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Perspectives in Shape Analysis

 Springer

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To our families and students

Preface

In everyday life, geometric shapes surround us, and thus the field of shape analysis has a growing variety of applications, including ergonomic design, virtual shopping, scientific and medical visualization, realistic simulation, photo-realistic rendering, the design of natural user interfaces, and semantic scene understanding. The efficient processing of shapes and the discovery and investigation of informative representations for shapes are core tasks in the context of shape analysis research.

Traditionally, the notion of shape has been studied either by analyzing a sparse set of marker positions on three-dimensional (3-D) shapes, primarily for medical imaging applications, or by analyzing projections of shapes in 2-D images, chiefly for image processing and computer vision applications. New challenges in the analysis and processing of such data arise with the increasing amount of data captured by sensors used to acquire shapes, and with modern applications such as natural user interfaces that require real-time processing of the input shapes. Recently, it has also become increasingly affordable to digitize 3-D shapes using multiple modalities, such as laser-range scanners, image-based reconstruction systems, or depth cameras like the Kinect sensor. Using these dense 3-D shapes in the above mentioned applications calls for processing and describing the shapes in an efficient and informative way.

The purpose of this book is to highlight recent advances that address these challenges from different perspectives with the help of the latest tools for geometric, algorithmic, and numerical concepts. As the analysis of 3-D shapes and *deformable shape models* has received considerable attention recently, classic shape analysis tools from differential geometry now have a fresh influence on the field. As they address the issue of how to represent shapes efficiently, the research areas of *sparse data representation* and *machine learning* have begun to influence shape analysis modeling and the numerics. Especially in the context of three-dimensional data (or even higher-dimensional data sets), efficient optimization methods will certainly become increasingly important, since many shape analysis tasks can be formulated as optimization problems. As the efficiency of shape analysis methods is of general importance in all of these fields as well as for the evolution of classic approaches, we also examine *numerical computing* as an important research theme.

As is typical for many fields within image processing, it is often impossible to distinguish a single aspect of the topics mentioned above as a given article's main contribution. For instance, a model for deformable shapes can be at the heart of a novel optimization approach derived from a sparsity concept, which in turn gives rise to an efficient computational model. Especially, the development of new model formulations is closely related to computational approaches. Naturally, this is also the case with regard to the contributions in this volume. Nevertheless, we have sought to emphasize the importance and originality of certain core developments by grouping the content into the following main areas:

Part I: Numerical computing for shape analysis

Part II: Sparse data representation and machine learning for shape analysis

Part III: Deformable shape modeling

Let us now give a brief account of the themes represented in the respective chapters.

A typical task in shape analysis is the segmentation of objects in images. With regard to the numerical computation of proper image segmentations, various approaches have been proposed in the literature. In the first chapter, a classical method for this purpose is reexamined, using the screened Poisson equation as a computational basis. The model is given via a *partial differential equation (PDE)* and, in this chapter, is employed for the purpose of ornament analysis.

The book then goes on to explore another PDE-based approach, this time to the classical shape-from-shading (SFS) problem. In contrast to the first chapter, where the elliptic Poisson equation was at the heart of the developments, here hyperbolic PDEs are addressed. The semi-Lagrangian method employed for the computations in the second chapter offers an efficient method for this purpose.

In turn, the third chapter shows how to make use of robust variational approaches to deal with the SFS problem. The computational problem that arises here in the corresponding *energy minimization* problem is based on solving a parabolic PDE for its elliptic steady state, and in the discrete scheme, also typical components from hyperbolic numerics are also employed. Therefore, the first three chapters nicely show that in today's shape analysis, models of all three fundamental types of PDEs and corresponding computational approaches are important.

Turning to the fourth chapter, which concerns morphological amoebas, again a method useful for segmentation is investigated. Let us emphasize that here the mathematical basis is provided by differential geometry. From a computational point of view, the adaptive amoeba construction shows a strong relation to nonstandard discretizations of the arising PDEs. Here, the task of the numerical description of image content such as texture, and of shapes themselves, is intimately related to segmentation ideas. These aspects are addressed in both Chaps. 4 and 5, while methodically we now turn from PDE-based methods to other approaches.

Chapter 5 especially focuses on numerical shape characteristics that have an intuitive meaning and are useful for building shape discriminators and classifying shapes. The latter issue is also part of the objective of Chap. 6, where the effect of shape distances in an energy minimization method is studied. At a technical level,

in this chapter we arrive very obviously at *optimization methods*. Here a specific trust region scheme is at the heart of the investigation, and the different shape distances are shown to define distinct trust regions. In the spectral method used for segmentation of point clouds in RGB-D data in Chap. 7, a large optimization problem is tackled via the numerical solution of the generalized eigenvalue problem for a specific graph Laplacian.

Summarizing Part I, we conclude that computational methods for PDEs and optimization problems are essential tools in the field of shape analysis. It is extremely difficult to say which techniques are the most prominent ones, as a large variety of different problems appear. We feel this is an intriguing aspect of shape analysis, as it leaves the field open for introducing advances from many branches of computational mathematics. Let us also note that, on a technical level, approaches for reducing the size of computational problems are also often employed (as especially apparent in Chap. 7). All these modeling and computational tools naturally resurface in several parts of this book.

Turning to Part II of this volume, a prominent aspect in the corresponding chapters when compared to those of Part I is that *fully discrete concepts* that lead to efficient shape representations are investigated, e.g., with the aim of reducing storage or for constructing shape abstractions (Chap. 8). In comparison to the works of Part I, this is especially important for analyzing 3-D shapes, which appears natural as the additional third dimension leads to large data sets, making it all the more important to reduce the data load. The topology of 3-D shapes is investigated in Chap. 9 via Morse theory, while the correspondence between sparse 3-D shapes, exploring shape similarity and also referring to *deformable shape models*, is the subject of Chap. 10. Concepts from machine learning and related optimization tools in the context of deformable shapes are also explored in Chaps. 11 and 12. Lastly, Chap. 12 discusses the extensive use of machine learning techniques for 2-D images.

Summarizing the key points from Part II, one may note that the sparsity and machine learning techniques explored here are naturally intimately related to the arising optimization methods and numerical computing, while some of the models are concerned with deformable shapes, as they deal with shape correspondence methods. However, we chose to group these works here in a separate section, given the high significance of introducing machine learning and sparsity concepts into these fields.

Coming finally to Part III, we show here that the field of deformable shapes is already rich in terms of the different aspects that can be explored, complementing and completing the previous works in the other parts of this volume. Beginning with correspondences between deformable shapes in the spectral domain (Chap. 13), which also connects to Chaps. 10 and 11, we turn to the use of morphable shape models in computer vision in Chap. 14. The use of multimodal data for shape recognition, as well as a related use of machine learning methods, is explored in Chap. 15. Moreover, one may find that the concept of a morphable model is related to the template fitting approach explored for shape analysis in MRI data in Chap. 16.

Summarizing important concepts from Part III, one may note that deformable shape modeling includes the important problems of correspondence computation

and statistical analysis and directly relates to a diverse range of applications. One recent trend is to extend classic applications of shape analysis techniques to cover new applications in other fields of science. An example of this is the application of shape analysis methods in computational linguistics and speech science in Chaps. 15 and 16.

The content of this book represents the contributions of respected experts in the field of shape analysis that highlight different new perspectives on the mentioned tasks. A key aspect of this book that sets it apart from other volumes is that it includes both discrete and continuous settings in shape analysis, as both are relevant for the modeling and processing of shape representations.

This volume originated in the inspiring research discussions that took place at a Dagstuhl seminar in February 2014. Both new scientific results and tutorial-style chapters that survey recent aspects in the field are included. As the demands in the individual fields are high, the research groups in which the most interesting techniques are proposed are highly specialized. This not only holds true for discrete and continuous-scale modeling and numerical computing but also for the areas of sparsity and machine learning highlighted here. Thus, in spite of the strong interconnections between the works as they are represented in this volume, at the moment there is no regular conference that could produce such a dedicated book.

It was a great pleasure to exchange scientific ideas with all of our colleagues who participated in the Dagstuhl seminar on New Perspectives in Shape Analysis and contributed to this volume. We hope that this collection will inspire new research ideas and promote further collaboration.

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