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A 3D Shape Benchmark for Retrieval and Automatic Classification of Architectural Data

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Abstract

When drafting new buildings, architects make intensive use of existing 3D models including building elements, furnishing, and environment elements. These models are either directly included into the draft or serve as a source for inspiration. To allow efficient reuse of existing 3D models, shape retrieval methods considering the specific requirements of architects must be developed. Unfortunately, common 3D shape benchmarks which are used to evaluate the performance of retrieval algorithms are not well suited for architectural data. First, they incorporate models which are not related to this domain, and second and even more important, the provided classification schemes usually do not match an architect's intuition regarding their notion of design and function. To overcome these drawbacks, we present a freely downloadable shape benchmark especially designed for architectural 3D models. It currently contains 2257 objects from various content providers, including companies specialized on 3D CAD applications. All models are classified according to a scheme developed in close cooperation with architects taking into account their specific requirements regarding design and function. Additionally, we show retrieval results for this benchmark using unsupervised and supervised shape retrieval methods and discuss the specific problems regarding retrieval of architectural 3D models.

Categories and Subject Descriptors (according to ACM CCS): H.3.1 [Information storage and retrieval]: Content Analysis and Indexing, I.3.m [Computer graphics]: Miscellaneous

1. Introduction

3D content has become a major ingredient in architects' daily work. Various 3D modeling tools specialized on architecture are available to support architects as they draft new buildings. Apart from creating new 3D content, architects intensively use existing models: In a survey of 48 architects including questions concerning their use of 3D content we found that 77% of the respondents use existing models like building elements or furniture. These models are either integrated into new drafts or they serve as source of inspiration.

To efficiently reuse existing models, there is a strong need for retrieval engines tailored to the specific requirements of architects. In our survey we found that 77% of the respondents would like to search for 3D models by text, either using a Google™-like interface or according to a hierarchic classification scheme taking into account an architect's intution of object function and design. Another 33% would like to search according to query-by-example. These results show that there exists a large necessity for shape retrieval and automatic classification methods tailored to architectural data.

The most crucial prerequisite for developing shape retrieval algorithms are benchmarks providing 3D objects and classification schemes, as only they allow to evaluate the retrieval preformance of developed algorithms. Unfortunately, existing benchmarks are not well suited for architectural data. First, they either include only some models which are relevant for architecture (e.g [SMKF04]) or they are tailored to a completely different data domain (e.g. [JKIR06]). Second, the classification schemes of common benchmarks usually do not match an architect's requirements regarding model function and form.

To overcome these drawbacks, we introduce a new 3D shape benchmark that focuses on architectural data. It currently contains 2257 models consisting of building elements (i.e. doors, pillars), furnishing (i.e. chairs, shelves), and environment elements (i.e. plants, trees). The mod-

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els are either part of different libraries of architectural CAD-applications or they belong to public services for architects of furniture manufacturers. Along with the shape database we provide classification schemes that were developed in close cooperation with architects to match their specific requirements. The benchmark will be extended by further models in the future. It can be downloaded at ftp://ftp.cg.cs.uni-bonn.de/pub/outgoing/ArchitectureBenchmark. In our experiments we will show how unsupervised and supervised 3D shape retrieval methods perform on our new benchmark and compare the results to those achieved on the Princeton Shape Benchmark (PSB) [SMKF04].

Summarizing the key contributions of our work, they are:

- We present a classification scheme for 3D models that is tailored to the specific requirements of architects.
- We provide a benchmark dataset including 2257 models collected from various 3D content providers. All models are manually classified by experts according to our newly introduced scheme. The benchmark and the classification scheme are both freely downloadable and can be used for evaluation of 3D shape retrieval methods.
- We provide an evaluation of existing shape retrieval methods on our benchmark dataset including unsupervised as well as supervised methods. We finally compare the results to those achieved on the PSB.

2. Related Work

Along with the increasing importance of 3D shape retrieval methods, a number of benchmarks differing in the field of interest the models belong to, in the object representation and in the type of classification scheme has been developed. The well-known Princeton Shape Benchmark [SMKF04] contains objects from various fields (e.g. planes, animals, plants, buildings). The models are represented as triangle meshes without consistent normal orientation and connectivity. Its hierarchic classification schemes include coarse levels which rather include functional aspects and fine-grained levels corresponding to rather form-based classifications. In [JKIR06], the PRECISE Engineering Shape Benchmark is presented, focusing on 3D objects related to engineering. The models are represented as triangle meshes. The classification scheme includes semantic- as well as shape-related categories. The McGill 3D Shape Benchmark [ZSMS05] was especially designed for retrieval of articulated objects, and consequently contains mostly animals and humans. Objects are represented by voxel grids as well as by triangle meshes. The classification scheme is non-hierarchic and rather related to semantics than to form. Several other benchmarks have been developed for different tracks of the SHREC Shape Retrieval Contest including datasets focusing on watertight models, faces or partial models [VtH07, VtH08]. The models of these benchmarks were collected from publicly available 3D repositories, from other benchmarks, or were generated for this event.

3. Classification schemes and benchmark objects

One of the eminent interests of architects is the concept of form. Regarding a statement of the functionalism age, there is a particular relation between form and function in the design process of buildings and objects: *"form ever follows function"* [Sul96]. The architectural drafting process is both, form- and function-oriented. Architects are *"working from abstract problem formulations to concrete solutions and splitting problems into subproblems iterative and recursive processes that rely upon anticipations of possible solutions"* [CR92]. While drafting buildings, architects first concentrate on the function of rooms and components. Consequently, they mainly think of an object according to its function during this phase. After defining the functions, more and more details are added to the draft. During this phase, architects rather think according to form, provided that this form is suitable for the intended function. Figure 1 shows an example for the two different ways of classification.

Taking this into consideration, a component-classification has to be both form- and function-oriented to allow intuitive searching within any stage of drafting. Nevertheless, it does not make sense for all components to be classified regarding both their form and function. For instance, the function/ context of beds is always sleeping/ bedroom. Beside classifications for building construction and technology (ISO 12006/2+3 [01-01] [07-07], CI/SfB [Roy68]) there exists a comprehensive, scientifically compiled vocabulary for the whole domain of art and architecture, the Getty Art & Architecture Thesaurus (AAT) [Pet94]. We used AAT as a starting point for developing our classification scheme because it (A) contains form-based and function-based classifications of components, (B) is hierachical analogous to the needs of architects within the design process (from abstract problem formulations to concrete solutions), (C) is currently consisting of around $34,000$ concepts, widely used by libraries and archives and in compliance with ISO-Standards. Architects were involved in the scheme development particularly by cooperation with the EU-project MACE.

Taking into account the two ways in which architects define 3D object similarity, we developed two hierarchic classification schemes, the first focusing on form and the second focusing on function. Regarding both schemes, the shape of an object serves as a starting point for retrieval and classification. Human beings are able to conclude about an object's function by its form only. Consider e.g. a rectangular plate. By its form, it could be considered a table board, or a part of a wall, or a door. But as soon as a handle is attached at a specific position, it can be immediately recognized as a door, i.e. one can conclude about an object's function by inspecting its form. On its finest level, the function-based scheme contains 183 classes, while the form-based scheme contains 180 classes. The classes were selected in a way such that most categories given in the AAT are represented. The schemes are provided in the same file format that is used for the PSB.

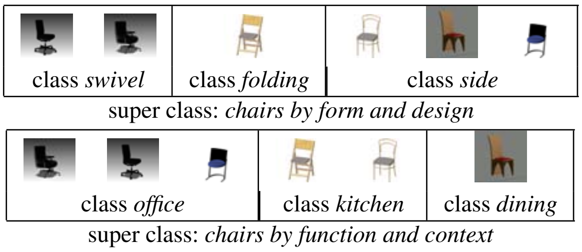

Figure 1: *Objects may either be classified by form or by function according to the perception within a certain stage of designing.*

Note that not all categories currently contain objects. In this first version we concentrated on furnishings considering especially the office domain regarding the eminent request for furnishing models within the design stages of detailing and visualisation in architectural practice. The next release of our benchmark will include more models, so that the categories will be balanced in a better way.

The models collected for our benchmark were delivered in various file formats including e.g. `.3ds` or `.gsm`. We converted all models into triangle meshes and stored them using the Wavefront OBJ format. The resulting files strongly vary in size. The smallest file contains 12 triangles while the largest one contains 901300 triangles. As is usually the case when dealing with real-world data, the quality of the meshes differs strongly with respect to consistent face orientation. There is also no guarantee that the meshes are watertight.

4. Retrieval results

To get an impression how current shape retrieval methods perform on our new benchmark, we conducted several experiments involving supervised and unsupervised methods using the form-based classification scheme as well as the function-based one. For unsupervised retrieval we used global Zernike moments descriptors [Nov03] (GZM), for supervised retrieval we chose the method presented in [WBK08] using local spin-images (LSI) as well as global Zernike moments. To make sure that enough training data for each category were available when using supervised methods, we selected all objects belonging to categories containing at least 20 objects, resulting in 1817 models subdivided in 25 classes using the form-based classification scheme, and 1774 models subdivided in 26 classes using the function-based classification scheme. For the global Zernike moments we used 156 coefficients. The similarity of two objects was computed as the Euclidean distance between the two according Zernike moments descriptors. We will now briefly describe the retrieval method introduced in [WBK08]. During a learning step this algorithm determines how characteristic certain local or global shape features are for certain object classes. The learning step is performed on a set of features derived from preclassified training models. When later presented unknown objects, the algorithm computes a

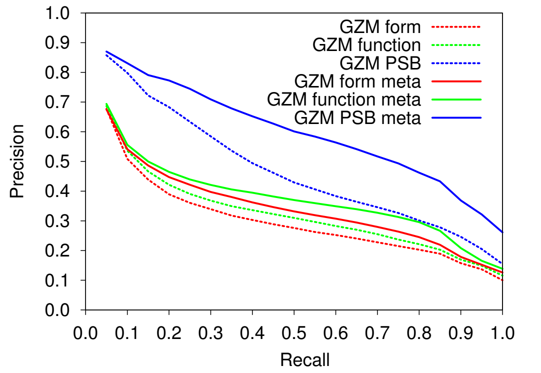

Figure 2: *Retrieval results using global Zernike (meta) descriptors.*

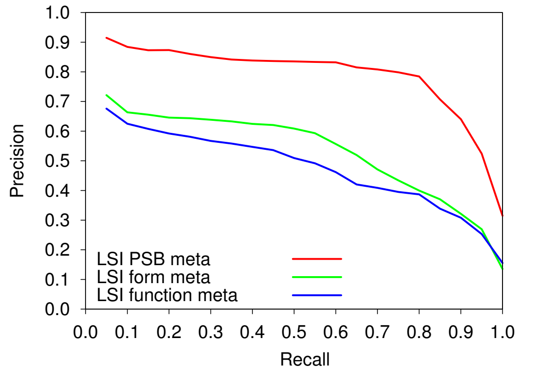

Figure 3: *Retrieval results using local spin-images and supervised learning.*

set of local or global features. Using the acquired knowledge about the training data, the new shape features are converted into a meta descriptor describing the conditional class probabilities that the object belongs to a certain class given the shape feature. Meta descriptors derived from several features can be combined into one single descriptor by simply multiplying and renormalizing the according conditional class probabilities. By that, features of different scale or type (e.g. local Spherical Harmonics descriptors or spin-images [Joh97]) can be easily merged. As the meta descriptors correspond to probabilities, the similarity of two objects is finally computed using a symmetric version of the Kullback-Leibler divergency which is the natural measure for the distance of two distributions. To evaluate this approach, we randomly selected 16 models from each category to build the training set. The remaining models were used to build the test set. For each object in the training and test datasets we computed 64 spin-images and one global Zernike moments descriptor. We then performed the learning step on the training dataset in the described way. Retrieval was then conducted on the test set computing meta descriptors for all local and global features. In Figures 2 and

CDD Method	1-NN	1-Tier	2-Tier	DCG
GZM Form	0.700	0.279	0.404	0.682
GZM Funct.	0.666	0.296	0.412	0.681
GZM PSB	0.729	0.405	0.532	0.719
GZM Form (M)	0.685	0.322	0.466	0.708
GZM Func.(M)	0.659	0.352	0.482	0.707
GZM PSB (M)	0.739	0.510	0.681	0.770
LSI Form (M)	0.646	0.531	0.623	0.792
LSI Funct. (M)	0.616	0.463	0.561	0.758
LSI PSB (M)	0.830	0.712	0.806	0.881

Table 1: *Results using global Zernike moments (GZM), meta descriptors from global Zernike moments (GZM (M)) and meta descriptors from local spin-images (LSI (M)).*

3 we show the results for both classification schemes. Additional retrieval performance measurements can be found in Table 1. We compared the retrieval performance on the test set using global Zernike moments (without learning), meta descriptors derived from global Zernike moments descriptors and meta descriptors derived from the local spin-images (both involving learning). To get an impression of how difficult our benchmark is regarding retrieval, we compared the results to those achieved by the same retrieval algorithms on the PSB. We therefore selected all objects belonging to categories containing at least 20 models from the PSB. This resulted in 739 objects divided into 21 classes. For training and retrieval, we conducted the same steps as for our benchmark. As can be seen in Figures 2 and 3 as well as in Table 1, the retrieval performance of all algorithms running on our benchmark is worse than on the PSB, especially when considering the good results that were achieved on the PSB using the meta descriptors of local spin-images. This is most probably due to the fact that our benchmark is restricted to architectural data, including classes that are very similar to each other in terms of shape (see e.g. Figure 1). For both classification schemes, the intra-class variability of global model shapes is still quite large, leading to similar retrieval results using global Zernike moments descriptors (see Figure 2). As the intra-class variability of local model shapes on the other hand is believed to be smaller within the form-based classification than in the function based-one, local descriptors provide better retrieval results regarding the form-based classification (see Figure 3).

5. Conclusion

In this paper we presented a new 3D shape benchmark that is tailored to architectural 3D models. The developed classification schemes take into account the specific requirements of architects regarding form and function. In our experiments using different shape retrieval methods we showed that retrieval on this benchmark seems to be more difficult than on the Princeton Shape Benchmark which is probably due to the restriction to architectural data. We therefore suggest that future shape retrieval algorithms in this field should be far more tailored to the domain of architecture by means of certain architectural rule sets, intensive use of supervised learning and capturing of shape features that are especially relevant for architectural objects. Our future work will include the extension of the current database by more models, so that the different categories will be well-balanced.

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