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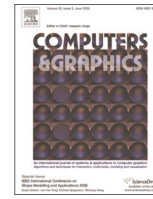

40 years of Computer Graphics in Darmstadt

A visual analytics perspective on shape analysis: State of the art and future prospects

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ABSTRACT

The combination of long established techniques in morphometrics with novel shape modeling approaches in geometry processing has opened new ways of visualizations of shape variability in different application areas like biology, medicine, epidemiology and agriculture. For the first time highly resolved 3D representations became accessible for statistical analysis as well as visualizations. In order to reveal causes for shape variability targeted statistical analysis correlating shape features against external and internal factors is necessary but due to the complexity of the problem often not feasible in an automated way. Therefore, visual analytics methods found their way into the field of morphometrics. This led to numerous publications in recent years that might be subsumed under the novel term visual shape analytics. In this paper we try to put these works into the context of visual analytics, outline the basic principles underlying these approaches and review the current state of the art. Finally, future challenges and possibilities in visual shape analytics are identified.

1. Introduction

In morphometrics and its application fields like medicine or biology experts are interested in causal relations of organismic shape to phylogenetic, ecological, geographical or epidemiological factors. In order to assist experts in getting *insight* into the variability of shapes and uncover potential sources a variety of different visual analytics methods for shape analysis have emerged in recent years that might be subsumed under the novel term *visual shape analytics*. These methods do not aim at a fully automated statistical analysis but instead rather provide interactive tools for an effective exploration of shape variation. This is achieved by means of interactive visualizations in order to stimulate quick hypothesis generation and feature assessment.

The visualizations used frequently during morphometric studies so far were designed primarily for the purpose of communicating final results of a statistical analysis [21,56]. Only recently the potential of an interactive approach for exploration of shape spaces has been recognized and targeted analysis tools, especially for population studies that deal with large data collections were developed [20,42,53,44] and as outlined by Botha et al. [17] further research is needed to come up with novel techniques to exhibit the complex correlations between shape variability and extrinsic as well as intrinsic factors.

In this paper it is shown that the combination of methods from interactive computer graphics and visualization with methods from statistical shape analysis deliver novel ways to investigate and explore complex morphological inter-dependencies. Both domains have a long tradition at the IGD where not only interactive computer graphics techniques and visualization were early in the focus of research [72] but also statistical shape models are extensively utilized in the context of medical image analysis until today [52]. Recently, a first visual analytics approach to provide a better understanding of the impact of particular optimization algorithms for medical image segmentation and their parameters on a local scale were introduced by Landesberger et al. who continued this long tradition at the IGD [89].

By reviewing the state of the art in modeling, navigation and visualization of shape spaces we summarize the current methods and identify new trends in this emerging field.

2. The visual analytics approach to shape analysis

As already stated by Daniel Keim et al. [47] in their work about the foundation of visual analytics, *Visual Analytics combines automated analysis techniques with interactive visualizations for an effective understanding, reasoning and decision making on the basis of very large and complex datasets*. The major task of visual shape analytics consists in linking abstract representations of the high

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dimensional shape space with a corresponding 3D visualization in such a way that an effective *navigation* in shape space is enabled. This requires efficient automatic analysis techniques as well as real-time sampling in shape space and 3D visualizations.

Initially, this idea of navigating shape spaces was brought forward in the work of Busking et al. [20], although they excluded any automated analysis. They present a manual navigation in the abstract representation of the shape space that is presented as a scatter plot in a 2D projection of a linear shape space. The selection of a position in the scatter plot triggers the sampling of a shape in the linear shape space by interpolation of the adjacent shapes that are identified in the two dimensional domain. Although the individual techniques were improved later on, their work already outlines the general visual analytics approach, see Fig. 1. In a first step shape variability is represented by registration of the individual shapes of the shape ensemble against a template which often coincides with their mean shape [37]. Based on this registration the individual shapes are represented by the transformation that deforms the template into the particular shape. After applying statistical analysis on the deformations novel samples are synthesized and can be visualized on demand. In the end this facilitates *navigation* in shape space, that is, sampling shapes at particular points, along any direction or even arbitrary trajectories in abstract data space. This *synthesis* of deformation provides the basic exploration facility of the visual analytics approach and therefore also must be real-time in order to allow interactive exploration. The crucial aspect of visual analytics in this general setting is to support the user in intelligent navigation in shape space and to apply further statistical analysis when needed. This way a feedback loop between statistical analysis and visualization is established. Following the visualization mantra "overview, zoom & filter, then details-on-demand" [77] methods targeting different levels of abstraction were developed, see Table 1. All of the methods can be used in combination, enabling the user to drill down into sub spaces of shape space for a targeted analysis of particular local or global aspects of shape variation.

Special care has to be taken to design a user interface accessible to the domain experts. An example of such an user interface is shown in Fig. 2.

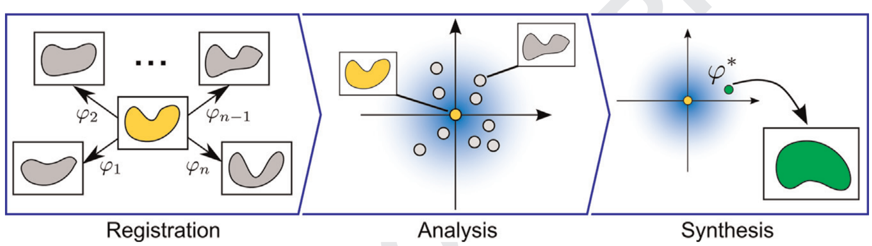

Fig. 1. The modeling pipeline for visual shape analytics.

Table 1
List of methods to navigate shape spaces, classified according to Shneiderman [77] into (o) overview, (f) focus and (d) detail view.

Sec.	Method		Purpose
4.1	Regression [13,2]	(f)	Define a direction in PCA space that parametrizes a labeled attribute
4.1	Classification [42]	(d)	Define a direction in PCA space corresponding to the characteristic shape difference between two groups
4.1	Likelihood volume [21]	(o)	Integrated visualization of direction in PCA space, e.g. overview of principal modes
4.2	Scatter plot [20]	(d)	Manual navigation in PCA space by specifying sample shapes via selecting positions in a scatter plot view
4.2	Barycentric coordinates [80]	(d)	Manual navigation in shape space by specifying a linear combination as generalized barycentric coordinate of a clicked point in a 2D convex polygon whose vertices represent the sample shapes
4.3	Interaction tensor [43]	(f)	Targeted analysis of covariation between points on the shape, e.g. to identify hypotheses on module limits
4.3	Model based editing [12]	(d)	Targeted analysis of covariation between points on the shape with respect to specific perturbation
4.3	Region of interest [42]	(f)	Define a PCA space w.r.t. a selected ROI to focus investigation on particular local structures
4.4	Group browser [44]	(f)	Comparative visualization of multiple factors by interpolating between group mean shapes

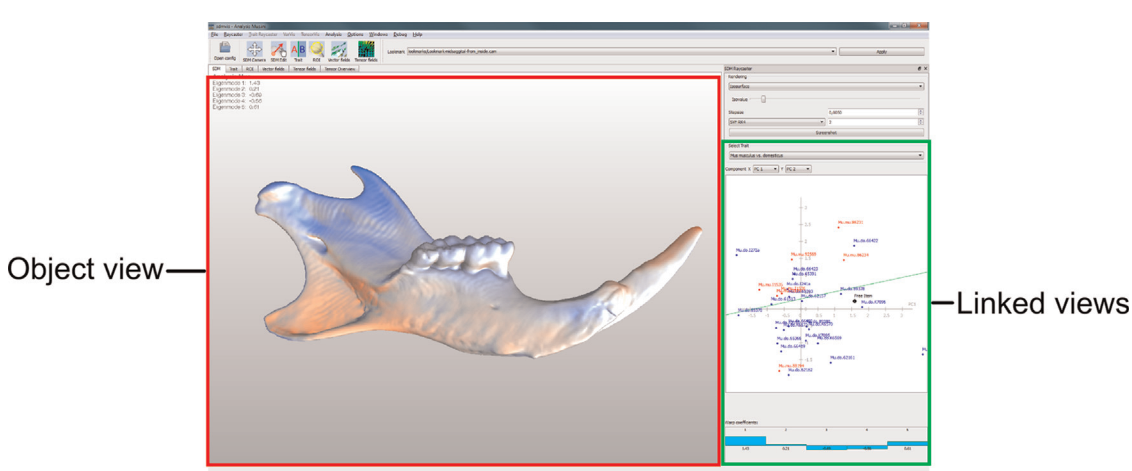

Fig. 2. The user interface of a visual shape analytics system is usually split into a 3D object view that provides different visualizations of shape variability and linked abstract views like the shown interactive scatter plot.

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