Motion Deblurring

A comprehensive guide to restoring images degraded by motion blur, bridging traditional approaches and emerging computational photography-based techniques, and bringing together a wide range of methods drawn from basic theory and cutting-edge research. It encompasses both algorithms and architectures, providing detailed coverage of practical techniques by leading researchers.

From an algorithms perspective, blind and non-blind approaches are discussed, including the use of single or multiple images; projective motion blur model; image priors and parametric models; high dynamic range imaging in the irradiance domain; and recognition of blurred images. Performance limits for motion deblurring cameras are also presented.

From a systems perspective, hybrid frameworks combining low resolution high-speed and high resolution low-speed cameras are described, along with the use of inertial sensors and coded exposure cameras. An architecture exploiting compressive sensing for video recovery is also included.

This book will be a valuable resource for researchers and practitioners in computer vision, image processing, and related fields.

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Algorithms and Systems

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Preface

The computer vision community is witnessing a major resurgence in the area of motion deblurring spurred by the emerging ubiquity of portable imaging devices. Rapid strides are being made in handling motion blur both algorithmically and through tailor-made hardware-assisted technologies. The main goal of this book is to ensure a timely dissemination of recent findings in this very active research area. Given the flurry of activity in the last few years in tackling uniform as well as non-uniform motion blur resulting from incidental shake in hand-held consumer cameras as well as object motion, we felt that a compilation of recent and concerted efforts for restoring images degraded by motion blur was well overdue. Since no single compendium of the kind envisaged here exists, we believe that this is an opportune time for publishing a comprehensive collection of contributed chapters by leading researchers providing in-depth coverage of recently developed methodologies with excellent supporting experiments, encompassing both algorithms and architectures.

As is well known, the main cause of motion blur is the result of averaging of intensities due to relative motion between a camera and a scene during exposure time. Motion blur is normally considered a nuisance although one must not overlook the fact that some works have used blur for creating aesthetic appeal or exploited it as a valuable cue in depth recovery and image forensics. Early works were non-blind in the sense that the motion blur kernel (i.e. the point spread function (PSF)) was assumed to be of a simple form, such as those arising from uniform camera motion, and efforts were primarily directed at designing a stable estimate for the original image. Research in this area then surged towards PSF estimation to deal with arbitrarily-shaped blur kernels resulting from incidental shakes in hand-held cameras and due to object motion in real scenes. This led to the evolution of blind deconvolution algorithms in which the PSF as well as the latent image had to be estimated. Initial works dealt with space-invariant kernels, only to quickly pave the way for investigation of methods for dealing with space-variant blur situations which are actually more prevalent. Parallel efforts addressing the motion blur problem from an acquisition point of view too were also being developed. Traditional approaches to motion deblurring have separated the sensor from the scene being sensed in that the motion-blurred images are post-processed to mitigate blurring effects. Given the recent advances in computational photography, novel approaches are being developed that integrate the sensor design and motion deblurring aspects. These have ranged from integrating inertial sensor data, to proposing hybrid system architectures consisting of multiple cameras with different sensor characteristics, to suitably tailoring the nature of the PSF itself through coded exposure cameras.

Research continues to grow at an amazing pace as portable imaging devices are becoming commonplace. Commercial significance of the motion deblurring problem is amply evident from the plethora of software and hardware-based approaches that have been reported in recent years and this can only be expected to grow in the coming years. In an attempt to provide a comprehensive coverage of early as well as recent efforts in this area, the contents of this edited book are spread across *thirteen* self-contained chapters. These can be broadly categorized under two major headings, namely, *Algorithms* and *Systems* for tackling the motion deblurring problem. We have deliberately refrained from sequestering the chapters along these themes and instead allowed the chapters to seamlessly weave through both these topics.

The first chapter by Jiaya Jia deals with shift-invariant or uniform single image motion deblurring and provides a systematic survey that covers early as well as recent developments for single-input motion blur models and solvers. Representative methods such as regularized and iterative approaches for model design and solver construction, and recent advances including construction of natural priors for a latent image and variable splitting solver for sparse optimization are described for the non-blind deconvolution problem. For blind deconvolution, marginalized estimation and alternating minimization strategies along with edge prediction for very large PSFs are presented.

The chapter by Joshi *et al.* addresses the problem of spatially-varying blur and presents a unified model of camera shake that can represent space-variant blur as a function of camera motion. The discussions range from fully blind methods to hardware design for deblurring using sensor data. A method for generation of sharp panoramas from blurry sequences is also presented.

The chapter by Ben-Ezra *et al.* involves hybrid-imaging system design targeting image deblurring due to camera shake and, to some extent, moving objects in a scene. This is a hardware-assisted technique that combines a high resolution camera along with an auxiliary low resolution camera to effect deblurring. The secondary imager is principally used to acquire information about the spatially-invariant or spatially-variant discrete parametric 2D motion field. The flow field is then used to derive the PSF corresponding to the primary camera so as to arrive at a high resolution non-blurred image.

The chapter by Whyte *et al.* describes a compact global parameterization of camera-shake blur, based on the 3D rotation of the camera during the exposure. A model based on three-parameter homographies is used to connect camera motion to image motion and, by assigning weights to a set of these homographies, this formulation can be viewed as a generalization of the standard, spatially-invariant convolutional model of image blur. A scheme for blur estimation from a single image followed by restoration is presented. Different approximations are introduced for the global model to reduce computational complexity.

The chapter by Šroubek *et al.* presents an attractive semi-blind implementation for image deblurring on a smartphone device. It is shown that information from the inertial sensors such as accelerometers and gyroscopes, which are readily available in modern smartphones, is accurate enough to provide camera motion trajectory and, consequently, to estimate the blurring PSF. A simple yet effective space-variant implementation of the deblurring algorithm is given that can handle complex camera motion as well as rolling shutter issues. The method works in practical situations and is fast enough to be acceptable by end users.

The chapter by Jingyi Yu presents two multi-sensor fusion techniques for sufficient and low-light conditions, respectively, that combine the advantages of high speed and high resolution for reducing motion blur. The hybrid sensor consists of a pair of high-speed color (HS-C) cameras and a single high resolution color (HR-C) camera. The HS-C cameras capture fast-motion with little motion blur. They also form a stereo pair and provide a low resolution depth map. The motion flows in the HS-C cameras are estimated and warped using the depth map on to the HR-C camera as the PSFs for motion deblurring. The HR-C image, once deblurred, is then used to super-resolve the depth map. A hybrid sensor configuration for extension to low-light imaging conditions is also discussed.

The chapter by Amit Agrawal describes coded exposure photography in which the key idea is to assist motion deblurring by modifying the imaging process to avoid loss of high frequency information during acquisition. In addition to optimal temporal code design, the role of coded exposure in enabling resolution enhancement of blurred moving objects is also dwelt upon. Hardware and implementational considerations for consumer-grade cameras are also discussed.

The chapter by Tai *et al*. describes a projective motion path blur model which, in comparison to conventional methods based on space-invariant blur kernels, is more effective at modeling spatially-varying motion blur. The model is applicable to situations when a camera undergoes ego motion while observing a distant scene. The blurred image is modeled as an integration of the clear scene under a sequence of planar projective transformations that describes the camera's path. A modified Richardson–Lucy algorithm is proposed that incorporates this new blur model in the deblurring step. The algorithm's convergence properties and its robustness to noise are also studied.

The chapter by Vijay *et al*. describes a method that operates in the irradiance domain to estimate the high dynamic range irradiance of a static scene from a set of blurred and differently exposed observations captured with a hand-held camera. A two-step procedure is proposed in which the camera motion corresponding to each blurred image is derived first, followed by estimation of the latent scene irradiance. Camera motion estimation is performed elegantly by using locally derived PSFs as basic building blocks.

By reformulating motion deblurring as that of recovering video from an underdetermined set of linear observations, the chapter by Veeraraghavan *et al*. presents an alternate viewpoint for tackling motion blur. An imaging architecture is introduced in which each observed frame is a coded linear combination of the voxels of the underlying high-speed video frames which in turn are recovered by exploiting both temporal and spatial redundancies. The architecture can tackle complex scenarios, such as non-uniform motion, multiple independent motions and spatially variant PSFs, naturally without the need for explicit segmentation.

The chapter by Scott McCloskey dwells on deblurring in the context of improving the performance of image-based recognition, where motion blur may suppress key visual details. The development of a motion deblurring system based on coded exposure is discussed, and its utility in both iris recognition and barcode scanning is demonstrated. A method is introduced to generate near-optimal shutter sequences by incorporating the statistics of natural images. Also described are extensions to handle more general object motion that can even include acceleration.

The chapter by Mitra *et al*. addresses the problem of recognizing faces from motion-blurred images, which is especially relevant in the context of hand-held imaging. Based on the conditional convexity property associated with directional motion blurs, they propose a bank-of-classifiers approach for directly recognizing motion-blurred faces. The approach is discriminative and scales impressively with the number of face classes and training images per class.

The final chapter by Cossairt *et al*. derives performance bounds in terms of signal-to-noise ratio for various computational imaging-based motion deblurring approaches including coded-exposure and camera-motion based techniques and discusses the implications of these bounds for real-world scenarios. The results and conclusions of the study can be readily harnessed by practitioners to not only choose an imaging system, but also to design it.

The contents of this book will benefit theoreticians, researchers, and practitioners alike who work at the confluence of computer vision, image processing, computational photography, and graphics. It can also serve as general reference for students majoring in Electrical Engineering and Computer Science with special focus in these areas. It would be suitable as both a textbook as well as an advanced compendium on motion blur at graduate level. Given the impact that an application such as motion deblurring has on consumer cameras, the material covered herein will be of great relevance to the imaging industry too. In short, this book can serve as a one-stop resource for readers interested in motion blur.

This comprehensive guide to the restoration of images degraded by motion blur bridges traditional approaches and emerging computational techniques while bringing together a wide range of methods, from basic theory to cutting-edge research. We hope that readers will find the overall treatment to be in-depth and exhaustive, with a right balance between theory and practice.

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