Filter and Filter Bank Design for Image Texture Recognition

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Abstract

The focus of this dissertation is on the design of two-dimensional filters for feature extraction, segmentation, and classification of digital images with textural content. The features are extracted by filtering with a linear filter and estimating the local energy of the filter response. The dissertation gives a review covering broadly most previous approaches to texture feature extraction and continues with proposals of several new techniques.

Texture feature extraction using a quadrature mirror filter (QMF) bank is proposed, utilizing both critically sampled and full rate implementations. In the critically sampled case, tremendous computational savings can be realized. One of the major conclusions of the experiments is that it is possible to use sub-sampled filters with only a modest degradation in segmentation accuracy – realizing considerable computational savings. Furthermore, the commonly used octave band decomposition is evaluated against alternative decompositions, concluding that non-octave decompositions are generally superior. The QMF filter bank features are tested on benchmark images, on document segmentation, and on image content search.

The use of linear least squared prediction error filters is also proposed, yielding an optimal representation of the textures. Compared to non-optimized filter banks, this approach yields a low number of feature images for problems with a moderate number of textures. Still good classification results are obtained in most cases. However, being optimal with respect to texture representation does not guarantee optimality with respect to discrimination. Therefore, approaches for the design of filters with optimal energy separation are proposed. For two-texture problems, an exact closed form solution optimizing the relative distance between the average feature values is derived. Furthermore, an approximate solution for the Fisher criterion is also derived. For both of these solutions, the coefficient vector of the optimal filter is selected from the eigenvectors of the same matrix. A generalized criterion leading to the same eigenproblem is therefore introduced. Motivated by this generalized criterion, a scheme selecting the filter coefficient vector with respect to minimum feature histogram overlap is proposed. The methods are also extended to multiple texture cases and unsupervised problems. A model for the feature extraction process is required for the optimization and is developed and assessed.

The performances of the proposed methods are shown in extensive experiments. These experiments also incorporate methods broadly covering most approaches to texture feature extraction with filters, along with a few non-filtering approaches. The results clearly justify the new approaches.

Finally, new methods for automated seismic interpretation are proposed. In these techniques, the dominating orientation of the seismic is estimated. It is shown that applying filters tuned with respect to the dominating orientation in the seismic signal, powerful features for the detection of discontinuities in the seismic data, i.e., faults, may be extracted. It is furthermore shown how the orientation flow yields tools for analyzing stratum interfaces.

Preface

This dissertation is submitted in partial fulfillment of the requirements for the degree of *doktor ingeniør* at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. Professors John Håkon Husøy of Stavanger College (HiS), Stavanger, Norway, and Tor Audun Ramstad of NTNU have been the supervisors.

The work, including compulsory courses corresponding to one year full time studies, as well as one year of undergraduate lecturer duties, has taken place in the period of June 1993 to August 1997. The research was carried out at the Electrical and Computer Engineering Department of HiS and with the Research and Engineering Department of Schlumberger Geco-Prakla, Stavanger, Norway. Three months were spent as a visiting scholar at the Pattern Recognition and Image Processing Laboratory at Michigan State University, East Lansing, Michigan, USA. The work was funded by scholarships from NTNU, HiS, and the Norwegian Research Council (grant number 110914/410) and by financial support from Schlumberger Geco-Prakla.

Parts of the work presented in this dissertation have been presented earlier in reports, journals, and conferences [97, 47, 102, 101, 104, 105, 103, 106, 107, 6, 108, 99, 78, 98, 110, 109, 100, 111, 112]. A few elements of the work reported herein have been conducted in cooperation with graduate students for whom I have been supervisor. This is *parts* of the work reported in Sections 5.5 [5] and 5.3.3 [95]. The work presented on filter banks in Chapter 3 was novel when it was conducted in 1993, but later a multitude of similar and related approaches have been presented.

The problem of pattern recognition in seismic signals, Chapter 8, was introduced during the dr.ing. work. This part of the work was carried out in close cooperation with Schlumberger Geco-Prakla. Due to commercial interests, the work on seismic signals has not been strictly texture related. However, the approaches presented in Chapter 8 are related to the other approaches in the use of filters and techniques based on filtering.

Reproducibility is a central concern in the publication of this dissertation. Consequently, most of the images and software used for this dissertation are available on the world wide web at *http://www.hsr.no/sigproc/*.

Stavanger, 1997

Trygve Randen

To my wife Oddveig

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Last but not least, I would like to thank my wife Oddveig for being supporting and bear with my never-relaxed attitude, my two year old son Markus for reminding me that life has more to it than texture, and my parents Agnes and Oddvar for teaching me to understand the value of hard work and supporting me during my 21 years of education as well as in life in general.

Contents

Chapter 1

Introduction

Webster's Dictionary [137] gives the following definition of texture: "The characteristic structure of the interwoven or intertwined threads, strands, or the like, which make up a textile fabric [...]. The characteristic physical structure given to a material, an object, etc., by the size, shape, arrangement, and proportions of its parts [...]". Most natural surfaces and naturally occurring patterns exhibit texture. A texture recognition system will therefore be a natural part of many computer vision systems. In texture segmentation, the problem is to automatically identify the different regions with homogeneous textures, like in the images in Figure 1.1. For detailed discussions on what is and what is not texture, see [55, 88]. For more definitions of texture, see [20].

This introductory chapter is organized as follows: In Section 1.1, applications of texture analysis are discussed. A discussion of various categories of approaches to texture analysis is given in Section 1.2. The scope and major contributions are discussed in Section 1.3, while an outline of the dissertation is given in Section 1.4.

1.1 Applications of texture analysis

A wide range of examples of the successful applications of texture recognition systems exists. A few examples are discussed briefly in this section. For more information on applications, refer to the overview article by Tuceryan and Jain [128] or to several of the other papers in the reference list of this dissertation.

Medical imaging: Images in medicine arise from non-intrusive techniques as photography, x-ray, ultrasound, tomography, etc. Furthermore, some medical images also arise from intrusive techniques as microscopic photography of biopsies. In several of these image types, textural properties are important for diagnosis. Cancer is often characterized by characteristic textures with different medical imaging techniques. Breast cancer is a leading cause of cancer deaths among women [41]. Early detection is the most effective way to reduce mortality, and mammographic screening is currently the best method for early detection. Texture techniques have been applied successfully to the detection of lesions in mammographic images [41, 40]. Another example of images where cancer is characterized by texture is electron microscope images of thin slices of liver cells. Also for this kind of

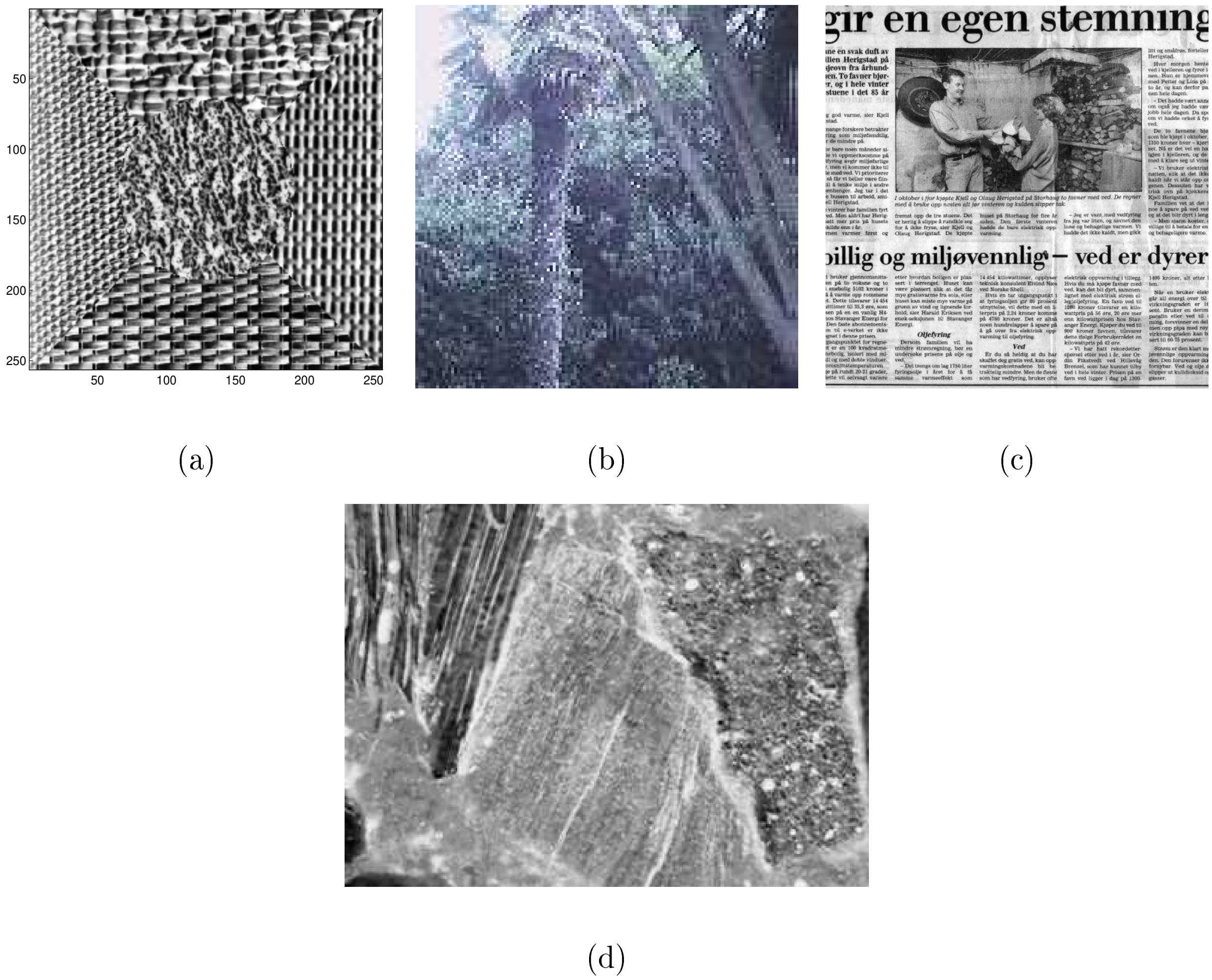

Figure 1.1: Examples of images with textural content. (a) Benchmark composite 256×256 5-texture image. (b) Vacation photo. (c) Scanned newspaper page. (d) Thin slice of a rock core sample from below the surface of the earth.

images, texture techniques have been applied successfully for cancer detection [4].

Remote sensing: Remote sensing is the measurement of properties of an object far away from the object. Remote sensing techniques include satellite photography, satellite multi-spectral measurements, seismic surveys, sonar surveys, etc. Numerous approaches to texture recognition in remote sensing have been presented. Applications include terrain classification [140, 120], cloud classification [61], sea floor mapping [63], and seismic pattern recognition [93].

Industrial inspection: In industrial processes, the detection of defects in manufactured products or in the raw material may be of a crucial importance. Manual visual inspection is often a tedious and laborious task, thus automation is of great interest. In many cases, the quality of a surface is well characterized by its texture. Hence, texture analysis plays an important role in inspection. Numerous approaches to inspection by texture techniques have been proposed. Two examples are quality inspection of painted metallic surfaces [32] and lumber defect detection [113].

Document segmentation: When viewed from a sufficient distance, the text regions of printed documents are by humans perceived as texture. For a particular language, font, etc., the text appears as a homogeneous texture, see for example Figure 1.1(c). By the use of texture analysis, it may be possible to segment regions of text from regions of graphics in scanned documents. Such segmentation is important for successful optical character recognition and may be utilized in for example digitizing of paper documents or periodicals. Examples are given in Section 7.1 and in references [49, 84].

Content based image search: Digital image data has been around on computers and on the Internet for a long time. However, locating an image with a specific content is not straight-forward. Without search tools, this requires manual labeling or browsing of the images. Hence, an evolving research area in computer vision is content based image search. Some content types, e.g., hair, leaves, sky, and grass, have texture as an important characteristic. Therefore, applications including texture recognition have been presented [34, 86, 88], see also Section 7.2.

Shape from texture: Texture analysis has also found its application in reconstructing three-dimensional shape from two-dimensional images. By analyzing how the texture pattern changes, the shape of an object may in principle be reconstructed from the texture [125].

Arbitrary-dimensional textures: The typical texture context is two-dimensional image processing, but it is also possible to extend the concept of texture to an arbitrary dimensionality. For instance, speech recognition systems using short-time spectral analysis can in this respect be regarded as texture analysis tools.

In order to measure the quality of a texture feature extraction scheme, numerous approaches have been devoted to the application on benchmark images. An example benchmark image is shown in Figure 1.1(a). Several experiments on benchmark images are presented in this dissertation, especially in the comparative study of Chapter 6. Most benchmark textures used in this dissertation, including Figure 1.1(a), are scanned from Brodatz [14].[1]

[1] The images from Brodatz [14] were scanned using a Hewlett Packard ScanJet II scanner with a 640×640 pixels resolution and eight bits per pixel. All test images are available on the Internet from http://www.hsr.no/sigproc/. It is noted that the scanning resolution will have significant impact on the performance of most texture features. Conclusions drawn from experiments are therefore highly dependent on scanning resolution.

1.2 Approaches to texture analysis

Approaches to texture feature extraction and recognition span a wide range of methods. Several books and articles give overviews of the available methodology [43, 48, 114, 128]. Four major categories may be identified [128];

Statistical: Co-occurrence and autocorrelation features.

Geometrical: Voroni tessellation and structural features.

Model based: Random field and fractal parameters.

Signal Processing: Spatial and spatial frequency filters and filter banks, wavelet transforms, wavelet packets, and wavelet frames.

The geometrical features are of limited practical utility [114] due to tight assumptions on the images. They are probably the least commonly applied features in texture recognition. The other three categories are included in experiments in this work.

1.3 Scope of this dissertation

The focus of this dissertation will be on the *signal processing approaches.* Multiple new filter bank and optimal filter and filter bank approaches will be proposed. Examples on the applications of the approaches will be presented and comparisons with previously published works will be given. For reference, experiments with statistical and model based features are also given. Briefly summarized, the major contributions of this dissertation are:

1. Introduction of the class of quadrature mirror filters (QMF) to texture feature extraction, along with the derivations of multi-rate local energy functions. Considerable improvements of the computational complexity are realized by the multi-rate (critically sub-sampled) filter banks.

2. It is shown how the multi-rate filter bank may be utilized for document segmentation and image content search.

3. Proposal of optimal prediction error filters for texture feature extraction. Class maps are formed by selecting the class corresponding to the minimum local prediction error.

4. Development of a powerful filter feature extraction model. The model includes expressions for estimating mean and variance of features extracted by a filter and a local energy function.

5. Proposals of several new filter optimization approaches for two-texture problems.

6. Proposal of a new multi-texture optimal filter bank design scheme.

7. Proposals of solutions to the problems of fault and stratigraphic pattern recognition in seismic signals.

A more detailed summary of the contributions is given in Section 9.1.

1.4 Outline of this dissertation

This dissertation can be divided into three parts; the introductory part, the methodology part, and the applications part. The methodology chapters constitute the core part of this dissertation. An overview of the chapters is given in this section.

1.4.1 Introduction

Chapter 1: Introduction to the problems and a brief overview of applications and approaches.

Chapter 2: A description of the principles of texture feature extraction with filters is given. Furthermore, a survey covering broadly most previous works on signal processing approaches to texture recognition is given.

1.4.2 Methodology

Chapter 3: An extension of the dyadic Gabor filter bank of Jain and Farrokhnia [50] to arbitrary sub-band decompositions is proposed. Furthermore, the class of QMF filter banks is introduced for texture filtering. In order to utilize sub-sampling of the QMF bank, a novel local energy function for sub-sampled filter banks is proposed.

Chapter 4: Two different filter optimization approaches are suggested in Chapters 4 and 5. In Chapter 4, an approach based on linear prediction error filtering is proposed. This approach is optimal with respect to representation of the textures, but not necessarily optimal with respect to discrimination.

Chapters 5: Several new FIR filter design techniques yielding filters optimal with respect to discrimination are proposed in Chapter 5. These are optimization approaches for two-texture problems with respect to several criteria, extensions to multiple textures, and an approach to unsupervised optimal filtering. Furthermore, necessary feature extraction models are developed.

Appendix A: The most involved details of the mathematical derivations and proofs of Chapter 5 are put in this appendix. Furthermore, a method to find the upper bound for one of the criteria, the Fisher criterion, is developed.

Chapter 6: Numerous approaches to texture feature extraction with filters are proposed in the literature and some novel techniques are proposed in this dissertation. However, no extensive comparisons covering most of the approaches have been presented previously. In Chapter 6, an extensive comparative analysis is compiled. These experiments cover broadly most published filters and filter banks for texture feature extraction. The study also includes the new approaches proposed herein. Special emphasis is put on making the experiments reliable and comparable, to be able to judge the quality of the different approaches. This chapter concludes the methodology part of the dissertation.

1.4.3 Applications

Chapter 7: The applications of the QMF filter banks of Chapter 3 to the problems of document segmentation and content based image search are addressed in Chapter 7.

Chapter 8: Another application, seismic pattern recognition, is addressed in Chapter 8. Solutions to two problems in seismic signal analysis, automated fault and automated stratigraphic boundary identification, are addressed. Not being strictly texture analysis, this chapter is somewhat on the side of the other chapters. However, since the approaches are based on feature extracting filters and other elements of the texture recognition systems, these approaches are closely related to texture approaches.

Chapter 9: The dissertation is summarized in Chapter 9, listing the major contributions and conclusions of this work and directions for future research.