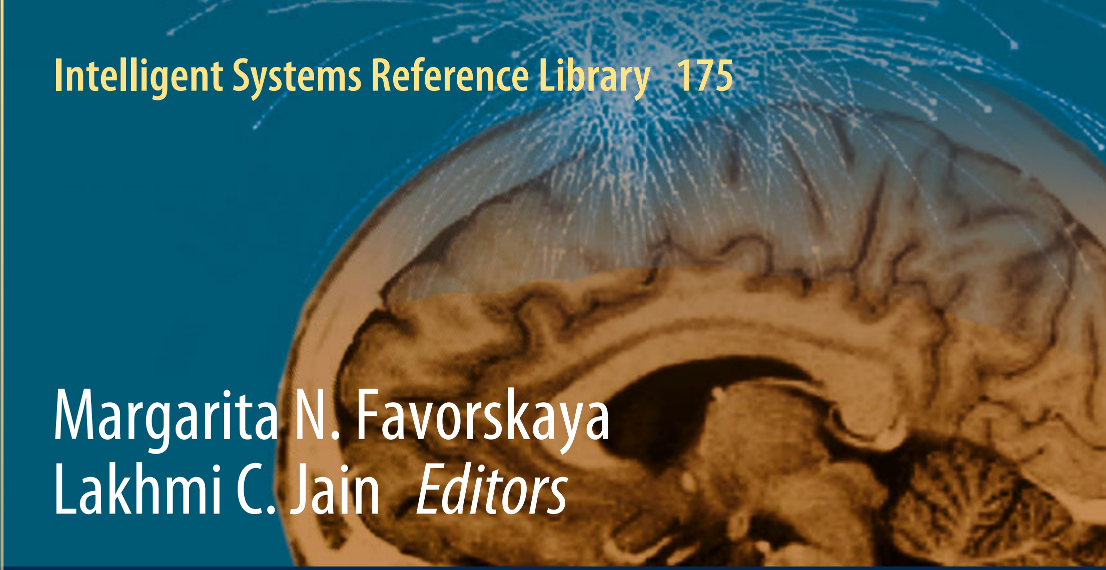
Intelligent Systems Reference Library 175



Margarita N. Favorskaya
Lakhmi C. Jain *Editors*

Computer Vision in Advanced Control Systems-5

Advanced Decisions in Technical and Medical Applications

Springer

Intelligent Systems Reference Library

Volume 175

The aim of this series is to publish a Reference Library, including novel advances and developments in all aspects of Intelligent Systems in an easily accessible and well structured form. The series includes reference works, handbooks, compendia, textbooks, well-structured monographs, dictionaries, and encyclopedias. It contains well integrated knowledge and current information in the field of Intelligent Systems. The series covers the theory, applications, and design methods of Intelligent Systems. Virtually all disciplines such as engineering, computer science, avionics, business, e-commerce, environment, healthcare, physics and life science are included. The list of topics spans all the areas of modern intelligent systems such as: Ambient intelligence, Computational intelligence, Social intelligence, Computational neuroscience, Artificial life, Virtual society, Cognitive systems, DNA and immunity-based systems, e-Learning and teaching, Human-centred computing and Machine ethics, Intelligent control, Intelligent data analysis, Knowledge-based paradigms, Knowledge management, Intelligent agents, Intelligent decision making, Intelligent network security, Interactive entertainment, Learning paradigms, Recommender systems, Robotics and Mechatronics including human-machine teaming, Self-organizing and adaptive systems, Soft computing including Neural systems, Fuzzy systems, Evolutionary computing and the Fusion of these paradigms, Perception and Vision, Web intelligence and Multimedia.

** Indexing: The books of this series are submitted to ISI Web of Science, SCOPUS, DBLP and Springerlink.

More information about this series at http://www.springer.com/series/8578

Margarita N. Favorskaya · Lakhmi C. Jain
Editors

Computer Vision in Advanced Control Systems-5

Advanced Decisions in Technical and Medical Applications

Springer

Editors
Margarita N. Favorskaya
Department of Informatics and Computer Techniques
Institute of Informatics and Telecommunications
Reshetnev Siberian State University of Science and Technology
Krasnoyarsk, Russia

Lakhmi C. Jain
University of Canberra
Canberra, SA, Australia

University of Technology Sydney
Sydney, Australia

Liverpool Hope University
Liverpool, UK

KES International
UK

ISSN 1868-4394 ISSN 1868-4408 (electronic)
Intelligent Systems Reference Library
ISBN 978-3-030-33794-0 ISBN 978-3-030-33795-7 (eBook)
https://doi.org/10.1007/978-3-030-33795-7

© Springer Nature Switzerland AG 2020
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The research book is a continuation of our previous books which are focused on the recent advances in computer vision methodologies and technical solutions using conventional and intelligent paradigms.

- Computer Vision in Control Systems—1, Mathematical Theory, ISRL Series, Volume 73, Springer-Verlag, 2015
- Computer Vision in Control Systems—2, Innovations in Practice, ISRL Series, Volume 75, Springer-Verlag, 2015
- Computer Vision in Control Systems—3, Aerial and Satellite Image Processing, ISRL Series, Volume 135, Springer-Verlag, 2018
- Computer Vision in Control Systems—4, Real Life Applications, ISRL Series, Volume 136, Springer-Verlag, 2018.

Image processing and analysis remain a vital part of numerous real-time applications in every discipline. The main contribution of this book is an attempt to improve algorithms by novel theories and complex data analysis in different scopes including object detection, remote sensing, data transmission, data fusion, gesture recognition, and medical image processing and analysis.

Recent research results in the image and video processing, transmission, and image analysis are included in Part I, while a wide spectrum of algorithms for medical image processing are included in Part II of the book.

The book is directed to the Ph.D. students, professors, researchers, and software developers working in the areas of digital video processing and computer vision technologies.

We wish to express our gratitude to the authors and reviewers for their contribution. The assistance provided by Springer-Verlag is acknowledged.

Krasnoyarsk, Russian Federation — Margarita N. Favorskaya
Canberra, Australia — Lakhmi C. Jain

Contents

Part I Technical Applications

Part II Medical Applications

About the Editors

Dr. Margarita N. Favorskaya is a Professor and Head of Department of Informatics and Computer Techniques at Reshetnev Siberian State University of Science and Technology, Russian Federation.

Professor Favorskaya is a member of KES organization since 2010, the IPC member, and the Chair of invited sessions of over 30 international conferences. She serves as an associate editor of *Intelligent Decision Technologies Journal*, *International Journal of Knowledge-Based and Intelligent Engineering Systems*, *International Journal of Reasoning-Based Intelligent Systems*, a Honorary Editor of the *International Journal of Knowledge Engineering and Soft Data Paradigms*, Guest Editor, and Book Editor (Springer). She is the author or the co-author of 200 publications and 20 educational manuals in computer science. She co-edited several books for Springer. She supervised nine Ph.D. candidates to completion and presently supervising four Ph.D. students.

Her main research interests are digital image and video processing, remote sensing, pattern recognition, fractal image processing, artificial intelligence, and information technologies.

Dr. Lakhmi C. Jain, Ph.D., ME, BE(Hons), Fellow (Engineers Australia) is with the University of Technology Sydney, Australia, and Liverpool Hope University, UK.

Professor Jain founded the KES International for providing a professional community the opportunities for publications, knowledge exchange, cooperation, and teaming. Involving around 5000 researchers drawn from universities and companies worldwide, KES facilitates international cooperation and generates synergy in teaching and research. KES regularly provides networking opportunities for professional community through one of the largest conferences of its kind in the area of KES.

http://www.kesinternational.org/organisation.php

Chapter 1
Advanced Decisions in Technical and Medical Applications: An Introduction

Margarita N. Favorskaya and Lakhmi C. Jain

Abstract This chapter presents a brief description of chapters pertaining to advanced decisions for technical and medical systems. Recent research results in the image and videos processing, transmission, and image analysis are included in Part I, while a wide spectrum of algorithms for medical image processing are included in Part II of this book. Each chapter involves detail practical implementations and explanations.

Keywords Autoregressive models · Random fields · Image analysis · Multidimensional image processing · Pseudo-inverse matrix singular-value · Copyright protection · Sign language · Clinical decision support system · Histological image processing · Convolutional neural network

1.1 Introduction

At present, image processing and analysis remain a vital part of numerous applications in many fields. In spite of numerous methods and algorithms developed in the past, this topic is of current interest in various control systems based on computer vision paradigms. Researchers are looking for more effective and accurate

---

M. N. Favorskaya (✉)
Institute of Informatics and Telecommunications, Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarsky Rabochy ave., Krasnoyarsk 660037, Russian Federation
e-mail: favorskaya@sibsau.ru

L. C. Jain
University of Technology Sydney, Ultimo, Australia
e-mail: jainlakhmi@gmail.com; jainlc2002@yahoo.co.uk

University of Canberra, Canberra, Australia

Liverpool Hope University, Liverpool, UK

M. N. Favorskaya and L. C. Jain (eds.), *Computer Vision in Advanced Control Systems-5*, Intelligent Systems Reference Library 175,
https://doi.org/10.1007/978-3-030-33795-7_1

algorithms to process the high resolution images in real-time mode with low computational costs. However, this requirement cannot be achieved fully at current stage of technical development. The main contribution of this book is the attempts to improve algorithms by novel theories and complex data analysis in different scopes including object detection, remote sensing, data transmission, data fusion, gesture recognition, and medical image processing and analysis. Part I includes the Chaps. 2, 3, 4, 5 and 6 and Part II of the book contains Chaps. 7, 8, 9 and 10.

1.2 Chapters Including in the Book

Chapter 2 explores the processing of multidimensional images, referring to aerospace images and remote sensing multispectral and hyperspectral images [1, 2]. New mathematical models of multidimensional images are proposed. Based on the procedures of vector Kalman filtering, optimal recurrent estimates of the autoregressive sequences with multiple roots of characteristic equations are constructed. Additionally to Kalman algorithm, Wiener filter was synthesized and investigated when processing random sequences generated by autoregressive model with multiple roots of characteristic equations. Compact analytical relations have been obtained for analyzing the effectiveness of random fields filtering algorithms with multiple roots of characteristic equations [3]. The behavior of filters was studied at various correlation intervals and in the processing of random fields with the roots of characteristic equations of various multiplicities. Thus, for large correlation intervals for the model with multiple roots, the filtering error variance is 5–10 times less than that for the ordinary autoregressive model. An algorithm for identification of the parameters and orders of the autoregressive models with multiple roots of characteristic equations based on solving Yule-Walker system of equations is proposed. Quasi-optimal and optimal filtering algorithms for random fields based on autoregressive models with multiple roots of characteristic equations have been developed and investigated. In particular, on the basis of Kalman filter, a solution of sequential row-by-row and column-by-column estimation was obtained, which makes it possible to reduce computational costs in comparison with optimal vector filtering. For models of the 1st and 2nd orders, the proposed algorithm loses no more than 10% in terms of the variance of the filtering error. The obtained algorithms are tested on real images. Experiments show that the use of autoregressive models with multiple roots provides a significantly lower filtering error variance than traditional approaches based on first-order models.

Chapter 3 studies the problems of multidimensional images and image sequences representation and processing within the framework of the Earth remote sensing [1]. Correlated data multidimensional arrays description and optimal and suboptimal processing are based on the proposed doubly stochastic autoregressive models. Application of doubly stochastic autoregressive models is twofold. First, the doubly stochastic models are used for description of multidimensional random fields and time sequences. A time sequence of multidimensional satellite images have four-dimensional random field with one-dimension corresponding to discrete time [4]. Second, doubly stochastic models allow to estimate the spatially heterogeneous images with probabilistic properties, such as rivers, forests, fields, etc. Doubly stochastic models are based on autoregressive with multiple roots models of characteristic equation. For two-dimensional case, random field model based on doubly stochastic model ought to have the characteristics of a real image [5]. Identification technique based on a combination of on doubly stochastic model varying parameters estimation by means of a sliding window and by means of pseudogradient procedures is developed. The proposed algorithms are available to synthesize multidimensional images filtering algorithms and even several classes of such algorithms can process the multispectral satellite images as the real-time sequences. Actual satellite observations obtained in 2001–2017 are used for experiments.

Chapter 4 covers the analysis of inverse problems related to the applied electrodynamics, and radio, acoustic and optical wave physics [6]. For this purpose, a concept of matrix or tensor equations technique for direct problem derivation, as well as, the inverse problem resolving, which deals with determination and localization of the radiated sources' distribution a few limited cases of canonical objects and media, is developed. Matrix-vector systems of linear equations allows to find a solution of the inverse problems occurring in the optic and radio communication, wired and wireless, presented in 1D and 2D forms [7]. It is shown that the most of the inverse problems can be declared via system of linear algebraic equations with singular-value decomposition based on Moore-Penrose matrix. For non-linear equations solutions, Levenberg–Marquardt algorithm is applied. Also, Wiener's filtering with regularization is investigated in order to increase the accuracy of solution of the inverse problem, for example, reconstruction of blurred images. Some practical examples regarding to inverse problems, viz. source localization, micro-strip sensors reconstruction, and signal analysis, are discussed.

Chapter 5 contains a detailed overview of the transmitting specifications of video content, such as H.264/AVC, H.264/SVC, and H.265/HEVC in the sense of authentication and copyright protection. Internet attacks against video sequence are classified as the intentional and accidental attacks. Intentional attacks are directed on the distortions of a part of video or a single frame and categorized into common image processing and geometric attacks. Accidental attacks are concerned to the common processing attacks of video. Authentication and copyright protection of videos represented in some formats are developed in this chapter. The proposed video watermarking method is robust to several types of typical Internet attacks, e.g. the common image processing attacks, global and local geometric attacks, and permutation attacks. Proposed method supports the detection of I-frames and selection the best regions for embedding using the joint map, which excludes moving and salient regions [8] and involves high textural regions [9] with prevailed blue component [10]. Invariance to the main types of attacks regarding the compressed videos is provided by a feature-based approach for embedding with the original procedures. The novelty is that the coordinate values of speeded up robust features as they were in the host frame are embedded in the stable regions.

This allows to avoid the corresponding matches between SURF descriptors in the host and watermarked frames and extend a volume of embedded information after desynchronization attacks. In order to provide invariance to rotation, scaling, and translation attacks, exponential moments on a unit circle were applied. The experiments were conducted with simulation of rotation, salt and pepper noise, Gaussian noise, gamma correction, blurring filter, median filtering, scaling, cropping, and JPEG compression. Also, combination of attacks was simulated. Obtained experimental results show that the proposed algorithm is robust to the most types of attacks but strongly depends of video content.

Chapter 6 describes the multi-threshold analysis of monochromatic images. Typical limitations arise from low signal-to-background ratio in the area of interest, low quality images, excessive quantization, fuzzy boundaries of objects and structures. The original idea is to select and set the optimal threshold value based on the results of the selection of objects in multi-threshold framework to achieve the best selection based on a posteriori information. This approach was originally proposed in [11] for the selection of small-scale objects. Further development of this idea is described in this chapter and includes the evaluation of certain geometric parameters of the object in binary images after multi-threshold processing and the corresponding selection of objects [12, 13]. The optimal threshold value is selected according to the extremum of the selected parameter. This geometric parameters are the area of the object, the ratio of the perimeter square to the area of the entire object, or the ratio of the square of the main axis to the area of the object. The authors develop the idea of reconstructing a three-dimensional hierarchical structure of objects based on the multi-threshold analysis of the raw image. The objects are separated from each other based on the percolation effect. This effect is associated with the elimination of empty pixels that appear below the enhanced threshold from the object content, which ultimately leads to the breakup of the integrity of the object and the emergence of new isolated objects as its fragments. Thus, the objects of interest are represented in the form of 3D structures spanning through a series of binary layers. After 3D reconstruction, one can select the objects of interest using various criteria, such as their percolation properties, geometric characteristics, or texture parameters.

Chapter 7 reports the recognition results of one-handed gestures represented by Russian sign language as a way of communication among deaf and hearing impaired community [14]. The distinguish feature of this research is a combination of hand movements and facial expressions (including lips position). The proposed methodology is applied for the static, dynamic, and both static and dynamic gestures simultaneously. The chapter provides extended review of methods for hand gestures recognition and lip reading in the context of sign language and datasets in this scope. Many techniques for recognition of static and dynamic gestures are analyzed, and deep neural network with long short-term memory cells was chosen for implementation. First, the motion relevant to signs regions (hands and face regions) are detected as the regions of interest. The wrists and mouth regions are localized by certain landmarks. Second, for detection of the hand region and shape of the hand classification, MobileNetV2 as a very effective feature extractor for object detection and segmentation was trained. Finally, deep neural network with long short-term memory cells is applied as the best decision from recurrent neural network modeling time or sequence dependent behavior. The recognition results are obtained on the single-hand part of the collected TheRuSLan database [15] with promising values.

Chapter 8 conducts the investigations in the development of new methods for endoscopic images processing and analysis, which can be used as a base for construction of clinical decision support systems. The important issue for high effective physician analysis is a high quality of images [16]. The propose methods of noise reduction and image enhancement process the endoscopic images with computational cost permitting a real-time realization and high signal/noise ratio. New method of virtual chromoendoscopy consists of two stages. The first stage is a visualization of tissues and surfaces of mucous membranes including vessels structure stressing and the second stage is a tone enhancement [17]. The experimental test of proposed method was conducted on open KVASIR dataset of endoscopic images. For differential diagnostic implementation, methods for polyp and bleeding detection and segmentation in conditional of small database for training were developed. The method of polyp detection is based on combination traditional machine learning technique (random decision forests) and convolutional neural network. The special data augmentation—the sinusoidal image transform is applied in order to solve the problem of insufficiently large endoscopic images dataset. Some original procedures permitted to obtain rather good characteristics of medical images classification under their high variability and, the same time, small dataset for training.

Chapter 9 examines the computational methods for evaluating the indicators of the tissue regeneration process using clinical experiment with mesh nickelide titanium implants. For processing of scanning electron microscopy and classical histological images, a set of algorithms with high accuracy estimates are developed. Algorithms based on the shearlet and wavelet transforms with brightness correction provide better edge information [18, 19]. Algorithms for elastic maps generation with color coding allows to obtain more representative visualization of spatial data. The designed software helps to analyze a sequence of medical images in order to understand a dynamics of reconstructed tissues. The modified fast finite shearlet transform increases the accuracy of selection of linear structures and visual quality of the studied clinical images. Brightness correction using Retinex algorithm [20] allows to obtain a unified average brightness of analyzed images and, in some cases, increase a local contrast. The estimates of morphometric indicators of histological images include a calculation error for the main studied parameters. Evaluation of tissue germination was performed on the basis of scanning electron microscopy images. More objective data were used for images obtained from different angles. As a part of the study, for the evaluation of computer techniques a medical expert specified objects that were defined as tissue, fibers, red blood cells, etc., and the areas with the implant structure were specified separately. For the specified reference samples, parameters were calculated taking into account the indicators of texture characteristics and color code.

Chapter 10 presents the algorithms for histological images segmentation by convolutional neural network with morphological post-filtration [21]. Such algorithms can be used in decision support systems for early diagnosis of breast cancer by pathologists, as well as, a means of training or control for beginners in the field of breast cancer diagnosis. Algorithm 1 based on AlexNet neural network provides the high quality of histological images segmentation. However, this approach cannot be used for direct analysis of medical images in real time due to significant time costs. Thus, Algorithm 1 can be used to create the markup of the training dataset automatically. Algorithm 2 based on U-Net convolutional neural network with subsequent morphological filtering can be successfully used to implement the segmentation of histological images based on automatically obtained markup in real medical practice. Algorithm 2 allows the histological images to be processed 2,700 times faster than Algorithm 1. The segmentation results were evaluated using such segmentation quality assessment metrics as a simple match coefficient, Tversky index, and Sørensen coefficient. Numerical experiments confirmed a necessity to use the morphological filtering as a means of additional processing of histological images binary masks obtained at the output of convolutional neural networks.

1.3 Conclusions

This chapter includes a brief description of the chapters with original mathematical theories, algorithms, and extended experimental results in the image and videos processing as the basic components for creation of intelligent decision making systems, as well as, clinical decision support systems. All investigations included in this book provide the novel ideas, decisions, and applications in computer vision.

References

1. Vasiliev, K., Dementiev, V., Andriyanov, N.: Representation and processing of multispectral satellite images and sequences. Procedia Comput. Sci. **126**, 49–58 (2018)
2. Andriyanov, N.A., Vasiliev, K.K., Dement'ev, V.E.: Analysis of the efficiency of satellite image sequences filtering. J. Phys.: Conf. Ser. **1096**, 012036.1–012036.7 (2018)
3. Andriyanov, N.A., Vasiliev, K.K.: Use autoregressions with multiple roots of the characteristic equations to image representation and filtering. CEUR Work. Proc. **2210**, 273–281 (2018)
4. Krasheninnikov, V.R.: Correlation analysis and synthesis of random field wave models. Pattern Recognit. Image Anal. **25**(1), 41–46 (2015)
5. Krasheninnikov, V.R., Vasil'ev, K.K.: Multidimensional image models and processing. In: Favorskaya, M., Jain, L.C. (eds.) Computer Vision in Control Systems-3, ISRL, vol. 135, pp. 11–64. Springer International Publishing, Switzerland (2018)
6. Blaunstein, N., Yakubov, V.P. (eds.): Electromagnetic and Acoustic Wave Tomography: Direct and Inverse Problems in Practical Applications. CRC, Taylor & Frances Group, Boca Raton, FL (2019)

7. Sergeev A.M., Blaunstein N.S.: Orthogonal matrices with symmetrical structures for image processing. Informatsionno-upravliaiushchie sistemy [Information and Control Systems] **6**, 2–8 (in Russian) (2017)
8. Favorskaya, M., Buryachenko, V.: Fast salient object detection in non-stationary video sequences based on spatial saliency maps. In: De Pietro, G., Gallo, L., Howlett, R.J., Jain, L. C. (eds.) Intelligent Interactive Multimedia Systems and Services, SIST, vol. 55, pp. 121–132. Springer International Publishing, Switzerland (2016)
9. Favorskaya, M., Pyataeva, A., Popov, A.: Texture analysis in watermarking paradigms. Procedia Comput. Sci. **112**, 1460–1469 (2017)
10. Favorskaya, M.N., Jain, L.C. Savchina E.I.: Perceptually tuned watermarking using non-subsampled shearlet transform. In: Favorskaya, M.N., Jain L.C. (eds.) Computer Vision in Control Systems-3, ISRL, vol. 136, pp. 41–69. Springer International Publishing, Switzerland (2018)
11. Volkov, V.: Extraction of extended small-scale objects in digital images. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-5/W6, 87–93 (2015)
12. Krasichkov, A.S., Grigoriev, E.B., Bogachev, M.I, Nifontov, E.M.: Shape anomaly detection under strong measurement noise: An analytical approach to adaptive thresholding. Phys. Rev. E **92**(4), 042927.1–042927.9 (2015)
13. Bogachev, M., Volkov, V., Kolaev, G., Chernova, L., Vishnyakov, I., Kayumov, A.: Selection and quantification of objects in microscopic images: from multi-criteria to multi-threshold analysis. Bionanoscience **9**(1), 59–65 (2019)
14. Ryumin, D., Kagirov, I., Ivanko, D., Axyonov, A., Karpov, A.A.: Automatic detection and recognition of 3D manual gestures for human-machine interaction. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W12, 179–183 (2019)
15. Ryumin, D., Ivanko, D., Axyonov, A., Kagirov, I., Karpov, A., Zelezny, M.: Human-robot interaction with smart shopping trolley using sign language: data collection. In: IEEE International Conference on Pervasive Computing and Communications Workshops, pp. 1–6 (2019)
16. Obukhova, N., Motyko, A., Alexandr Pozdeev, A.: Review of noise reduction methods and estimation of their effectiveness for medical endoscopic images processing. In: 22nd Conference on FRUCT Association, pp. 204–210 (2018)
17. Obukhova, N., Motyko, A.: Image analysis in clinical decision support system. In: Favorskaya, M.N., Jain, L.C. (eds.) Computer Vision in Control Systems-4, ISRL, vol. 136, pp. 261–298. Springer International Publishing, Switzerland (2018)
18. Cadena, L., Espinosa, N., Cadena, F., Kirillova, S., Barkova, D., Zotin, A.: Processing medical images by new several mathematics shearlet transform. In: International MultiConference on Engineers and Computer Scientists, vol. I, pp. 369–371 (2016)
19. Zotin, A., Simonov, K., Kapsargin, F., Cherepanova, T., Kruglyakov, A., Cadena, L.: Techniques for medical images processing using shearlet transform and color coding. In: Favorskaya, M.N., Jain, L.C. (eds.) Computer Vision in Control Systems-4, ISRL, vol. 136, pp. 223–259. Springer, Cham (2018)
20. Zotin, A.: Fast algorithm of image enhancement based on multi-scale Retinex. Procedia Comput. Sci. **131**, 6–14 (2018)
21. Khryashchev, V., Lebedev, A., Stepanova, O., Srednyakova, A.: Using convolutional neural networks in the problem of cell nuclei segmentation on histological images. In: Dolinina, O., Brovko, A., Pechenkin, V., Lvov, A., Zhmud, V., Kreinovich, V. (eds.) Recent Research in Control Engineering and Decision Making. ICIT 2019. SSDC, vol. 199, pp. 149–161. Springer, Cham (2019)

Part I
Technical Applications

Chapter 2
Image Representation and Processing Using Autoregressive Random Fields with Multiple Roots of Characteristic Equations

Konstantin K. Vasil'ev and Nikita A. Andriyanov

Abstract An analytical review of mathematical models of images was performed, and their main advantages and disadvantages were noted. It is proposed to use Random Fields (RF) generated by AutoRegressive (AR) models with multiple roots of characteristic equations for describing images with a smooth change in brightness. Results of the study of the proposed models probabilistic properties are presented. The results obtained for Random Sequences (RS) are generalized to multidimensional RF. The filtering efficiency of simulated images is investigated. Analytical expressions are obtained for the relative variance of the filtering error of the arbitrary dimension and multiplicities RF against the background of white noise. Algorithm for identifying the parameters and the multiplicity of the model using the Yule–Walker equations is proposed. The possibilities and efficiency of application of the developed algorithms on real images are considered.

Keywords Autoregressive models · Roots of characteristic equations · Random fields · Image analysis · Covariance function · Correlation interval · Optimal filtering · Kalman filtering · Multidimensional wiener filtering · Model parameters identification

---

K. K. Vasil'ev · N. A. Andriyanov (✉)
Ulyanovsk State Technical University, 32 Severny Venets st., Ulyanovsk 432027, Russian Federation
e-mail: nikita-and-nov@mail.ru

K. K. Vasil'ev
e-mail: vkk@ulstu.ru

N. A. Andriyanov
Ulyanovsk Civil Aviation Institute, 8/8 Mozhaiskogo st., Ulyanovsk 432071, Russian Federation

M. N. Favorskaya and L. C. Jain (eds.), *Computer Vision in Advanced Control Systems-5*, Intelligent Systems Reference Library 175,
https://doi.org/10.1007/978-3-030-33795-7_2

2.1 Introduction

Nowadays methods of multidimensional statistical analysis are widely used in various fields of science and technology. One of the most important classes of applied tasks for such an analysis is the representation and processing of multidimensional images. Examples of such images are aerospace images, remote sensing data (Earth remote sensing), medical image sequences, etc. In recent years, sensors have been increasingly used to obtain multispectral (up to 10 spectral ranges) and hyperspectral (up to 300 ranges) images. As a result, multidimensional arrays of information are obtained, which are described by coordinates in the space, time, and range of the spectrum. Thus, there is a rapid increase in the amount of information received, and new methods of presenting and analyzing data as a single multidimensional set are required.

It is obvious that obtaining and processing large amounts of information is a very complex task and requires significant computational cost [1–8]. The most important stage of image preprocessing is filtering stage [9–13]. The effectiveness of the filtering largely determines the results of post-processing. Errors obtained at this stage can have a significant impact when solving subsequent problems, such as image clustering or detecting anomalies. In this regard, it is important to use various methods of noise suppression in the images to be received [14–17].

Another important task is the identification of model parameters [18, 19]. It is clear that the more accurately the model describes a real image, the better its model-based processing will be. However, choice of a model assumes the necessity of its complexity analysis. For example, the development of algorithms for some models can be a simple task from a mathematical point of view. However, the processing efficiency based on such models will be low. On the other hand, increasing the complexity of the model leads to significant computational cost. Thus, it is necessary to describe images using models that combine possibility of analytical study and do not require significant computational cost for image processing tasks.

This chapter is devoted to development and investigation of new mathematical models of multidimensional images, which allow to solve simple recurrent processing algorithms synthesis problems and to analyze the effectiveness of using such algorithms.

The rest of the chapter describes the advantages and disadvantages of known mathematical models of images (Sect. 2.2), the one-dimensional AR with multiple roots model and its processing (Sect. 2.3), the properties and processing of RF generated by multidimensional AR with multiple roots (Sect. 2.4), and the real image processing results (Sect. 2.5). Section 2.6 contains more significant conclusions of the work.

2.2 Mathematical Models of Images

When solving problems of image processing, an important step is the choice of an adequate model for observations. Currently, there is no universal way to form RF with arbitrarily specified characteristics. In addition, there is no sufficiently complete solution to the problem of describing real images. Therefore, the well-known models of RF correspond to real images only by a limited number of parameters, such as the form of Correlation Function (CF), the distribution of amplitudes, etc. There are a large number of methods for simulating RF. In [20], all models of RF are divided into two classes. First class models describe fields with continuous distributions. Gauss and Markov RF [21] models can be categorized into this class. Such models are usually obtained either using spectral transformations or by shaping filter method. Given the discrete nature of real systems of spatial information sensors and additional time sampling when transmitting signals over digital communication channels, it is possible to consider only those models that represent RF on multidimensional space-time grids [22–26].

Let us analyze a number of well-known RF models that can be used for description of images during the synthesis of various image processing procedures, such as, for example, filtering, segmentation, or restoration and prediction. AR stochastic models are usually considered as the most well-known models.

It is possible to describe the images by RF, defined on multidimensional grids. In this case, a general description of RF is achieved using tensor difference stochastic equations [27]. Then the sequence of multidimensional frames is defined as changing in the discrete time RF, specified on the multidimensional grid $J_t = \{\bar{j} = (j_1, j_2, \ldots, j_N), j_1 = 1, M_l, l = 1, 2, \ldots, N\}$, where $j_1, j_2, \ldots, j_N$ are the space coordinates. Figure 2.1 shows an example of such image.

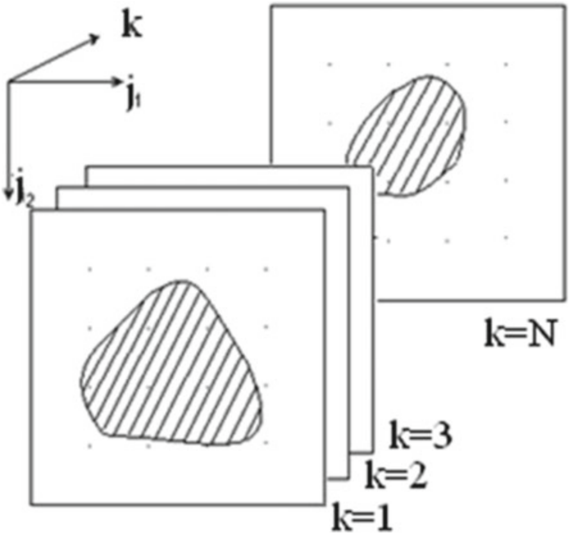


Fig. 2.1 Multizone image frames

The elements of RF are scalar values, which describe brightness of the image at a given point. Thus, the sequence of changing frames of the analyzed image can be considered as RF on the direct product $J_t \otimes T$ [3], elements of which will be denoted as x (the value of RF at the time moment t at the point $\bar{j}$).

In some cases, the following linear tensor stochastic difference equation [27] can be taken as the mathematical model of RF:

$$x_{\bar{j}}^{\ t} = \rho^{t}_{\bar{j}\,\bar{l}} x_{\bar{j}}^{\ t-1} + \vartheta_{\bar{j}\,\bar{l}}^{\ t} \xi_{\bar{l}}^{t} \bar{j}, \bar{l} \in J_t, \tag{2.1}$$

where $\{\xi_{\bar{l}}^{t}, \bar{l} \in J_t\}$ is RF of independent standard Gaussian Random Variables (RV), $\rho^{t}_{\bar{j}\bar{l}}$, $\vartheta^{t}_{\bar{j}\bar{l}}$ are the tensors with two group indices. This ratio determines Gaussian Markov RF on the direct product $J_t \otimes T$. Such RF supposes that previous elements $(\varGamma_t^{-} = \{x_{\bar{j}}^{q}, \bar{j} \in J_q, q < t\})$ and future elements $(\varGamma_t^{+} = \{x_{\bar{j}}^{q}, \bar{j} \in J_q, q > t\})$ are frame $\varGamma_t = \{x_{\bar{j}}^{t}, \bar{j} \in J_q\}$ independent. Problems of analysis and synthesis of this model are considered in [27].

However, such a representation of a multidimensional RF leads to considerable computational difficulties. In this regard, it is advisable to use the representation of RF by recurrent procedures both in time and in spatial coordinates [28]:

$$x_{\bar{j}} = \Phi_{\bar{j}}(x_{\bar{l}}, \xi_{\bar{l}}), \bar{l} \in G_{\bar{j}}, \tag{2.2}$$

where $G_{\bar{j}}$ are the areas of elements $\bar{l} \in J$, on which the previous values of RF $\{x_{\bar{j}}\}$ are already determined, i.e. causal window.

In 1956, Levi [29] was the first to introduce Markov RF (MRF) models. Discrete two-dimensional MRF based on the continuous case proposed by Levi have been described by Woods [30]. The discrete MRF model describes each pixel as a weighted sum of neighboring pixels and normal RV. Such RF provides a probabilistic basis for modeling and integrating prior knowledge of images and scenes, and is widely used in digital image processing.

The most studied RF class is the class of AR models [31–33]. One of the main reasons for the widespread use of AR models is the mathematical apparatus developed for RS simulation. The class of AR models of RF is generated by linear stochastic difference equations of the following form [27]:

$$x_{\bar{i}} = \sum_{\bar{j} \in D} \alpha_{\bar{j}} x_{\bar{i}-\bar{j}} + \beta \xi_{\bar{i}}, \ \bar{i} \in \Omega, \tag{2.3}$$

where $X = \{x_{\bar{i}}, \bar{i} \in \Omega\}$ is RF to be simulated, which is determined on N-dimensional grid $\Omega = \{\bar{i} = (i_1, i_2, \ldots, i_N) : \{i_k = \overline{1 \ldots M_k}\},\ k = \overline{1 \ldots N}\}$; $\{\alpha_{\bar{j}}, \beta, \bar{j} \in D\}$ are the coefficients of the model; $\{\xi_{\bar{i}}, \bar{i} \in \Omega\}$ is RF of standard Gaussian RV; $D \subset \Omega$ is the causal region of local states.

It is quite convenient and simple to choose a normally distributed RF with independent components for the generating process. In this case, RF X also has a Gaussian distribution. Let us consider the formation of RF $X = \{x_{\bar{i}}, \bar{i} \in \Omega\}$, using AR model supposed by Habibi [33]:

$$x_{i,j} = \rho_x x_{i-1,j} + \rho_y x_{i,j-1} - \rho_x \rho_y x_{i-1,j-1} + \xi_{i,j}, i = \overline{1\ldots M_1}; j = \overline{1\ldots M_2}, \tag{2.4}$$

where ρ_x and ρ_y are the correlation coefficients of neighboring elements column-wise and row-wise, respectively; $\{\xi_{i,j}\}$ is two-dimensional field of independent Gaussian RV with zero mean $M\{\xi_{i,j}\} = 0$ and variance $\sigma_\xi^2 = M\{\xi_{i,j}^2\} = (1 - \rho_x^2)(1 - \rho_y^2)\sigma_x^2$; $\sigma_x^2 = M\{x_{i,j}^2\}$, $M_1 \times M_2$ is the size of simulated image.

RF generated in this way is anisotropic, and its CF due to anisotropy is a generalization of CF of a one-dimensional first-order AR to the two-dimensional case. It can be shown [34] that it is described by the following expression:

$$B(k_1, k_2) = \sigma_x^2 \rho_x^{|k_1|} \rho_y^{|k_2|}, \tag{2.5}$$

where σ_x^2 is the variance of RF X, ρ_x and ρ_y are the model parameters, k_1 and k_2 are the distances between the elements of RF X along the axes x and y, respectively.

The analysis of probabilistic properties of RF is considerably simplified if their spectral density can be factorized. So called separable RF is a convenient object for research. Since these fields have normalized CF $R(\bar{k}) = \prod_{i=1}^{N} R_i(k_i)$ which can also be factorized, then to solve the problem of statistical analysis of CF of a multidimensional RF, it suffices to use the properties of the RS generated by one-dimensional AR with characteristics $R_i(k_i), i = \overline{1\ldots M_i}$, where M_i characterizes the multidimensionality of such RF.

AR models have significant drawbacks associated with the limited size of the local state regions, which do not allow it to be fully used as a model of a multi-zone image. Therefore, for an adequate representation of real images, it is necessary to expand the region of local states, which leads to a significant increase in computational costs when simulating RF.

Models [35–39] based on the possibility of extending to the multidimensional case of AR of the second and higher orders with multiple roots of characteristic equations serve as a certain compromise. For example, for the second order AR process with multiple roots of characteristic equations:

$$x_i = 2\rho x_{i-1} - \rho^2 x_{i-2} + \xi_i \tag{2.6}$$

the corresponding eight-point model of a two-dimensional RF can be obtained:

$$\begin{aligned} x_{ij} = {} & 2\rho_x x_{i-1,j} + 2\rho_y x_{i,j-1} - 4\rho_x\rho_y x_{i-1,j-1} \\ & - \rho_x^2 x_{i-2,j} - \rho_y^2 x_{i,j-2} + 2\rho_x^2\rho_y x_{i-2,j-1} \\ & + 2\rho_y^2\rho_x x_{i-1,j-2} - \rho_x^2\rho_y^2 x_{i-2,j-2} + b\xi_{ij}, \end{aligned} \tag{2.7}$$

where b is the normalization coefficient, which allows to simulate RF with a given variance.

The analysis shows that increase of multiplicity of the model makes RF realization form close to isotropic. Obviously, the corresponding changes should influence the form of CF. Thus, we first consider the two-dimensional case with multiplicity $m = 2$. Then CF of one-dimensional sequence takes the following form:

$$R_i(k) = (1 + \frac{(1-\rho_i^2)}{(1+\rho_i^2)}|k|)\rho_i^k, i = 1, 2, \ldots. \tag{2.8}$$

If $1 - \rho_i \ll 1$, the asymptotical expression for CF of two-dimensional RF assumes the following form:

$$R(k_1, k_2) = R(k_1)R(k_2) = 1 - \frac{k_1^2}{a^2} - \frac{k_2^2}{b^2} + k_1^2 k_2^2 (1-\rho_x)^2 (1-\rho_y)^2 A(\rho_x)B(\rho_y), \tag{2.9}$$

where $a = \sqrt{\frac{1+\rho_x^2}{(1-\rho_x^2)(1-\rho_x)}}$, $b = \sqrt{\frac{1+\rho_y^2}{(1-\rho_y^2)(1-\rho_y)}}$, $A(\rho_x) = \frac{1+\rho_x}{1+\rho_x^2}$, $B(\rho_y) = \frac{1+\rho_y}{1+\rho_y^2}$.

It is obvious that cross sections of CF $R(k_1, k_2)$ at the level near $R(k_1, k_2) = 1$ can be approximated by ellipsoids.

It can be shown that subject to minor assumptions, CF of two-dimensional RF (Eq. 2.9) generated by AR with multiple roots of characteristic equations can be written as follows [34]:

$$R(k_1, k_2) = R(k_1)R(k_2) = 1 - \frac{k_1^2}{a^2} - \frac{k_2^2}{b^2} + k_1^2 k_2^2 (1-\rho_x)^{m_1} (1-\rho_y)^{m_2} A(\rho_x)B(\rho_y), \tag{2.10}$$

where m_1, m_2 are the multiplicities of roots of one-dimensional AR.

Along with AR or causal models of RF on flat and spatial rectangular grids, there are a number of non-causal models. Non-Causal AR (NCAR) models represent the values of each pixel as a linear combination of the pixel values of local states and the addition of additive white noise. The difference between the MRF and NCAR models is the spatial correlation of these RV. In [40], an iterative estimation method and an algorithm for synthesizing two-dimensional NCAR models were proposed. This work illustrates the application of NCAR model for representing near-real images with local repetitive properties.

It is possible to get an isotropic model by search for an adequate model in a non-autoregressive class. For example, there is the class of wave models [34]. For wave models, RF is formed as follows:

$$S(x,t) = \sum_{\{i:\tau \leq t\}} f(x,t;\ u_i,\tau_i;\ \bar{\varpi}_i), \tag{2.11}$$

where $x = (x_1, x_2, \ldots, x_n)$, $u = (u_{i_1}, u_{i_2}, \ldots, u_{i_n})$ are the points of n-dimensional space, t and τ_i is the time characteristics, $\{(u_i, \tau_i)\}$ is the discrete Field of Random Points (RPF), $\bar{\varpi}_i$ is the function random parameter vector.

Such RF can be interpreted as the result of the cumulative effect of random perturbations or waves $f(x,t;\ u_i,\tau_i;\ \bar{\varpi}_i)$, occurring in random places u_i at random times τ_i and varying according to some law in time and space. Choosing a wave formation method f, parameters of RPF and $\bar{\varpi}_i$ allows one to get a wide range of types of RF. Examples of such RF are Poisson fields, a model of weighted sums, models of random walks.

Simulation of such RF requires significant computational costs. At present the problem of analytic representation of the laws of probability distribution of wave models is not resolved and is a very difficult task.

Obviously, discarding the connection of elements throughout the image and taking only the connections between the nearest elements as a basis, it is impossible to fully describe the properties of real images. The crucial reason for the incompleteness of such a description is the fact that in a real image different sections are usually characterized by different statistical properties. A typical example would be images containing outlines. In [41, 42], a version of the model is proposed that considers the image as the sum of two independent components namely a piecewise-smooth (contour) spatial component defining global brightness changes, and a high-frequency component defining texture, noise, and small details.

Also, non-causal models include Gibbs fields [43, 44], when the value of RF at a point depends on the nearest pixels that do not precede this point in the order of a certain image scanning. The stochastic equations of such RF have the following form [44]:

$$x(p) = f(\{x(u), u \in G_p\}, \xi_p), \tag{2.12}$$

where $x(p)$ is the value of RF at point p; G_p is the set of nearest neighbors; ξ_p is the random disturbance.

In linear models, Eq. 2.12 can be written as:

$$x(p) = A \cdot (x(u), u \in G_p) + \xi_p, \tag{2.13}$$

where A is the matrix, $(x(u), u \in G_p)$ is the vector of RF samples by the set of nearest neighbors G_p, ξ_p is the random disturbance. When simulating RF using this model, disturbances ξ_p are first generated and then linear equation system (Eq. 2.13) is solved.

If all the eigenvalues of the matrix A are modulo less than one, then it is possible to implement the model provided by Eq. 2.13 by running through, starting, for example, with the identically zero approximation. Such a case occurs, when Eq. 2.13 is the averaging over the nearest samples with the sum of the modules of coefficients less than one.

In [43, 45], the image synthesis of Gibbs model is considered as an iterative process using Monte Carlo–Markov Chain (MCMC) methods, for example Metropolis Exchange Algorithm (MEA). Given the symmetry of the neighborhood, it is possible to determine Gibbs energy on the grid. The joint probabilities corresponding to the Gibbs energies form Gibbs RF:

$$P(x) = \frac{1}{Z}\exp\left\{-\frac{1}{T}E(x)\right\}, \tag{2.14}$$

where Z is the constant; T is RF temperature.

It is considered [43] that the parameter T changes on each iteration step according to the law:

$$T_i = \frac{c}{\lg\left(1 + \frac{i}{i_{cq}}\right)}, \tag{2.15}$$

where $i = 0, 1, \ldots$ is the current iteration number, i_{cq} is the total iteration number, c is the constant.

By varying these parameters, it is possible to get different fields. The main disadvantage of this approach is the need to perform a large number of iterations in the simulation. In addition, the analytical description of this model is very cumbersome.

In image processing, textures are widely used [46, 47]. This is due to the large range of the resulting images, which can be matched quite close to real. In addition, aerospace observations have rather complex space-time properties, which makes it difficult to analyze data only by spectral features. Unfortunately, there are currently no methods for the synthesis of textures that could provide recognition with a minimum average error.

In [48], the simulation of multispectral spatially inhomogeneous dynamic brightness fields is carried out based on the use of random texture synthesis methods. The phase spectrum method is used as a basic mathematical model for generating realizations of two-dimensional stochastic textures. Such RF are realizations of a two-dimensional spatial spectral model that generalizes the results of processing images of the brightness fields of natural formations obtained in aerospace experiments for different observation conditions.

The power spectral density can be represented as: