Caricaturistic Visualization

Peter Rautek, Ivan Viola, M. Eduard Gröller

Abstract—Caricatures are pieces of art depicting persons or sociological conditions in a non-veridical way. In both cases caricatures are referring to a reference model. The deviations from the reference model are the characteristic features of the depicted subject. Good caricatures exaggerate the characteristics of a subject in order to accent them. The concept of *caricaturistic visualization* is based on the caricature metaphor. The aim of caricaturistic visualization is an illustrative depiction of characteristics of a given dataset by exaggerating deviations from the reference model. We present the general concept of caricaturistic visualization as well as a variety of examples. We investigate different visual representations for the depiction of caricatures. Further, we present the caricature matrix, a technique to make differences between datasets easily identifiable.

Index Terms—Illustrative Visualization, Focus+Context Techniques, Volume Visualization

1 Introduction

The high popularity of caricatures indicates the widespread ability of humans to identify outstanding features of faces. In addition, caricaturists have the ability to exaggerate these features and draw hyperbolized pictures. The exaggeration of features takes place in dependence to a reference model in the caricaturist's brain. A beholder of a caricature can interpret its meaning only if he has a similar reference model in his mind. In Figure 1 an example of a reference model, the subject and the caricature of the subject are shown. The reference model can be seen as an idealized model within the domain of subjects. Each specimen within the domain is characterized by deviations to the reference model. The deviations of the specimen are the features of interest for the caricaturist. The caricature is the outcome of a hyperbolized depiction of the deviating features. It accents the essence of the depicted subject.

In Redman [16] the caricaturist is advised to differentiate between exaggeration and distortion: *"Exaggeration is the overemphasis of truth. Distortion is a complete denial of truth"*. Caricatures exaggerate but do *not* distort deviations. The goal of traditional caricature is the entertainment of the beholder. Caricaturistic visualization follows the same principles as traditional caricature but with a different goal. It aims to accent the characteristics of the depicted object. Many properties of caricatures correspond to specific techniques of illustrative visualization. Caricatures therefore provide a powerful metaphor for illustrative visualization.

Focus+Context techniques provide the user with detailed information at the focus of interest while the context is still present. Good caricatures accent the characteristics and salient details while sparsely sketching the context. The focus in caricatures is on the characteristics of the depicted object which are often the details of interest.

Communication of Visual Content is as effective as the chosen visual representation. Caricatures are expressive depictions of the content of interest simultaneously avoiding the depiction of details which are not of immediate interest. Therefore caricatures are well suited for the communication of visual content.

Augmentation of Images aids the viewer to correctly interpret the image. The augmentation is a descriptive visual information sparsely overlaid over but not occluding the image. Therefore sparse visual representations are necessary to augment images. Caricatures are extremely sparse representations of visual content and can therefore be used to augment an image.

• *Peter Rautek, Ivan Viola, and M. Eduard Gröller are with the Institute of Computer Graphics and Algorithms, Vienna University of Technology, Austria, E-mail: {rautek| viola| groeller}@cg.tuwien.ac.at.*

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For information on obtaining reprints of this article, please send e-mail to: tvcg@computer.org.

Steering Attention to regions of interest is done by visual cues. Caricatures provide intensive cues toward the details of interest. Highly exaggerated regions attract the user's attention to aid in the recognition of differences. Photorealistic rendering often fails to direct the attention to the focus of relevancy.

Caricaturistic visualization is suitable for areas where differences between datasets or deviations to a reference model are of interest. We give some ideas of potential applications for caricaturistic visualization:

Quality Control aims to find subtle differences of workpieces to the reference model. Irregularities of surfaces are of immediate interest. The visual exaggeration of such irregularities leads to clearer visible cues to the regions of interest.

Comparative Biology is concerned with the evolution and changes of species over time as well as with the differences between species. Caricaturistic visualization helps to make the subtle differences visible even for lay persons and could for example also be used in education.

Case-based Education deals with learning by examination of different cases. Medical students for example have to learn different cases of diseases. Each case is a deviation from the reference model. By exaggerating these small deviations the learning process could be aided. The same approach can be used for patient communication. The patient as a layperson often fails to see the abnormalities in the data. Illustrative visualizations accenting the deviations can aid the patient to understand the diagnosis. Caricaturistic visualization can bridge the gap in communication between medical experts and laypersons.

Deformation Surveillance is used to detect changes of objects over time. Small deformations are measured to estimate further deformations. For example the deformation of facades is monitored in order to guarantee the safety of a building. Caricaturistic visualization is able to exaggerate these deformations in order to make them visible and easily detectable.

In Section 2 we briefly discuss related work. We derive a mathematical formulation of a feature in Section 3 and provide some simple guidelines for the design of features. In Section 4 we further illustrate the idea of caricaturistic visualization with some examples of simple caricaturistic operations using the provided mathematical framework. In Section 5 we present the *caricature matrix*, a technique for the visualization of divergences of datasets to each other. It is based on the caricaturistic visualization metaphor and exploits the feature based approach of caricaturistic visualization. In Section 6 we describe the implementation of our caricaturistic visualization prototype. We give ideas about feature design and a user interface for feature specification. In Section 7 we present the results of our caricaturistic visualization system and show examples of visual representations that are suitable for caricaturistic visualization. In Section 8 our work is concluded and ideas for future work are given.

reference model specimen caricature

Fig. 1. Example of a non automatic caricature drawing: In the left image the head of Michelangelo's David statue is shown as analogy for the reference model. In the middle image the specimen (i.e., Rowan Atkinson) is shown. In the right image the caricature of the specimen is shown. The caricature presumes the existence of a reference model.

2 Related Work

Related work to this paper mostly focuses on facial caricatures. Computer aided facial caricature generation was addressed in several previous works [1, 2, 4, 17, 21]. The perception and recognition of faces in association to caricatures was an extensive subject of research [3, 9, 15, 17, 18, 19, 21]. While some works [3, 17, 18, 19] report an advantage in recognition or learning using facial caricatures, other works [9, 15] found no evidence that caricatures of people are better than photographs. Gooch et al. [8] present a more extensive discussion about human facial illustration and an evaluation of caricature techniques for face illustration. For objects in general it was reported [6, 20] that stylized, accentuated drawings are more easily identified. They aid learning more than photographs of the same objects.

The work dealing with illustrative volume visualization focuses on imitating traditional illustration techniques. High level abstraction techniques as presented in the work of Viola et al. [23, 24] and Svakhine et al. [22] control the appearance of different features at varying degrees of sparseness and complexity. An illustrative visualization approach for time varying data was presented by Joshi et al. [11].

Weigle et al. [25] present a related technique for the comparison of different datasets. They investigate visualization techniques for intersecting surfaces and compare the performance of existing techniques and a novel glyph based approach. Wynblatt [26] present visual representations of web pages called caricatures. The caricaturization of web documents allows for fast browsing through a large number of documents. Liu et al. [14] present an approach to make subtle motions in video scenes clearly visible. The motions are accentuated by exaggerating the motion of objects in video scenes.

3 Mathematical Framework

Caricaturists identify features and exaggerate certain properties of these features such as spatial extent, displacement, or angularity. We want to exaggerate the deviations of a specimen from the corresponding reference model. Therefore we measure the difference between the model and the specimen for each property. For example the displacement of the specimen's ear relative to the ideal model is a typical property in facial caricature.

For each property we define a difference function over the domain of the property. The domain of property i is denoted as P_i and the difference function is denoted as $\ominus_i$. In a facial caricature a typical property is the angular offset of the ear to the reference model. Jug ears have a high value for the angular offset property while tight-fitting ears have a value close to zero. The defined domain of the angular offset of the ears could for example be $P_i = \{x | x \in (0, \frac{\Pi}{2})\}$. The difference operation for two values of P_i is the difference between the two angles.

Another example for a property is the three dimensional position of the ear. The domain of this property is a specific subspace of three dimensional space $P_i \subset \Re^3$. The distance measure for the position of the ear is simply the Euclidean distance.

A feature describes the characteristics of the specimen with respect to the reference model. A feature is therefore defined as a property vector. The property vector space is defined as

$$P = P_1 \times P_2 \times \ldots \times P_{n-1} \times P_n \tag{1}$$

In the analogy of facial caricature a possible feature would be the ear given by its position, angular offset and spatial extent along its major axis. We define an exaggeration function for each property of the feature. This function describes the behavior of a feature as its properties are exaggerated. It is desirable that the deviating properties of the feature are even further deviated. In terms of facial caricatures the displacement of the ears would lead to even further displacement. We call this kind of exaggeration of a property *intra property exaggeration*. In contrast to that an *inter property exaggeration* is the exaggeration of a property caused by the deviation of another property. In the above example the inter property exaggeration of the displacement of the ears would also lead to an exaggeration of the scaling of the ears (i.e., the increase of the spatial extent of the major axis). We therefore define the exaggeration function e_i for property i as:

$$e_i(x_i, \delta) = x_i + (c_{i1} d_1(x_1, \widetilde{x_1}) + \ldots + c_{in} d_n(x_n, \widetilde{x_n})) \, \|x_i \ominus_i \widetilde{x_i}\| \, \delta \tag{2}$$

where δ is the exaggeration parameter, d_j is the distance function for property j, $\widetilde{x_j}$ is the value of the reference model for the property j, $c_{ij} \in \Re^+$ for $i, j = 1 \ldots n$ are the coefficients describing the inter and intra property exaggeration, and $\|x_i \ominus_i \widetilde{x_i}\|$ is given by

$$\|x_i \ominus_i \widetilde{x_i}\| = x_i \ominus_i \widetilde{x_i} \frac{1}{d_i(x_i, \widetilde{x_i})} \tag{3}$$

where x_i, $\widetilde{x_i} \in P_i$. The coefficient c_{ij} determines the influence of the deviation of property j on the exaggeration of property i. Intra and inter property exaggerations can be observed in real caricatures. In our approach we focus on intra property exaggerations. We therefore set all coefficients $c_{ij} = 0$ for $i \neq j$.

Guidelines for Features Each feature consists of a set of properties. Simple features may only consist of few properties like position, orientation and elongation. More complicated features may consist of hundreds of properties describing the shape of the feature. Designing appropriate features is crucial for caricaturistic visualization. We designed our features to meet the following constraints:

Flexibility The set of properties is able to describe a wide variety of features.

Simplicity Each property is easy and fast to specify. Features which are complicated to specify may distract the user. Following the constraint of simplicity is not a restriction to the complexity of the feature. The automatically generated shape may be complicated while the user only specified few settings.

Measurability Each property is measurable and has a corresponding distance function. A pair of corresponding features differs only in the specified values of the properties. The distance between these values must be measurable.

While the first two constraints are guidelines to design good features the third constraint is a technical prerequisite for the caricaturization of features. The flexibility and simplicity constraints seem at first glance to result in a trade-off. On one hand the features should have the flexibility to describe the subject of caricaturization, on the other hand it should not be too complicated for the user to specify. To meet both constraints we propose to use automatic or semi-automatic approaches. In Section 6 we show an example of an automatic approach as well as examples of semi automatic approaches.

4 Caricature Space

Based on the above framework we illustrate the idea of caricaturistic visualization and show an example of the caricature space. For the purpose of demonstration we define a three dimensional superquadric which is given by the implicit function

$$f(x,y,z) = \left(\frac{x}{s_x}\right)^{\frac{2}{\gamma}} + y^{\frac{2}{\gamma}} + z^{\frac{2}{\gamma}} \tag{4}$$

We define $\gamma, s_x \in \Re^+$ to be the properties of the implicit function. The property vector space $P = P_1 \times P_2$ of the implicit function is therefore defined as $\Re^+ \times \Re^+$. As a reference model we choose the superquadric with the property vector (1,1) which is a sphere. We define eight deviating objects with all combinations of the properties $s_x = 0.8, 1.0, 1.2$ and $\gamma = 0.6, 1.0, 2.5$. As visual representation for the implicitly defined function $f(x,y,z)$ we choose the iso-surface of the function

$$g(x,y,z) = \frac{1}{f(x,y,z)^2} \tag{5}$$

at an iso-value of 0.5.

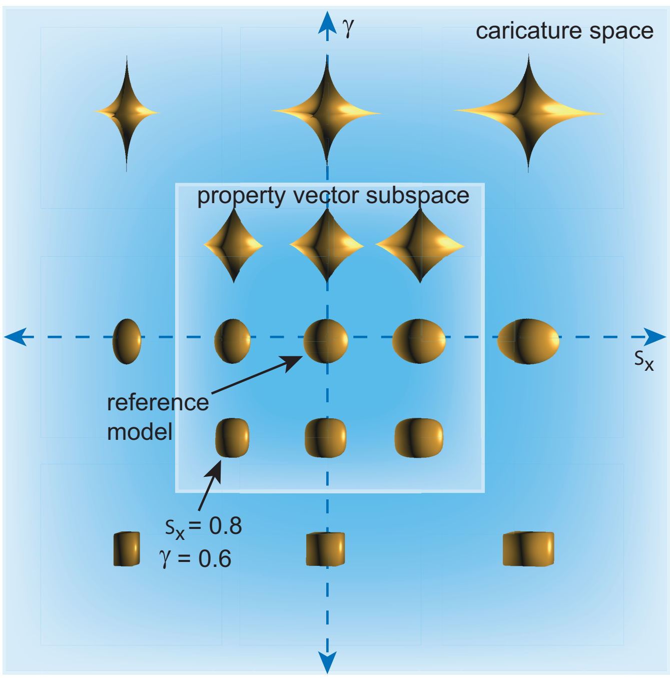

Fig. 2. Examples for caricaturistic operations. In the center of the inner square the reference model is depicted. The remaining eight objects in the inner square are examples of deviating specimen. The vertical axis corresponds to property γ which describes the actual shape of the iso-surface of the implicit function. The horizontal axis corresponds to the property s_x which describes the spatial extent of the iso-surface in x-direction. The outer square shows the caricatures of the corresponding inner square's objects.

In the inner square of Figure 2 eight deviating objects (i.e., the specimen) are shown. In the center of this square the reference model is shown. The vertical axis corresponds to the property γ which describes the actual shape of the iso-surface of the implicit function. The horizontal axis corresponds to the property s_x which describes the spatial extent of the iso-surface in x-direction. The object in the lower left corner of the inner square for example has the property values $s_x = 0.8$ and $\gamma = 0.6$. The properties s_x and γ form the property vector space. The inner square corresponds to a subspace of the property vector space which contains all occurring objects. The outer square in Figure 2 is the caricature space. The properties are exaggerated resulting in more distinctive visual representations of the objects. The object in the lower left corner of the inner square differs in both properties from the reference model. Its visual representation is still close to the visual representation of the reference model. The caricature of this object makes use of a larger property vector space (i.e., the caricature space) and therefore results in a more distinct visual representation.

The objects in the upper row of the inner square are visually similar. The corresponding caricatures of these objects are shown in the upper row of the outer square. Due to the exaggeration of their descriptive properties they are visually more distinctive. The exaggeration of properties to make datasets more distinctive from each other is described in more detail in Section 5.

5 The Caricature Matrix

While artists drawing caricatures do not explicitly make use of a reference model (as illustrated in Figure 1), for caricaturistic visualization an explicit reference model is necessary. The exaggeration function assumes the existence of a difference function, which by itself assumes the existence of a reference model. Therefore caricaturistic visualization fails without a reference model. Collections of datasets about a given subject often lack the explicit existence of a reference model. In some cases this might be compensated by calculating the average of the available datasets. The average can then be used as reference model.

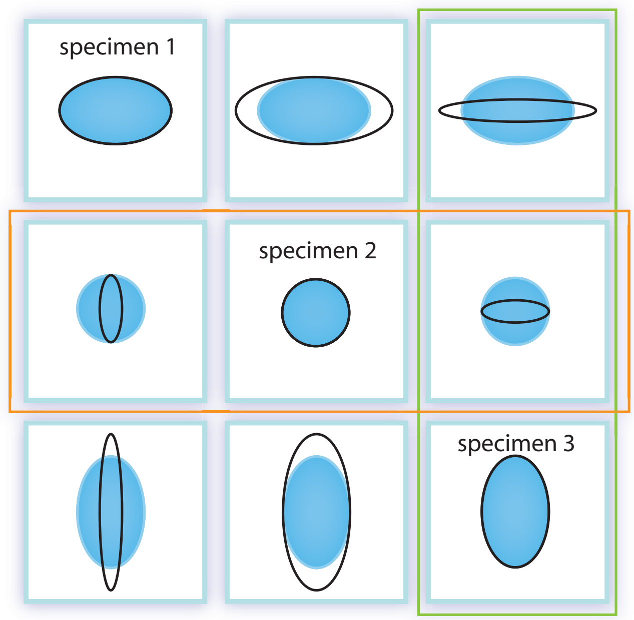

Fig. 3. Illustration of the caricature matrix. In the main diagonal the actual objects are shown in blue. Caricatures of the objects are drawn as black outlines. The rows of the matrix can be read as the caricatures of the object using the remaining objects as reference models.

The direct visualization of differences between the datasets is a more expressive option. Each dataset from a given collection can be used as the reference model for all remaining datasets. A collection of n datasets leads to n^2 caricaturistic visualizations. We call this set of images the *caricature matrix*. In Figure 3 we illustrate the structure of the caricature matrix. The main diagonal is depicting the specimen. Row i of the matrix shows all caricatures of the object i using the remaining objects as reference models. Column j of the matrix shows all caricatures using object j as the reference model. For example the second row in Figure 3 (outlined in orange) shows all caricatures of specimen two. The third column in Figure 3 (outlined in light green) shows all caricatures which use the third specimen as reference model. Therefore the element $(2,3)$ of the matrix shows the caricature of the specimen 2 using the specimen 3 as the reference model. The caricature matrix is not necessarily meant to be completely shown to the user at once. It is a concept requiring further visualization and exploration techniques. While the average of datasets is distorted by outliers the caricature matrix depicts the direct comparison of all datasets to each other. Therefore we expect the caricature matrix to be more robust.

6 Caricaturistic Visualization - Application Scenarios

For a proof of concept for caricaturistic visualization we implemented three different systems. The system described in Section 6.1 is an approach to visualize differences in images of deformed facades. It follows a fully automatic feature specification approach. In Section 6.2 a system for visualizing differences in volumetric datasets is described. The feature specification in this system follows a user driven approach. In Section 6.3 a system for the specific case of CT angiography data is described. For the specification of features a semi automatic approach was implemented. The aim of the implementation is to explore the abilities of caricaturistic visualization in different scientific areas and to demonstrate the applicability of the caricaturistic visualization concept on a variety of datasets. In Section 7 the results of the different systems are presented.

6.1 Caricaturistic Facade Deformation

The deformation of facades can be monitored by taking pictures at different points in time. These images are compared in order to find deformations that might require human intervention to guarantee the safety of the building. The subtle deformations are difficult to observe and therefore usually statistically evaluated. Caricaturistic visualization can enhance the subtle differences to make them clearly visible.

We tested our approach with simulated data from geodesists which they use to develop statistics for classifying facade deformations. In Figure 4 (left column) an image of the reference facade and of the deformed facade is shown. The feature specification is done fully automatically. The Harris [10] and the Förstner [7] interest operators are applied to find a set of relevant points in the reference image and in the deformed image (see Figure 4 middle column). A matching algorithm is applied to find corresponding pairs of points of interest in the two images. Each pair of corresponding points specifies a deformation vector. The result of this procedure is an unstructured vector field describing the deformation of the facade.

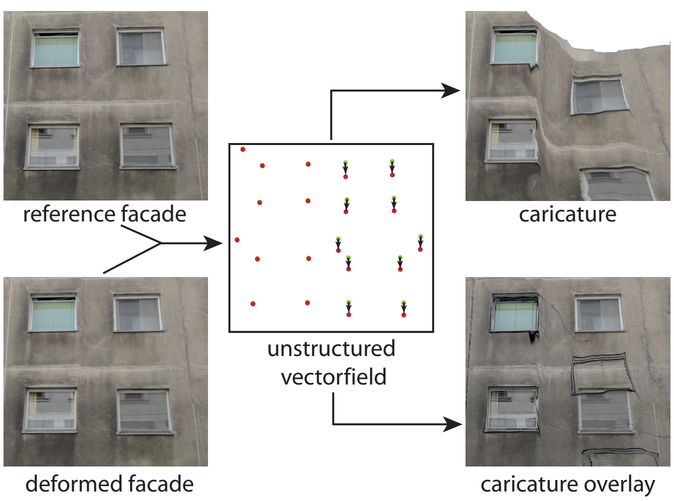

Fig. 4. Workflow for caricaturistic facade deformation. Left column: The reference model is shown on top and the deformed facade is shown below. Two irregular point sets are computed from the input images. Middle column: Illustration of two point sets and the corresponding unstructured vector field. Right column: Two visual representations of caricatures of the deformed facade. The upper caricature shows a deformed grid textured with the original image. The lower caricature shows the same deformed grid textured with an edge image.

We use this vector field to exaggerate the observed deformation. We first compute a Delaunay triangulation of the unstructured points of interest. This enables us to interpolate a vector for each position on the image plane. The user of the system controls only the exaggeration parameter which determines the interactive deformation of a textured grid. The deformed grid is textured either with the original picture of the deformed facade or with a more sparse representation of the image. For the sparser representation we chose an image showing only the edges of the deformed facade image. We automatically derive this image through an edge detector. The sparse edge image is overlaid onto the original image. Both examples are shown in the right column of Figure 4.

6.2 Caricaturistic Volume Visualization

We implemented a system for the generation of caricaturistic volume visualizations. To achieve a caricaturistic visualization the user has to specify a certain number of features in the reference model and corresponding features in the datasets of interest. Once the corresponding feature pairs are specified, the exaggeration function provides a feature vector for each value of the exaggeration parameter δ. This exaggerated feature vector is mapped to a visual representation. Caricaturistic visualization is not restricted to a specific visual representation. The exaggeration of features can be mapped to sparse representations such as contours, iso-lines, hatched surfaces, etc., or to dense representations such as polygonal surfaces or iso-surfaces. The possible visual representations also vary in the degree of abstraction and range from very tangible representations like iso-surfaces to high-level abstractions such as explanatory glyphs or automatically placed captions.

We implemented three different approaches for feature specification and investigated different visual representations which widely vary in the level of sparseness. For each approach we describe the feature design and the visual representation used to generate the result images. The first approach (Section 6.2.1) augments direct volume rendering with NURBS surfaces in order to depict an exaggerated shape of the underlying feature. The second approach (Section 6.2.2) takes the user specified features to deform the volume of the specimen. This results in a more distinct visualization of the specified features.

6.2.1 Caricature by Visual Augmentation

Our caricaturistic visualization system provides the user with an interface for feature specification. The user has to specify corresponding features in the reference model and in the specimen datasets respectively. The features used in our implementation consist of the following properties: the position, a major axis, and a minor axis. These properties implicitly define a local feature coordinate system. Further, the feature is defined by the spatial extent in the axis directions of the local coordinate system. These properties are specified and manipulated directly by the user. An additional property is derived automatically once the user has specified the other properties. This property describes the normal distance between the feature's major axis and a specific iso-surface in the volumetric object. In Figure 5 the local coordinate system of the feature is shown. On the left hand side the feature is shown in 3D. The blue circle in Figure 5 is the unit circle in a plane perpendicular to the major axis. x_f is a parameter varying along the major axis of the local coordinate system. In the example in Figure 5 x_f is set to x_0. $s(x_f, \theta)$ is the distance of point x_f on the major axis to the iso-surface in the direction θ. θ is the angular offset of the ray to the minor axis. $s(x_f, \theta)$ therefore corresponds to the normal distance of the iso-surface to the major axis. On the right hand side of Figure 5 the feature is shown in the volume (illustrated in 2D). The rays in general intersect many iso-surfaces. In our current prototype implementation the user can choose to either store the distance to the first or to store the distance to the last intersection point. We discretize the parameters x_f and θ in order to precompute the normal distance of the iso-surface to the major axis. The granularity of the discretization can be adjusted by the user.

For the specification of a feature in volumetric space the user has to specify values for properties like position and spatial extent of the

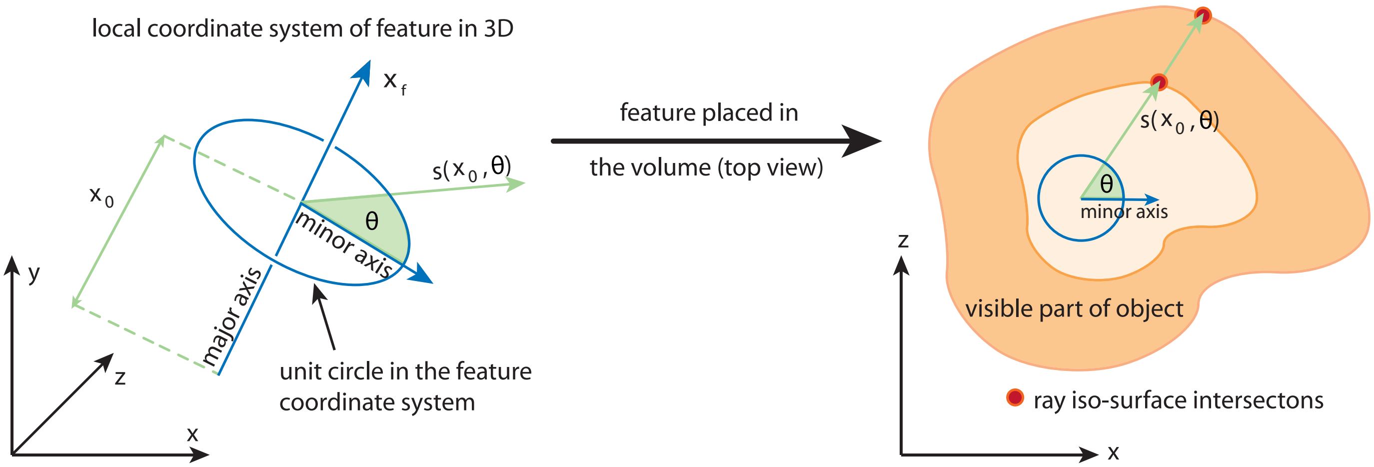

Fig. 5. Illustration of the feature local coordinate system. On the left hand side the feature is shown in 3D. The direction and extent of the major and minor axis is specified by the user. The blue circle depicts a unit circle in the plane perpendicular to the major axis. The parameter x_f determines the position of the plane along the major axis. In this example the parameter is set to x_0. $s(x_0,\theta)$ is the distance of x_0 to the iso-surface in the direction θ, where θ is the angular offset of the ray to the minor axis. $s(x_f,\theta)$ corresponds to the normal distance of the major axis to the iso-surface. On the right hand side the feature is placed in the volume. The ray given by $s(x_0,\theta)$ intersects the volumetric object at two positions.

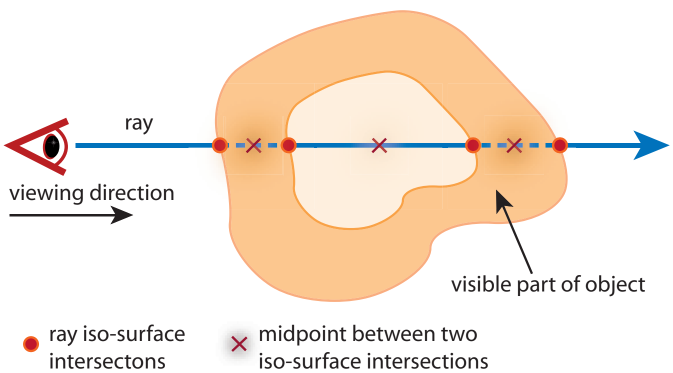

Fig. 6. Specification of a position in volumetric space. A ray is cast in the viewing direction intersecting the iso-surfaces of the volumetric object at several locations. Regions of homogeneous color in the figure correspond to regions of homogeneous visibility. The ray iso-surface intersections and the midpoints between two consecutive intersection points are candidates for the specified position.

major axis. Therefore it is necessary to provide a method for specifying a position in three dimensional space. By clicking on the image plane the user selects a ray in the viewing direction. The ray is intersected with the iso-surfaces of the volumetric object. In Figure 6 the ray intersects the iso-surfaces of the object at several positions. The user decides if the chosen ray specifies a point at the hit iso-surface, or a point in the middle between two consecutive iso-surface intersections. This approach allows the placement of a feature in the middle of a homogeneous region or directly on the iso-surface. This spacial positioning of a point enables a wide variety of feature specification methods. In our approach the user sets the position of the feature as well as the direction and the spatial extent of the major axis by two consecutive mouse-clicks. The first click specifies the position and the second click the remaining properties. The extent of the two remaining axes as well as their direction can be immediately manipulated by the user. When the local feature coordinate system is specified the normal distance to the major axis is derived automatically.

As visual representation for the caricature we chose NURBS curves and NURBS patches that are displaced from each other. We exaggerate the normal distance of the major axis to the iso-surface according to Equation 3. The exaggerated distances are taken to compute a set of control points. The control points define NURBS patches and NURBS curves. An example of *caricature by augmentation* can be seen in Figure 9.

6.2.2 Caricature by Volume Deformation

Caricature by volume deformation is an approach based on the deformation of the volume during ray casting. Our approach is similar to the approach of Lerios et al. [13] who describe a technique for interpolating two volumetric models. In our method we extrapolate from the volumetric model through exaggerations in the feature coordinate system. This results in a volume deformation driven by the characteristics of the volume dataset. We describe the approach first for one feature and later extend it to an arbitrary number of features.

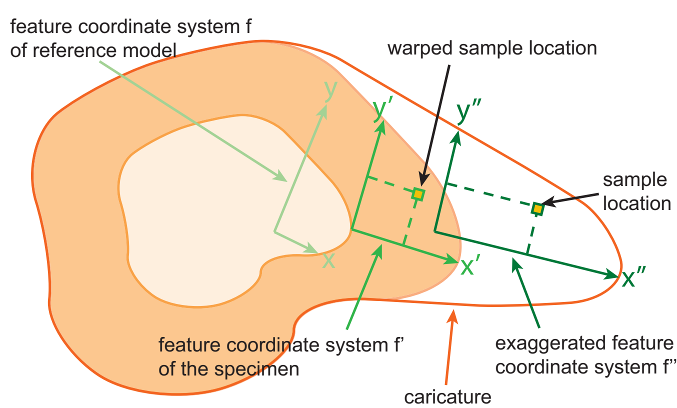

Fig. 7. Warping of a sample location. The feature coordinate system of the specimen dataset f' is exaggerated according to the feature coordinate system of the reference model f resulting in the exaggerated coordinate system f''. Each sample is warped from f'' to f'. The density value is derived by transforming the warped sample into volume space.

Features are specified as described in Section 6.2.1. Each corresponding pair of features is defined by their local coordinate systems. During ray casting we warp the exaggerated feature coordinate system

Fig. 8. Caricaturistic visualization of a facade deformation. The image of the deformed facade is overlaid by the caricatures. The exaggeration parameter is increased from left to right.

back to the original position of the feature's local coordinate system. The idea is sketched in Figure 7.

The volume deformation is determined by the feature coordinate system of the reference model f and by the feature coordinate system of the specimens dataset f'. First the exaggerated feature coordinate system f'' is computed according to Equation 3. In Figure 7 the three different feature coordinate systems are shown. We implemented a ray tracing approach where each sample position is transformed into the exaggerated feature coordinate system f''. The coordinates of the sample in the exaggerated feature coordinate system are then warped into f' the coordinate system of the specimen. The warped sample coordinates are finally transformed back into volume space to access the density value needed for ray-casting. The resulting caricature of the object is illustrated as an orange outline in Figure 7. Following the approach described by Lerios et al. [13], we extend our approach to more than one feature. We define a weighting function for each feature which is inversely proportional to the squared distance from the sample position to the position of the exaggerated feature. This allows a local control of the volume deformation specified by each feature. The above described warping calculation is done for each feature. The final density value for an arbitrary sample is computed as the weighted sum of all resulting density values. Examples of *caricature by volume deformation* can be seen in Figure 10.

6.3 Caricaturistic Angiography Visualization

For the specific case of angiography data we implemented an approach that caricaturizes the radius of blood vessels. Different vessel trees are compared to each other and subject to caricaturistic visualization. The hierarchical structure of a vessel tree is given as a tree of segments. Each segment except the first one has exactly one predecessor segment and can have several successor segments. In order to compare two different vessel trees the hierarchical structures of the trees must correspond. The radius and the direction of the centerline are given on discrete points along the centerline of the vessel. This information is derived in a semi-automatic process described in the work of Kanitsar et al. [12]. To compare the radii along two segments we normalize the length of the segments to obtain corresponding values. With these corresponding values we exaggerate the radius and map it to a visual representation for the caricature. As visual representation we use small strokes placed at the boundaries of the exaggerated vessels.

In order to control occlusions of the vessel tree from different viewpoints we use a ghosting technique. The opacity of the volume is reduced in front of the vessel tree to a user defined value between zero and one. Zero corresponds to full occlusion of the vessel tree while one results in a full cut-out view on the vessel. We achieve this ghosting by first rendering spheres along the vessels into a depth texture. This depth texture is used during volume rendering to determine the entry points of the rays.

Further, the user can control the sparseness of the placed strokes. Occluded regions are automatically drawn sparser as non occluded regions. This is achieved by first rendering the dense set of strokes into a color buffer and into a depth texture. This depth texture is used during volume rendering for the termination of the rays. All strokes behind opaque parts of the volume are occluded. As an overlay a sparse set of strokes is rendered sketching the shape of the caricature in occluded regions. Examples of *caricaturistic angiography visualizations* can be seen in Figure 11.

7 Results

All results were obtained in short interactive sessions. The feature specification and the visualization runs in real time on an AMD Athlon64 dual core 4400+ with a GeForce 7800 GTX with 256 MB memory. For the volume deformation approach we use a low quality mode for user interaction. The high quality image is rendered in about 1 second.

Figure 8 shows a caricaturistic facade deformation as described in Section 6.1. The deformation is exaggerated and overlaid over the original image of the deformed facade. The exaggeration parameter is increased from left to right.

Figure 9 shows a caricature by visual augmentation as described in Section 6.2.1. On the left of Figure 9 a fish of the species *Polypterus senegalus* is shown. It is used as reference model for the caricaturistic visualization of the carp dataset shown in the middle of Figure 9. The carp is augmented with NURBS surfaces which depict the exaggerated shape of the hollow space in the carp's interior. The right image in Figure 9 shows a caricature of the carp's shape. Both caricatures are derived using the feature specification approach described in Section 6.2.1. For each of the caricatures a feature is placed in the reference model as well as in the specimen. For the caricature in the middle of Figure 9 the feature is placed in the hollow space of the fishes. Rays are cast perpendicular to the major axis of the feature. The first ray iso-surface intersection is used for the estimation of the diameter. For the right image of Figure 9 the feature is placed inside the fishes from the head to the caudal fin. For the estimation of the shape rays are cast perpendicular to the major axis where the last iso-surface intersection is stored.

In Figure 10 an example of a caricaturistic volume deformation specified by two feature pairs is shown. The features are specified to describe the extent and rotation of the nose and the right ear. The two depicted datasets where used as reference models for each other.

In Figure 11 results of the caricaturistic angiography visualization are shown. On the left of Figure 11 a caricaturistic angiography visualization is depicted. The vessel tree in green is augmented with black strokes representing the caricature. A ghosting technique was used to show the vessel in regions where it is behind the opaque bone. The caricature is sketched more sparsely (as dashed line) where it is occluded resembling the style of occluded objects in illustrations.

On the right of Figure 11 a caricature matrix for three different blood vessel trees is shown. Each vessel tree is presented together with a close-up of the lower *arteria femoralis*. The images in the main

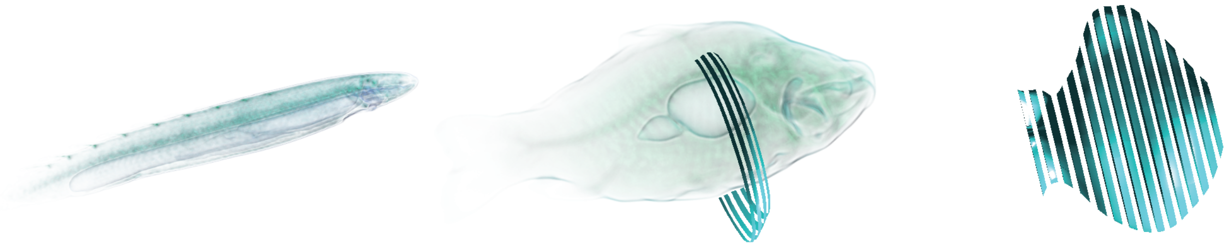

Fig. 9. Caricaturistic visualization of a carp. Left: reference model, Middle: direct volume rendering of a specimen augmented with a caricature of the diameter of its gas bladder. Right: caricature of the carp's shape.

diagonal show the three different vessel trees.

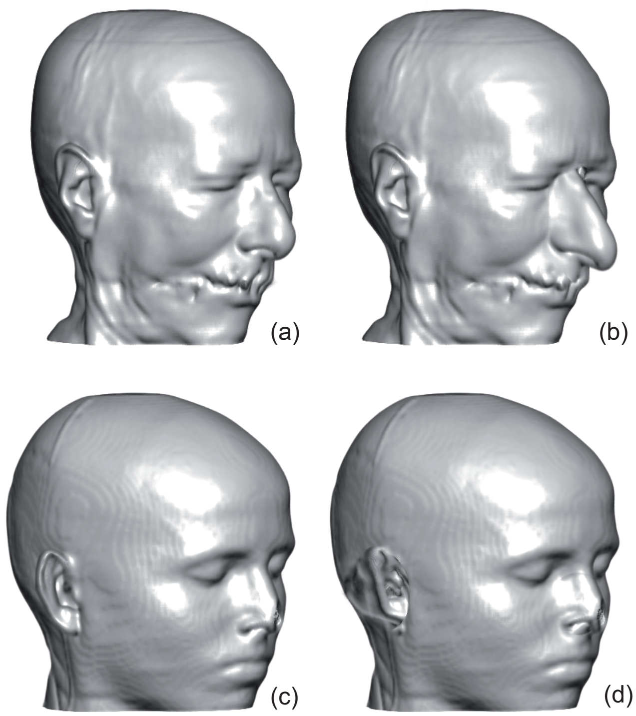

Fig. 10. A caricaturistic volume deformation. In (a) and (c) iso-surface renderings of the two datasets are shown. In (b) a caricature by volume deformation is shown using (c) as reference model. In (d) a caricature of (c) is shown using the features of (a) as reference model.

8 Conclusion and Future Work

Caricatures exaggerate feature deviations between a specimen and a reference model. These deviations are the characteristics of the specific specimen. Caricatures depict the essence of a subject of interest. The caricature metaphor seems well suitable for visualization since caricatures have many goals in common with visualization. We presented a mathematical framework for caricaturistic visualization adequate for a wide variety of applications. Further, we introduced the caricature matrix, a technique based on the caricature metaphor. It makes subtle differences between datasets visible without the need of an explicit reference model. The design of features that accurately describe the characteristics of objects with low user interaction during feature specification is subject to further research. Further, we will analyze the usefulness of inter property exaggerations for visualization. This paper proposes caricaturistic principles for usage in visualization. While we motivated the approach through several different applications, a more formal and quantitative evaluation still has to be done.

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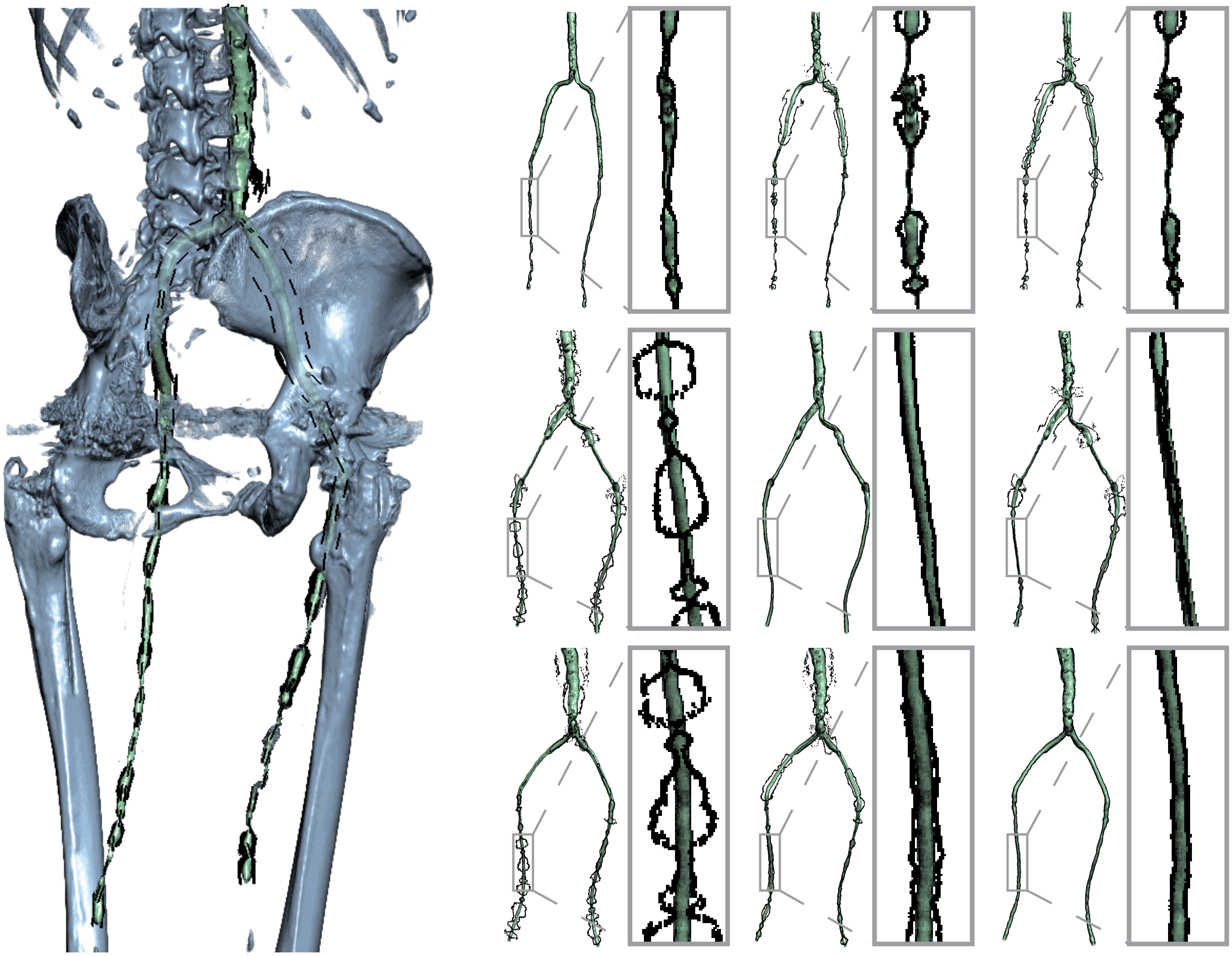

Fig. 11. Left: A caricaturistic angiography visualization. The occluded parts of the vessel tree shine through the opaque bones. The occluded strokes of the caricature are drawn more sparsely. Right: 3x3 Caricature matrix of three different vessel trees with a close-up of the caricatures.

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