Illustrative Shadows: Integrating 3D and 2D Information Displays

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ABSTRACT

Many exploration and manipulation tasks benefit from a coherent integration of multiple views onto complex information spaces. This paper proposes the concept of *Illustrative Shadows* for a tight integration of interactive 3D graphics and schematic depictions using the shadow metaphor. The shadow metaphor provides an intuitive visual link between 3D and 2D visualizations integrating the different displays into one combined information display. Users interactively explore spatial relations in realistic shaded virtual models while functional correlations and additional textual information are presented on additional projection layers using a semantic network approach. Manipulations of one visualization immediately influence the others, resulting in an informationally and perceptibly coherent presentation.

Categories & Subject Descriptors: H.5.2 [Information Interface and Presentation]: User Interfaces—*Screen design*; I.2.4 [Artificial Intelligence]: Knowledge Representation Formalisms and Methods—*Semantic networks*; I.3.6 [Computer Graphics]: Methodology and Techniques—*Interaction techniques*

General Terms: Design, Human Factors

Keywords: Information visualization, Spreading activation

INTRODUCTION

In many areas knowledge about structures and their meaning as well as their spatial and functional relations are required to comprehend possible effects of an intervention. For example, engineers must understand the construction of machines as a prerequisite for maintenance whereas the spatial composition of molecules and hence possible reactions are of importance for the discovering of new drugs in chemistry. Medical students need to imagine the wealth of spatial and functional correlations within the human body to master anatomy.

To date, novices as well as domain experts are required to consult several, often voluminous documents in parallel to extract information for a certain intervention. *Spatial relations*, characteristics of structures inherently three-dimensional, such as the shape and location of structures, however, are difficult to convey on paper. Besides requiring a significant amount of images to illustrate spatial relations between only a few structures, the mental integration of multiple views to form a three-dimensional picture in mind is demanding. Spatial relations can be conveyed more effectively by means of 3D models [18]. Using interactive 3D graphics, available to more and more people due to recent advances in consumer graphics hardware, the user may actively explore the spatial correlations of structures within a photorealistic virtual model (see upper left of Figure 1). Here, the visual realism of the model facilitates recognition on real encounters.

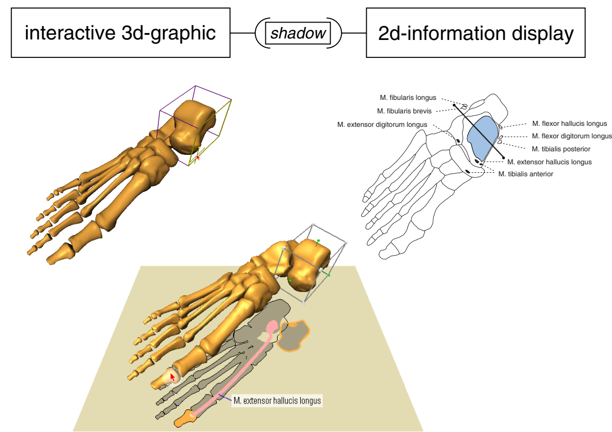

Figure 1: *Illustrative Shadows* provide an intuitive, visual link between spatial (3d) and non-spatial (2d) information displays integrating them into one combined information display.

Information about *functional correlations*, such as the interplay of muscles causing an upward motion of the human foot, has been traditionally provided by means of text and illustrations as found in textbooks. Simple, non-photorealistic drawings enriched with annotations and metagraphical symbols can be extremely powerful in conveying complex relationships and procedures (see upper right of Figure 1). Abstraction techniques reduce the complexity of the depicted structures to illustrate the important aspects thereby guiding the attention of the viewer to relevant details. In contrast to the visualization of spatial relations, 3D graphics add no significant value to the illustration of functional correlations.

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The integration of both aspects in one visualization is difficult since each serves to fulfill a different goal with, partly mutually exclusive, visualization techniques. It becomes even more complicated if the 3D model is frequently manipulated, such as in construction or recent interactive learning environments. Here, occludings by annotations and metagraphical symbols are annoying and may even interrupt the current manipulation for the user. Additional views, whether as insets [20], separate objects like mirrors [8], or in form of lenses and volumetric cursors changing the rendition of embedded structures [7, 21, 23], are either not close enough to the manipulated structures to be fully recognized without dividing the users attention between different views [13] or require sometimes tedious manipulations to be placed or moved within the scene. Nonetheless, additional information as to restrictions or functional correlations pertaining the current manipulated structures is highly desired, even necessary.

In this paper we present an approach called *Illustrative Shadows* that provides an intuitive, visual link between an actively manipulated 3D visualization and a supplemental 2D information display integrating them into one combined information display (see Figure 1). One of the main ideas behind Illustrative Shadows is the integration of secondary information, or in other words, background information, into an interactive 3D scene. By analyzing the users' manipulation of 3D structures and finding correlations, graphical and textual information about the current interaction context, such as graphical object-details and textual labels, are displayed in the "background"—the shadow—to give guidance as well as to further enhance the users' understanding of the context.

The paper is structured as follows: After reviewing related approaches to combine multiple visual and textual information displays, we present the design of Illustrative Shadows. Furthermore, an architecture realizing these concepts is discussed in this section. Thereafter, the major components of this architecture are described. Realization issues are subject of the subsequent section, whereas application examples and the summary conclude the paper.

RELATED WORK

Recently proposed tools for the exploration of virtual scenes extend possibilities to display covered structures or hidden details. A complementary view called Magic Mirror that mimics a hand mirror has been introduced in [8]. In addition to providing the optical effects of a real mirror, it also allows to explore the insight of objects by clipping against the mirror front-frustum. Magic lens filters as presented in [7, 21] go further by combining an arbitrarily-shaped region with an operator that changes the view of objects viewed through that region thereby displaying different aspects of the visualized information space. In [5, 23] the 2D lens approach is extended to 3D using volumetric lenses. All aforementioned techniques require the user to actively manipulate a tool within the scene. These techniques assume the user already knows which parts of the presented visualization offer additional information or is willing to explore the model. While this might be feasible in explorative environments where navigation is the main interaction task, it certainly hinders manipulation.

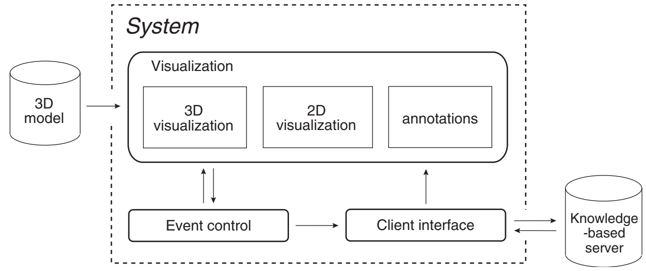

Figure 2: Architecture of a system incorporating the Illustrative Shadows approach.

Several approaches to combine 3D and 2D visualizations have been made using a corner cube environment (). The three orthogonal sides show image slices that provide a visual context for a 3D model or structures displayed in the center. In [11] the images have been integrated as backplanes to ground the 3D representation of anatomic structures visually. By outlining the 3D structures in the images, the spatial correspondence between the 3D renditions of activated foci in the context of human brain slices is emphasized in [16]. The images, however are precomputed and do not change according to the users' interaction nor is there any visualization of functional correlations. An interesting interactive approach has been proposed by [10]. The projection of the 3D model onto the sides of the corner cube can be manipulated by the user in order to change the position and orientation of the model. Fully rendered shadows of certain objects resemble real-world mirrors and may be used to stress importance. There is, however, no discussion on how to use this feature to provide, for instance, additional context information for the user.

To establish hypotheses on the interaction context in order to be able to display additional context information and to provide meaningful descriptions of relationships knowledge modeling is required. Promising approaches to connect those knowledge with 3D graphics have been developed in the area of medical applications. The DIGITAL ANATOMIST [4] incorporates a logic-based description comprising class and subclass relationships (is-a) as well as partitive and qualitative spatial relationships (has-parts, is-superior-to). The information is presented in tree-like textual form that can be explored by folding and unfolding. Corresponding structures are displayed in a 3D visualization aside. There is no visual integration of both information displays. The semantic network described in [14] is used to create various 'views' in which correlating structures are displayed to communicate specific aspects with a voxel model of the human anatomy. The highly detailed visualization, however, cannot be interactively explored, nor is there any kind of abstraction to focus the users' attention. Interaction is only possible by tree-like menus.

A SYSTEM DESIGN USING ILLUSTRATIVE SHADOWS

With the term Illustrative Shadows we refer to a coherent integration of photorealistic depictions of a virtual model with abstract illustrations and textual explanations. Both kinds of depictions serve to fulfill different and somehow contradicting goals: on the one hand to enable navigation and manipulation of complex spatial models and on the other hand to provide adjusted visualizations that guide the user's attention to additional information about the most relevant objects in the current interaction context. Both visualizations are achieved by applying photorealistic *and* specific non-photorealistic rendering techniques [22] to geometric models.

Furthermore, textual information describing the most relevant structures and functional correlations between them must be integrated. The estimation of the relevance with respect to the current interaction context as well as the selection or generation of textual explanations heavily rely on non-geometric formal and informal representations and are therefore determined by external inference mechanisms. Moreover, co-referential relations between the entities within the geometric model and the formal and informal representations have to be established in order to link the different representations.

Based on these requirements we designed a system architecture which comprises three basic components (see Figure 2):

- The *visual component* renders a photorealistic 3D model with a standard camera model as well as a non-photorealistic illustration that is projected onto a ground plane. A *client interface* enables external control of the non-photorealistic rendering techniques. Finally, the visual component also renders text and metagraphical annotations, such as labels, hypertext and arrows.
- The *event control* allows the user to modify the parameters of a virtual camera and to select and manipulate geometric objects within the scene. Interactions are tracked and ranked within an interaction history to communicate the current interaction context via a client interface to an external knowledge-based component.
- The *knowledge-based server* receives notification of user manipulations and establishes hypotheses on the degree of interest values (DOI) for geometric objects. These DOI values guide the selection of appropriate text fragments presented in text annotations as well as the modification of parameters of the non-photorealistic rendering techniques for emphasizing in the illustration.

The following sections discuss important aspects of these system components.

VISUALIZATION

Besides displaying a photorealistic rendition of a 3D model that the user can manipulate, the illustration of functional correlations between structures of the model in the "background" has to be accomplished. To focus the user's attention on relevant structures and to facilitate perception, important objects must be emphasized and surroundings abstracted. Furthermore, both visualizations must be integrated in a coherent manner, so that a visual connection between the 3D and 2D renditions of the relevant objects is established by the user. Several crucial aspects have to be considered:

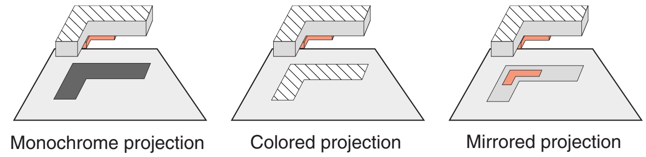

Figure 3: Different types of model projections onto the illustration plane. Beside simple, monochrome projections (shadows), the color of individual structures can be preserved. The mirrored projection shows details otherwise hidden in the current view.

- How can objects be emphasized such that they attract the user's attention while still being in the background?
- Are additional graphical elements required to establish a visual correlation between the two model representations?
- What illustration techniques can be applied to differentiate between important and less important objects?
- Is a continuous synchronization between the photorealistic and the schematic representation of the model necessary during user interactions?

Integrating Different Model Representations

The question coming up at this point is how a secondary, schematic model representation can be integrated such that the following requirements are fulfilled:

- The second representation must be placed near the original 3D representation in order to perceive structures in both representations [13].
- The secondary representation may never occlude the central, realistic 3D visualization, which a user manipulates directly. The relevant information, however, must be visible in order to be recognized but should not distract from the interaction with the 3D model.

An exact copy of the 3D model representation is not appropriate for the task of depicting functional correlations, because their illustration in the "background" requires abstraction. Without abstraction, a lot of the users' attention would be required to extract the relevant information. An exact copy, however, can be used to provide a mirrored view below the 3D model to visualize structures otherwise not visible for the user (see Figure 9 at the end). The integration of a secondary view as inset [20] has some disadvantages too. Firstly, the inset must not occlude the 3D model, thus it must be placed in distance which in turn means visual separation. Secondly, the inset framing complicates the visualization of object correlations, e.g. by lines.

An ideal solution in many respects is to project the 3D model onto a plane below the model, just like casting a shadow. This 2D representation may then be modified in various ways to illustrate associated concepts and relations and therefore is called Illustrative Shadows. Besides, this approach satisfies the requirements specified above.

Illustrative Shadows

Cast shadows [3] have proven to be beneficial for perceiving spatial relationships and to facilitate object positioning

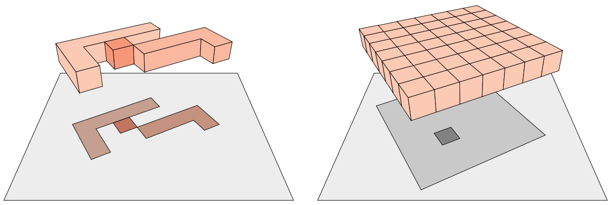

Figure 4: Recognition of individual objects in different scenes. To the left, unequivocal correspondence of shape and color facilitates identification. To the right, no clear correspondence.

[24]. Thus, their use, if already present, occupies no additional space for the display of additional information, or in the case of prior absence, also add valuable depth cues to the 3D visualization. Furthermore, the shadows can be used to interact with the underlying information context or, as proposed in [10], with the shadowing 3D objects. To sum up:

- The shadow projection results in an abstraction which is very important for illustrations.
- Additional depth cues facilitate the perception of spatial relations and accelerate the relative positioning of objects while manipulating the 3D model.
- The projection establishes a link between a 3D object and its 2D shadow providing additional information.

Displaying and Focusing in the Illustration Plane

Besides simple, monochrome shadow projection further possibilities to project the 3D model representation onto the illustration plane come to mind (see Figure 3). Preserving the colors of the different structures of the model, for instance, enables distinct renditions and perception of the objects in the shadow. As an extension, the objects can be mirrored before projecting them. Hence, objects or hidden details of objects otherwise not visible become visible in the illustration plane.

To illustrate correlations or to annotate structures, the relevant objects must be emphasized to be easily distinguished from the remaining 2D visualization. Also, the viewer must be able to differentiate between relevant and less relevant objects. For monochrome shadow projections, the object color must contrast with the shadow color. The selection of emphasizing colors should be based on a perception oriented color model, such as the HSV. Moreover, an outline can be used to attract the viewer's interest. A colored projection makes it somewhat more difficult since the variation of the color won't always result in a noticeable distinct representation. By using a conspicuous texture or shaded representations of the relevant object whereas the remaining objects are flat-shaded, the viewer's attention can be directed to those relevant objects.

Significance of Accentuations

In addition to objects being significant to the current interaction context supplementary objects have to be included in the illustration. These objects are not of primary importance within the concepts to be illustrated but guide the viewer and maintain context. It is important that such objects are recognized by the viewer as objects of minor significance. The relevance of objects that have been emphasized by outlining, for instance, can be judged by line width or line style (e.g. contrast, waviness). Also preserving the objects color as well as the use of texture indicates a higher importance than an interpolation of the object's color and the background color.

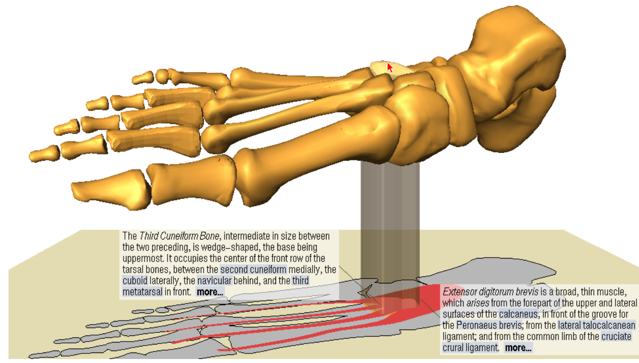

Figure 5: A direct connection to an object's shadow is established by displaying its semi-transparent shadow volume. The integration of annotations gives meaning to unknown objects and relationships.

Recognition of Correlations between both Representations

An important aspect in using two different but coherent representations of the same model is the identification of correlations between those visualizations by the viewer. If an object is being emphasized in the illustration plane, it must be possible for the viewer to find its counterpart in the detailed photorealistic representation too. Often shape and color give enough hints. However, if the projection of the relevant objects results in uniform shapes, the viewer may have difficulties to recognize individual objects in the 3D visualization (see Figure 4). Besides accentuating those objects in the 3D representation, the integration of additional elements can be beneficial. Semi-transparent shadow volumes originally developed to facilitate object positioning in 3D [19] indicate direct correspondence (see Figure 5).

Integration of Annotations

The conveyance of important related facts by means of graphical abstraction, accentuation, or modification of relevant structures alone is difficult. Therefore conventional book illustrations often contain annotations with short descriptions. Those annotations must be placed close to the described objects and should not occlude relevant parts of the presentation. The latter, however, cannot always be guaranteed. A simple but effective solution places the annotation on a semi-transparent background face that increases the contrast between text annotation and illustration and still does not block vision (see Figure 5). To further facilitate absorption of shown concepts, single words or groups of words can be emphasized and graphically linked to relating structures in the illustration. Hypertext functionality reduces the amount to which textual annotations must be displayed at once. The user can request more detailed information by activating links.

INTERACTION

A human illustrator is required to identify important aspects and characteristic features of the subject or concept that is to be conveyed in order to draw a focussed visualization. One way to identify those features for the computer is to watch the user interacting with the information space. Since our goal has been to enhance the users' understanding by providing background information in the current interaction context, an Illustrative Shadow depicting correlations in that context must be generated.

By navigating within the 3D model on the one hand, the user is free to explore spatial relations by changing the view. Here, single structures may be tracked by the computer regarding their visibility hence obtaining information about the users' current focus. On the other hand, the user may interact with the structures, thus expressing specific interest. As a result of the integrated 3D/2D visualization, interaction is possible within the 3D visualization as well as in the projection layers, a technique inspired by [10]. Using the shadow for interaction facilitates certain tasks, such as selection, since structures hidden in the 3D visualization may be visible in the projection. Furthermore, 2D input device coordinates can be mapped directly onto the plane thereby enabling the use of 2D interaction techniques.

The provided manipulation tasks highly depend on the application that employs the concept of Illustrative Shadows. In our application, the user is able to compose and to decompose a given 3D model like a 3D jigsaw. Thus, translation and rotation of individual structures are main interaction tasks.

action	*parameter*	*value*	*relevance*
mouseOver	time	short	1
		long	2
mouseButtonPressed	location	3D object	4
		2D object	4
		annotation	6

Table 1. Relevance of certain user interactions

User-interactions are tracked within an interaction history. By assigning relevance values to each interaction task, accumulations of these values show a distribution of interest within the model over time. Thus each single structure's degree of interest (DOI, a normalized value) is a measure for its importance to the user at a certain time. As shown in Table 1, touching a structure with the mouse pointer has a much lower relevance than actually selecting it. The degree of interest is communicated to the knowledge server which in turn may modify the 2D visualization of the shadow. To give an example, the user is interested in a certain structure of an anatomic 3D visualization, such as a ligament, that is part of a functional relation between a bone and a muscle. Only one of those objects, that is the bone or the muscle, should be highlighted and annotated, because of space restrictions in the shadow layer. At this point, the DOI is used to decide. If the interaction history shows more user-interest for muscles, information about the functional relation between the ligament and the muscle is displayed.

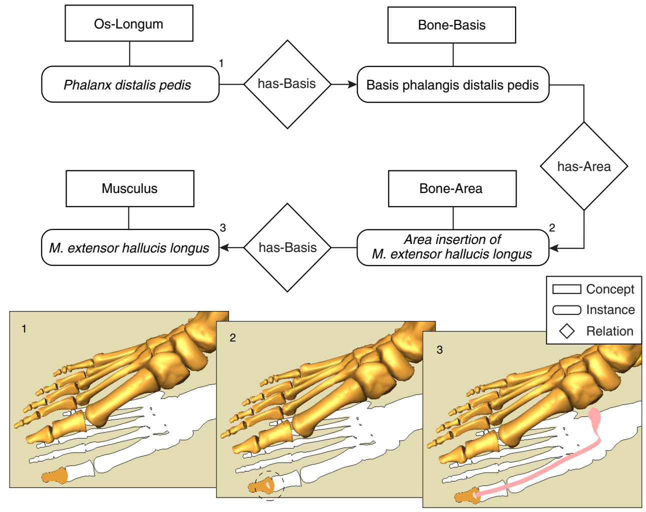

Figure 6: Visualization of intermediate steps within a retrieval which discovers the association between the distal phalanx of the big toe and the extensor hallucis longus.

KNOWLEDGE MODELING

While segmentation of the 3D model into individual structures (objects) provides a spatial description, the presentation of correlations also requires a linked symbolic, textual description. Moreover, in order to establish hypotheses on the current interaction context, formal knowledge is required. Thus, the system presented in this paper comprises a knowledge base, i.e. a media-independent formal representation, media-specific realization statements of entities within the formal representation as well as a large multi-lingual text corpus. Realization statements establish co-reference relations between independent formal representations describing different aspects of the underlying information space. They also guide the generation or selection of texts used to annotate structures in the 2D visualization.

The medical education application presented later in this paper is based on a knowledge base describing the objects and functional correlations of the musculo-skeletal system. It covers the area of the lower limb and the pelvic girdle. The knowledge base was created by manually analyzing several anatomy textbooks, anatomy atlases, medical dictionaries, and lexica. This analysis reveals important concepts, their hierarchical classification, and the instance attribute values forming a complex *semantic network*. Our system contains a hierarchical representation of basic anatomic concepts such as bones, muscles, articulations, tendons, as well as their parts and regions. The corpus contains fragments of several anatomic textbooks describing global concepts of the osteology, syndesmology, and myology as well as descriptions of all the entities of these anatomic systems within the lower leg and the pelvic girdle.

In order to present appropriate system reactions the event control informs the knowledge server of user interactions. First, exploiting the visual annotations, the knowledge

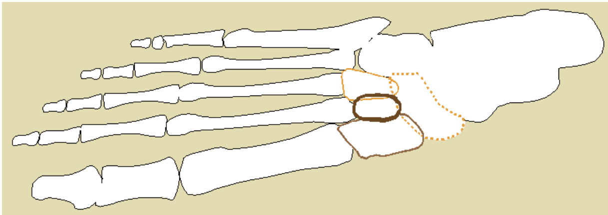

Figure 7: Application of different emphasize techniques to the 2D information representation according to decreasing dominance values.

server extracts co-referring formal entities and assigns relevance values according to Table 1. Subsequently, the knowledge server searches for associations between the most relevant entities. Our system pursues two alternative strategies: retrievals and suggestions.

Retrievals discover relations between entities by tracking predefined paths within the knowledge base. Figure 6 illustrates the intermediate steps in order to extract relations between bones and muscles. From a functional point of view (i.e. the muscle mechanics), bones are insertions or origins of muscles. Its contraction produces force, which in turn changes the orientation of these bones. These retrievals also need to consider substructures (e.g. bone-volumes and bone-area). The following retrieval extracts those muscles, which originate in a given bone (first logic order):

$$\{\, muscle \mid \exists bone\text{: } \mathit{Bone}(bone) \wedge \mathit{Musculus}(muscle) \wedge (\mathit{is\text{-}Origin\text{-}of}(bone, muscle) \vee \exists part\text{: } \mathit{has\text{-}Part^*}(bone, part) \wedge \mathit{is\text{-}Origin\text{-}of}(part, muscle)) \,\}$$

The *has-Part** relation represents the transitive hull over several spatial part-of-relations [1] (e.g. the *has-Basis* relation between *Bone*s and *Bone-Volume*s and the *has-Area* relation between *Area*s or *Volume*s and *Area*s).

These retrievals rely on knowledge about the structure of the knowledge base. Moreover, they refer to a small number of relevant objects. In many situations, however, the event control comes up with a huge number of potential relevant objects, which cannot easily be mapped to a predefined query. Hence, we adopt a bottom-up search approach within a complex semantic network developed within cognitive psychology.

In his model of human comprehension [15] Quillian assumed that spatially and temporally independent aspects of human long-term memory are organized in a semantic network. Furthermore, he assumed that cognitive processes that access a node of the semantic network activate all connected nodes in parallel. The term *spreading activation* refers to a recursive propagation of initial stimuli. Nowadays, this term subsumes breadth-first search algorithms for paths connecting the nodes of a start and a destination set in directed graphs satisfying an evaluation criterion. Collins and Loftus [6] modify the propagation algorithm to consider activation strength.

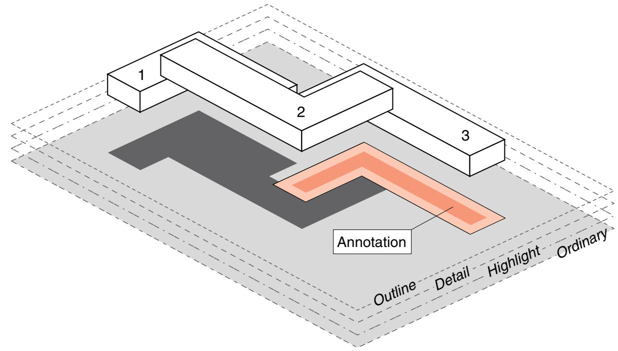

Figure 8: Multiple layers are used to place the different visual information in order. Thereby, occluded details may be visible in the shadow (3).

In our system, the knowledge server uses the objects' DOI from the event control as an initial activation, which spreads through the semantic network. These initial activations also take the content presented on textual labels and inspected by the user into account. The spreading activation approach generates a *focus structure* which contains information how dominant graphical objects must be presented in the schematic illustration [9]. Figure 7 illustrates how visual dominance values control the render parameters.

REALIZATION DETAILS

The visual component of the prototypical implementation extends the OPEN INVENTOR graphical library with powerful scenegraph nodes to display hypertext on overlay regions and to render semi-transparent shadow volumes. Other nodes encapsulate the mirror and shading projection onto the ground plane as well as the user interaction, and emphasize techniques (e.g. computation of silhouette lines). The layer management (see Figure 8) employs the OPENGL polygon offset feature to allow graphics to overlap specifically whereas visibility-tests of individual structures are accomplished by offscreen rendering and analyzing OPENGL p-buffers. Additional OSF MOTIF widgets enable the user to add personalized annotations, which are inserted into the knowledge base.

The knowledge base encodes both the media-independent formal knowledge representation as well as media specific realization statements using XML topic maps [2]. To process this information, XML statements are transformed into LISP-code. The authoring system contains export filters for the NEOCLASSIC and the LOOM [12] description logic inference machine. In the current version it covers about 50 basic anatomic concepts, 70 relations, and over 1500 instances, with linguistic realization statements in Latin, German and English. Furthermore, visual annotations refer to a small number of geometric models and 2D illustrations.

The interface between the knowledge server and the visual component is described using CORBA's interface definition language (IDL). The CORBA-based interface implementation enables us to experiment with several knowledge serv-

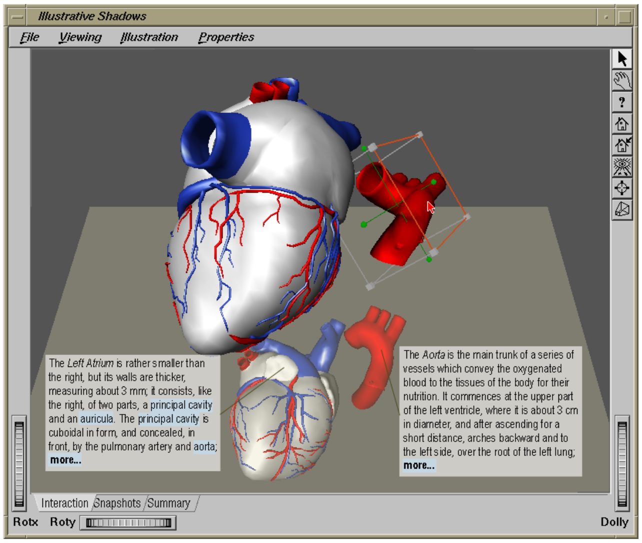

Figure 9: Alternative visualization. The Mirror facilitates manipulation in 3D, by providing a better view of the structures. The central representation is never occluded by annotations.

ers implemented in Common-LISP (LOOM) and C++ (NeoClassic).

APPLICATIONS

We applied the concept of Illustrative Shadows to an application of medical education. This system had been previously designed to foster the understanding of spatial relationships by means of 3D models based on a virtual 3D jigsaw approach [19]. While composing anatomical structures has proven to help medical students to build an understanding of the spatial composition [17], most of the users expressed their desire for detailed information about functional relations between structures. Consequently, students would be able to playfully study human organs including their spatial and functional correlations. Figures 9 and 10 depict the screen of the prototype in typical learning sessions. Individual objects can be detached and moved within the scene to expose occluded structures. In Figure 9, one of the alternative visualization, the mirror, is shown to demonstrate the various employments of the plane. It enables the user to simultaneously look at two different views of the 3D model. Graphical accentuations are used to attract the viewer's attention (left atrium). Additional textual annotations are assigned to correlating structures in a hypertext representation which can be explored by following separately marked links.

Another application that has not yet been realized is to support users of CAD systems by Illustrative Shadows. CAD systems are not only used to design individual components in 3D but also to assemble complex systems. Information about parameters of single components and relationships are of major importance. Being able to retrieve this information directly from the scene while interacting with the components is of great benefit for the design engineer.

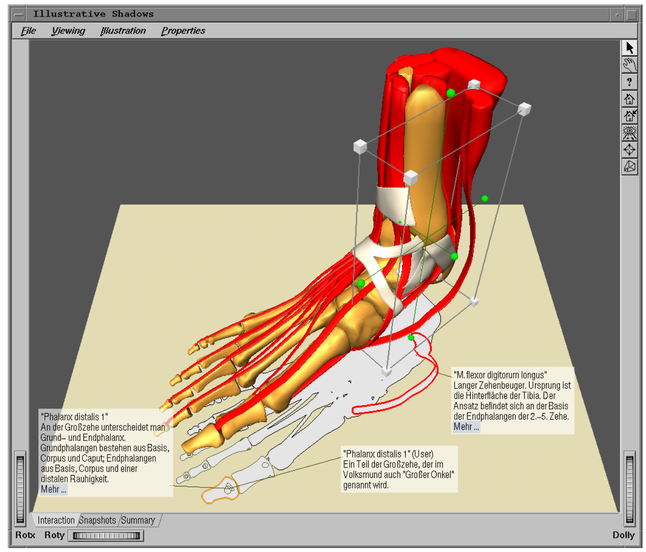

Figure 10: German annotation of objects previously selected. Realization statements of the semantic network provide alternative German, English, and Latin phrases referring to formal entities.

CONCLUSIONS

For educational, engineering, or maintenance purposes a wealth of information about spatial and functional correlation as well as textual information is required. In this paper we developed a new metaphor-based approach to coherently integrate different views onto such a complex information space within an interactive system. Illustrative Shadows provide an intuitive visual link and a level of integration between interactive 3D graphics and supplemental 2D information displays that is hard to achieve with other concepts.

Shadow projections have proven to be beneficial for perceiving spatial relationships and to facilitate object positioning. Thus, their use, if already present, occupies no additional space for the display of additional information, or in the case of prior absence, also add valuable depth cues to the 3D visualization. The shadow projection onto a flat plane enables schematic illustrations which are focused on specific information extraction tasks and facilitates the integration of generated textual information that leads to further meaning. Thus, Illustrative Shadows promote the comprehension of complex spatial relations *and* functional correlations. Furthermore, the secondary information display does not hinder manipulations of the 3D model. Our approach is well suited for compact 3D models, and has been successfully applied to an application of medical education.

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