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by

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To Marleen and Annick

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Preface

One of the most intriguing questions in image processing is the problem of recovering the desired or perfect image from a degraded version. In many instances one has the feeling that the degradations in the image are such that relevant information is close to being recognizable, if only the image could be sharpened just a little. This monograph discusses the two essential steps by which this can be achieved, namely the topics of *image identification* and *restoration*. More specifically the goal of image identification is to estimate the properties of the imperfect imaging system (blur) from the observed degraded image, together with some (statistical) characteristics of the noise and the original (uncorrupted) image. On the basis of these properties the image restoration process computes an estimate of the original image.

Although there are many textbooks addressing the image identification and restoration problem in a general image processing setting, there are hardly any texts which give an indepth treatment of the state-of-the-art in this field. This monograph discusses *iterative* procedures for identifying and restoring images which have been degraded by a linear spatially invariant blur and additive white observation noise. As opposed to non-iterative methods, iterative schemes are able to solve the image restoration problem when formulated as a constrained and spatially variant optimization problem. In this way restoration results can be obtained which outperform the results of conventional restoration filters. In image identification an efficient iterative procedure, known as the EM-algorithm, is used in order to compute maximum likelihood estimates of the parameters describing the image properties and blur.

Chapter 2 discusses various aspects of modeling the image formation process. These models form the groundwork for the mathematical treatment of the image identification and restoration problem as discussed in this monograph.

Chapters 3 through 5 address many aspects of the use of iterative methods in image *restoration*. In Chapter 3 we will first discuss the ill-conditionedness of the restoration problem, which means that the observation noise that is inevitably mixed with the data is amplified enormously if an inverse filter is employed in the restoration process. Next a concise introduction is given to some well-known restoration filters. All of these regularized restoration filters make use of either a stochastic, algebraic, or deterministic formulation of *a priori* knowledge about the image to be estimated in order to find a compromise between the amplification of the observation noise and the accuracy of the solution.

Chapter 4 discusses another method to incorporate the fact that the observed blurred image is always contaminated by noise, namely by terminating the iterative implementation of the inverse filter prior to convergence. As a result a partially restored image is obtained which usually does not show any serious noise amplification. Additional advantages are that no matrix inverses need to be implemented, and that the method can be extended to more complex schemes. Several variations on the standard iterative restoration filters are derived. Although initially a basic steepest descent iterative scheme is employed, a number of more efficient implementations are considered as well.

In Chapter 5 we show that as a result of regularizing the restoration process, ringing artifacts are introduced in restored images. The iterative restoration algorithm introduced in this chapter incorporates two methods to suppress these ringing artifacts, namely (i) the use of deterministic *a priori* knowledge, and (ii) the local regulation of the magnification of the observation noise. Experimental results demonstrate that the proposed iterative scheme leads to results which are to be preferred to conventional restoration results in both numerical and visual respects.

Chapters 6 through 8 are concerned with recent methods to solve the image *identification* problem via a maximum likelihood approach. First, in Chapter 6 several conventional identification methods are discussed. Next the image identification problem is formulated as a maximum likelihood (ML) problem. The computation of the ML estimator turns out to be a highly complicated and nonlinear optimization task. We show that all identification algorithms known sofar in the literature are merely different implementations of this estimator, resulting from different modeling assumptions (such as noisy or noiseless data), and/or considerations about the computational complexity or computer resources available.

In Chapter 7 the iterative expectation-maximization (EM) algorithm is applied to the ML image identification problem. This leads to a particularly elegant algorithm which simultaneously identifies and restores the noisy blurred image. Whereas the original ML image identification method requires the solving of a nonlinear optimization problem, the proposed iterative identification procedure requires the solving of linear equations only.

Although the algorithms presented in Chapters 6 and 7 are mathematically well defined, they are subject to a number of restrictions in practical applications such as numerical inaccuracies and the sensitivity of the solution with respect to the initial estimate. Therefore in Chapter 8 two more practically oriented image identification techniques are proposed, both of which are based on the identification method developed in Chapter 7. In the first method structural knowledge about the blur and image model is incorporated into the identification process. The second method employs resolution pyramids in order to estimate the blur in a hierarchical manner. Experimental results on both synthetic and photographic motion and defocusing blurs are given.

This monograph was originally written by Reginald L. Lagendijk as a doctoral thesis under supervision of Prof. Jan Biemond at the Delft University of Technology. Throughout the research that has led to this monograph, we have been fortunate to have had many lengthy and beneficial discussions with research collegues at several universities. We wish to express our gratitude to them all. In particular we would like to thank Prof. R.M. Mersereau from Georgia Tech (Atlanta GA), Profs. J.W. Woods and H. Kaufman from Rensselaer Polytechnic Institute (Troy NY), Prof. A.K. Katsaggelos (Northwestern University, Evanston Il.) and Prof. A.M. Tekalp (University of Rochester, Rochester NY) for their involvement in the work reported here.

REGINALD L. LAGENDIJK AND JAN BIEMOND

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