Signal Processing for Intelligent Sensor Systems with MATLAB®

Second Edition

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This book is dedicated to all who aspire to deeply understand signal processing for sensors, not just enough to pass an exam or assignment, or to complete a project, but deep enough to experience the joy of natural revelation. This takes more than just effort. You have to love the journey. This was best said by one of America's greatest inventors, George Washington Carver, in the quote "Anything will give up its secrets if you love it enough..."

Preface

The second edition of *Signal Processing for Intelligent Sensor Systems* enhances many of the unique features of the first edition with more answered problems, web access to a large collection of MATLAB® scripts used throughout the book, and the addition of more audio engineering, transducers, and sensor networking technology. All of the key algorithms and development methodologies have been kept from the first edition, and hopefully all of the typographical errors have been fixed. The addition of a chapter on Digital Audio processing reflects a growing interest in digital surround sound (5.1 audio) techniques for entertainment, home theaters, and virtual reality systems. Also, new sections are added in the areas of sensor networking, use of meta-data architectures using XML, and agent-based automated data mining and control. This later information really ties large-scale networks of intelligent sensors together as a network of thin file servers. Intelligent algorithms, either resident in the sensor/file-server nodes, or run remotely across the network as intelligent agents, can then provide an automated situational awareness. The many algorithms presented in *Signal Processing for Intelligent Sensor Systems* can then be applied locally or network-based to realize elegant solutions to very complex detection problems.

It was nearly 20 years ago that I was asked to consider writing a textbook on signal processing for sensors. At the time I typically had over a dozen textbooks on my desk, each with just a few small sections bookmarked for frequent reference. The genesis of this book was to bring together all these key subjects into one text, summarize the salient information needed for design and application, and organize the broad array of sensor signal processing subjects in a way to make it accessible to engineers in school as well as those practicing in the field. The discussion herein is somewhat informal and applied and in a tone of engineer-to-engineer, rather than professor-to-student. There are many subtle nuggets of critical information revealed that should help most readers quickly master the algorithms and adapt them to meet their requirements. This text is both a learning resource and a field reference. In support of this, every data graph in the text has a MATLAB m-script in support of it and these m-scripts are kept simple, commented, and made available to readers for download from the CRC Press website for the book (http://www.crcpress.com/product/isbn/9781420043044). Taylor & Francis Group (CRC Press) acquired the rights to the first edition and have been relentless in encouraging me to update it in this second edition. There were also a surprising number of readers who found me online and encouraged me to make an updated second edition. Given the high cost of textbooks and engineering education, we are excited to cut the price significantly, make the book available electronically online, as well as for "rent" electronically which should be extremely helpful to students on a tight budget. Each chapter has a modest list of solved problems (answer book available from the publisher) and references for more information.

The second edition is organized into five parts, each of which could be used for a semester course in signal processing, or to supplement a more focused course textbook. The first two parts, "Fundamentals of Digital Signal Processing" and "Frequency Domain Processing," are appropriate for undergraduate courses in Electrical and/or Computer Engineering. Part III "Adaptive System Identification and Filtering" can work for senior-level undergraduate or a graduate-level course, as is Part IV on "Wave Number Sensor Systems" that applies the earlier techniques to beamforming, image processing, and signal detection systems. If you look carefully at the chapter titles, you will see these algorithm applications grouped differently from most texts. Rather than organizing these subjects strictly by application, we organize them by the algorithm, which naturally spans several applications. An example of this is the recursive least-squares algorithm, projection operator subspace decomposition, and Kalman filtering of state vectors, which all share the same basic recursive update algorithm. Another example is in Chapter 13 where we borrow the two-dimensional FFT usually reserved for image processing and compression and use it to explain available beam pattern responses for various array shapes.

Part V of the book covers advanced signal processing applications such as noise cancellation, transducers, features, pattern recognition, and modern sensor networking techniques using XML messaging and automation. It covers the critical subjects of noise, sensors, signal features, pattern matching, and automated logic association, and then creates generic data objects in XML so that all this information can be found. The situation recognition logic emerges as a cloud application in the network that automatically mines the sensor information organized in XML across the sensor nodes. This keeps the sensors as generic websites and information servers and allows very agile development of search engines to recognize situations, rather than just find documents. This is the current trend for sensor system networks in homeland security, business, and environmental and demographic information systems. It is a nervous system for the planet, and to that end I hope this contribution is useful.

Acknowledgments

I am professionally indebted to all the research sponsors who supported my colleagues, students, and me over the years on a broad range of sensor applications and network automation. It was through these experiences and by teaching that I obtained the knowledge behind this textbook. The Applied Research Laboratory at The Pennsylvania State University is one of the premier engineering laboratories in the world, and my colleagues there will likely never know how much I have learnt from them and respect them. A special thanks goes to Mr. Arnim Littek, a great engineer in the beautiful country of New Zealand, who thought enough of the first edition to send me a very detailed list of typographical errors and suggestions for this edition. There were others, too, who found me through the Internet, and I really loved the feedback which served as an inspiration to write the second edition. Finally to my wife Nadine, and children Drew, Anya, Erik, and Ava, your support means everything to me.

Author

David C. Swanson has over 30 years of experience with sensor electronics and signal processing algorithms and 15 years of experience with networking sensors. He has been a professor in the Graduate Program in Acoustics at The Pennsylvania State University since 1989 and has done extensive research in the areas of advanced signal processing for acoustic and vibration sensors including active noise and vibration control. In the late 1990s, his research shifted to rotating equipment monitoring and failure prognostics, and since 1999 has again shifted into the areas of chemical, biological, and nuclear detection. This broad range of sensor signal processing applications culminates in his book *Signal Processing for Intelligent Sensor Systems*, now in its second edition. Dr. Swanson has written over 100 articles for conferences and symposia, dozens of journal articles and patents, and three chapters in books other than his own. He has also worked in industry for Hewlett-Packard and Textron Defense Systems, and has had many sponsored industrial research projects. He is a fellow of the Acoustical Society of America, a board-certified member of the Institute of Noise Control engineers and a member of the IEEE. His current research is in the areas of advanced biomimetic sensing for chemicals and explosives, ion chemistry signal processing, and advanced materials for neutron detection. Dr. Swanson received a BEE (1981) from the University of Delaware, Newark, and an MS (1984) and PhD (1986) from The Pennsylvania State University, University Park, where he currently lives with his wife and four children. Dr. Swanson enjoys music, football, and home brewing.

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Part I

Fundamentals of Digital Signal Processing

It was in the late 1970s that the author first learned about digital signal processing as a freshman electrical engineering student. Digital signals were a new technology and generally only existed inside computer programs and as hard disk files on cutting edge engineering projects. At the time, and reflected in the texts of that time, much of the emphasis was on the mathematics of a sampled signal, and how sampling made the signal different from the analog signal equivalent. Analog signal processing is very much a domain of applied mathematics, and looking back over 40 years later, it is quite remarkable how the equations we process easily today in a computer program were implemented eloquently in analog electronic circuits. Today there is little controversy about the equivalence of digital and analog signals except perhaps among audio extremists/purists. Our emphasis in this part is on explaining how signals are sampled, compressed, and reconstructed, how to filter signals, how to process signals creatively for images and audio, and how to process signal information "states" for engineering applications. We present how to manage the *nonlinearity* of converting a system defined mathematically in the analog s-plane to an equivalent system in the digital z-plane. These nonlinearities become small in a given low-frequency range as one increases the digital sample rate of the digital system, but numerical errors can become a problem if too much oversampling is done. There are also options for warping the frequency scale between digital and analog systems.

We present some interesting and useful applications of signal processing in the areas of audio signal processing, image processing, and tracking filters. This provides for a first semester course to cover the basics of digital signals and provide useful applications in audio and images in addition to the concept of signal kinematic states that are used to estimate and control the dynamics of a signal or system. Together these applications cover most of the signal processing people encounter in everyday life. This should help make the material interesting and accessible to students new to the field while avoiding too much theory and detailed mathematics. For example, we show frequency response functions for digital filters in this part, but we do not go into spectral processing of signals until Part II. This also allows some time for MATLAB® use to develop where students can get used to making m-scripts and plots of simple functions. The application of fixed-gain tracking filters on a rocket launch example will make detailed use of signal state estimation and prediction as well as computer graphics in plotting multiple functions correctly. Also, using a digital photograph and two-dimensional low- and high-pass filters provide an interesting introduction to image processing using simple digital filters. Over 40 years ago, one could not imagine teaching signal processing fundamentals while covering such a broad range of applications. However, any cell phone today has all of these applications built in, such as sampling, filtering, and compression of the audio signal, image capture and filtering, and even a global positioning system (GPS) for estimating location, speed, and direction.