8, are results of our joint collaboration), and Prof. Qi-Ye Zhang (who translated the first edition of this book into Chinese in 2014).

During the writing of this second edition, I interacted with the following people who helped me with some technical issues: Prof. Peter Sussner (who was an

enormous help in straightening out the notations for type-2 fuzzy sets), Prof. Dongrui Wu, Feilong Liu, Prof. Qilian Liang, Nilesh Karnik, Prof. Tufan Kumbasar and Ondrej Linda. Professor Frank Rhee provided me with Fig. 6.4. All the inputs from these people helped me in reaching the final version of the book. Any remaining errors in content or publishing are my responsibility.

I would also like to acknowledge Prof. Hani Hagras for his many works on extremely interesting and novel applications of interval and general type-2 fuzzy systems, applications that have greatly influenced many other researchers to work on type-2 fuzzy sets and systems.

I gratefully acknowledge material quoted from books or journals by AIAA, American Association for the Advancement of Science, Elsevier, IEEE, McGraw-Hill, Prentice-Hall, Springer, and Wiley. When a quote is used, a reference is made to a specific publication that is listed at the end of each chapter. I also gratefully acknowledge Prof. Vladik Kreinovich for letting me quote some material about similarity and subsethood in Exercises 2.44 and 2.45 from a conference paper (see Nguyen and Kreinovich 2008) that is listed at the end of Chap. 2).

I am also very grateful to my Springer editors Mary James and Zoe Kennedy who guided me through the final production of the book; and to other staff members at Springer for their help in the production of this book.

I want to thank my wife Letty for providing me, for more than 56 years, with a wonderful environment that has made the writing of this book possible. Finally, I want to thank Prof. Lotfi Zadeh, the father of fuzzy logic, for his seminal works without which there would not have been even a first edition of this book and to whom this second edition is dedicated.

Los Angeles, CA, USA Jerry M. Mendel
January 2017

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