Feature-Based 3D Object Retrieval

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SYNONYMS

3D Similarity Search; Shape Descriptors

DEFINITION

3D objects are an important type of data with many applications in domains such as Engineering and Computer Aided Design, Science, Simulation, Visualization, Cultural Heritage, and Entertainment. Technological progress in acquisition, modeling, processing, and dissemination of 3D geometry leads to the accumulation of large repositories of 3D objects. Consequently, there is a strong need to research and develop technology to support the effective retrieval of 3D object data from 3D repositories.

The feature-based approach is a prominent technique to implement content-based retrieval functionality for 3D object databases. It relies on extracting characteristic numerical attributes (so-called features) from a 3D object, usually forming high-dimensional vectors which represent the 3D object, or parts of it. The 3D feature vectors in turn are used to estimate object similarity for content-based retrieval, and can also be used for multidimensional indexing of 3D database content. There exist several degrees of freedom in obtaining 3D features. Important specifications to be made include the type of 3D characteristics or its level of detail considered, or invariance properties required, among others. Finding efficient and effective features for a given 3D repository is usually addressed by benchmarking.

HISTORICAL BACKGROUND

The development of 3D object retrieval methods can be regarded as part of the larger multimedia retrieval research area. The availability of increasing volumes of multimedia data such as digital images, digital video, or digital audio induced the need to develop content-based retrieval methods supporting these data types. Image retrieval has roots in image processing and database research of the 1980s, and was joined in the 1990s by similar efforts in the video and audio domains. Roughly, beginning by 2000, 3D objects increasingly came into focus of multimedia retrieval research. Driving motivation in the research and development of 3D retrieval methods are the increasing use of 3D object data in a range of application areas.

While retrieval of 3D objects is a prominent topic in multimedia database research, the definition of similarity notions for 3D data is also considered in related disciplines. In Geometry Processing, the registration or alignment of geometry is of interest, using certain definitions of geometric similarity. Computer Vision is concerned with the recognition of objects in images taken by a camera or other scanner device, requiring appropriate segmentation and description methods for the objects in the scene under concern. In Shape Analysis, shapes and scenes are often analyzed for certain structural features, supporting e.g., classification and compression.

From the multimedia database research perspective, the focus of 3D retrieval implementations not only concerns the effectiveness of the retrieval, but also, their efficiency, demanding for real-time query processing on large repositories. The feature vector approach is therefore especially suited, as it allows the efficient evaluation of object similarity, usually by calculating a Minkowski distance between feature vectors representing underlying 3D objects.

SCIENTIFIC FUNDAMENTALS

To represent 3D object data as points in feature vector space, it is necessary to find characteristics that describe the objects in a meaningful, discriminating way. A suitable feature extraction function calculates characteristic features from the 3D objects, thereby mapping them into d-dimensional feature vector space. With these feature vector representations, a similarity query in the original 3D object space is reduced to a search for close points in d-dimensional feature vector space.

Common requirements of 3D feature extraction

For 3D object data, based on the given retrieval application, certain properties of the features extracted can be deemed desirable. The features may be required to be invariant with respect to changes in rotation, translation, and scale of the 3D models in their reference coordinate frame. Ideally, an arbitrary combination of translation, rotation and scale applied to one object should not affect its similarity measure with respect to another object. Another desirable property is robustness with respect to variation of the level-of-detail in which the 3D objects are given, and to small geometry and topology variations of the models. These invariance and robustness properties are especially important if the retrieval is expected to support 3D objects from heterogeneous data sources. This is because in such cases, the reference frames or levels-of-detail in which the models are represented may differ, and it cannot be assumed that respective meta data is available from all possible object sources.

3D feature extraction process model

A process model of 3D feature extraction is depicted in Figure 1 and can be described as follows. Firstly, if required by the application, a preprocessing step normalizes the 3D object to approximate invariance to rotation, translation, scaling, and reflection [11]. A second step abstracts the 3D object according to a selected shape characteristic. For example, one can abstract a 3D object as a volume, or as an infinitely thin surface with precisely defined properties of differentiability, or as a set of 2D images formed by projections from different perspectives. The third step captures the main features of the 3D object under the selected abstraction by means of a numeric transformation. As a result of this step, a numerical representation of the original 3D object is obtained. The last step of the feature extraction process model produces the final descriptor of the object from the numerical description. Generally, the descriptor may be a vector of numerical features, but it may also be a histogram of the measured characteristics, or a graph-based representation of the analyzed 3D object. Feature-based methods for 3D model retrieval usually are efficient, robust, and easy to implement. This does not imply, however, that statistical or graph-based methods should be disregarded. In fact, most of those methods have their particular strengths and may well be the ideal candidate for a specific application.

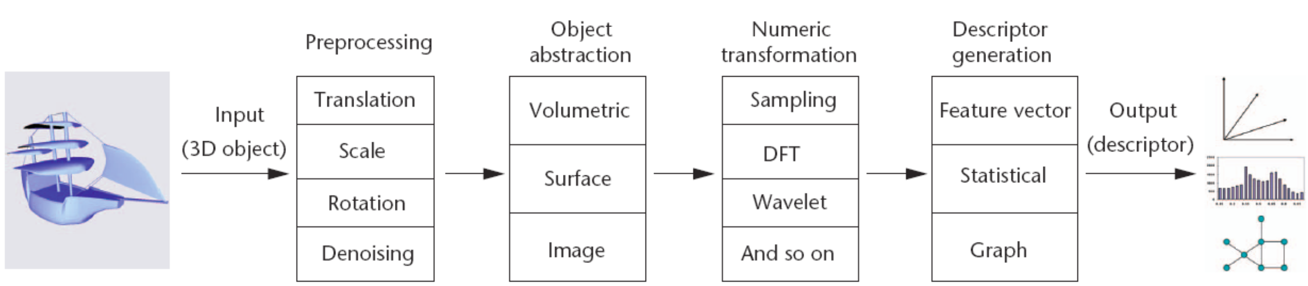

Figure 1: Feature extraction process for 3D objects

3D feature types

As surveys indicate [2, 7, 10], there is a wealth of different features that so far have been used to build 3D retrieval systems. The situation is comparable to content-based image retrieval (CBIR), where also, many different features have been proposed over the recent years. It can be stated that many of the 3D features proposed were heuristically introduced, motivated by techniques and practices from Computer Graphics (e.g., projection-based features), Geometry Processing (e.g., features based on surface curvature statistics), or Signal Processing (e.g., features obtained by representing object samples in the frequency domain). Some of the most effective 3D feature vector extractors proposed to date rely on features extracted from 2D projections of 3D objects.

Usually, it is a priori unclear which of the potentially many different features should be preferred for addressing the 3D retrieval problem. Each of the many possible descriptors captures specific model information, and their suitability for effective retrieval in a given application domain needs to be experimentally evaluated. In practice, it often shows that the effectiveness of 3D retrieval systems can benefit from using not a single, but several different types of features in combination.

Efficient 3D object retrieval

Similarity queries in 3D object databases may be answered by performing a sequential scan on the database, comparing the query object with all 3D objects stored in the database. This naive method might be too slow for real-world applications. In feature-based 3D object retrieval, the search system may use an index structure (e.g., spatial access methods or metric access methods) for efficient retrieval if the distance function used to compute the (dis)similarity of two 3D objects holds the properties of a metric (strict positiveness, symmetry, and the triangle inequality).

Spatial access methods [1] (also known as multidimensional indices) are index structures especially designed for vector spaces which, together with the metric properties of the distance function, use geometric information to discard points from the search space. Usually, these indices are hierarchical data structures that use a balanced tree to index the database. Metric access methods [4] (also known as metric indices) are index structures that use the metric properties of the distance function (especially the triangle inequality) to filter out the space's zones, thus avoiding the sequential scan.

KEY APPLICATIONS

Content-based 3D retrieval methods are potentially useful in all applications involving 3D object repositories, from which elements need to be retrieved based on geometric similarity. Several exemplary applications are detailed in the following, more exist.

Industrial applications

Engineering and industrial design, the animation, and the entertainment industry heavily rely on digitized models of products or parts thereof. Computer-Aided Design allows the digital modeling of 3D content. Given effective retrieval capabilities, the re-usage of content from existing repositories can be supported for a more efficient production processes [5].

Medicine

In medical imaging applications, often 3D volume data is generated, e.g., using MRI scans. A possible application lies in automatic diagnosis support by analysis of organ deformations, by matching actual images with medical database of known deformations.

Molecular biology

Structural classification is a basic task in molecular biology. This classification can be supported by geometric similarity search, where proteins and molecules are modeled as 3D objects, which can be compared against bio-molecular reference databases using geometric similarity measures.

FUTURE DIRECTIONS

Feature-based 3D retrieval research is still in a rather early stage. Current approaches mostly consider features describing the geometry of whole models, that is, they support global similarity between objects. Recently, approaches also considering local features based on identification of salient object regions have been proposed. These are expected to support not only the retrieval of complete models, but also, be suited for retrieval based on local similarity. Future work will address 3D retrieval under additional similarity models, including similarity models invariant w.r.t. non-rigid and structural object deformations. It is also expected that application specific, specialized similarity notions will become increasingly important.

EXPERIMENTAL RESULTS

The effectiveness of 3D features for retrieval is usually determined experimentally based on reference benchmarks, and measured by Information Retrieval metrics [3]. Well-known 3D retrieval benchmarks include the Princeton Shape Benchmark [9] and the Purdue Engineering Shape Benchmark [8]. The SHREC contest [6] is an International shape retrieval contest held in conjunction with IEEE's Shape Modeling International conference.

CROSS REFERENCE

Multimedia Information Retrieval Model, Multimedia Retrieval Evaluation, Information Retrieval, Feature Extraction, Index Structures.

RECOMMENDED READING

Between 3 and 15 citations to important literature, e.g., in journals, conference proceedings, and websites.

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