3D Model Search Engine Based on Lightfield Descriptors

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Abstract

With the development of modern 3D modelling and digitizing tools, more and more models have been created recently, which leads to the necessity of the technique of 3D model retrieval system. Our 3D model search engine has been designed with the goal to meet entertaining, industrial, commercial, medical, and educational needs. The system is available on the Web (http://3d.csie.ntu.edu.tw) with a database containing over 10,000 models free downloaded through the Internet. Users can query 3D models by text, drawing 2D shapes using a friendly painting interface, or selecting one 3D model as a query key interactively. The features representing a 3D object, namely, the Lightfield Descriptors, are extracted from 2D images, which are rendered from cameras positioned on the vertices of a regular dodecahedron. The Lightfield Descriptors of each model are used to compare similarities among each other, and the retrieval process takes only 2 and 0.1 seconds with a 3D model and 2D shapes, respectively. During four months, the system has been widely used for querying over three thousand times from 418 IP addresses in at least 27 countries.

Categories and Subject Descriptors (according to ACM CCS): H.3.3 [Information Search and Retrieval]: Retrieval Models

1. Introduction

1.1. Motivation and applications

An information retrieval system is a system that is capable of storage, retrieval, and maintenance of information. Original definitions focused on "documents" for information retrieval rather than multimedia integrated information [26]. More and more multimedia information has become available from sources all over the world, and may be represented in various forms, including still pictures, graphics, 3D models, audio, speech, and video. Nevertheless, the value of information often depends on how easy it can be found, retrieved, accessed, filtered and managed [15]. As we can see, the transition between the second and the third millennium abounds with new ways to produce, offer, filter, search, and manage digitized multimedia information, the trend is getting clear: in the next few years, users will be confronted with a large number of contents provided by multiple sources that efficient and accurate access to these boundless contents seems unimaginable today [15]. Therefore, the need of multimedia information retrieval has increased.

Recently, the development of 3D modelling and digitizing technologies has made the model generating process much easier. The 3D modelling tools, including 3ds Max [29], MAYA [30], AutoCAD [31], 3D freeform design systems [14] and sculpting systems [19, 20], facilitate users to create 3D models directly on the computers. The 3D digitizing tools, on the other hand, digitize 3D objects from the real world, and include 3D scanner machines [32], registration from range data [16, 17], automatic modelling from multi-view video [18], etc. Since it is obvious that the 3D modelling and digitizing techniques will be developed and improved in the future, more and more 3D models, accordingly, will be created easier, faster and less expensive. The need of developing efficient techniques for content-based 3D model retrieval is also increasing.

The technique of 3D model retrieval can be applied to many practical applications, and is introduced with the following scenario. Suppose a user, Vincent, wants to create a digital content, for example, a slide show for presentation or a 3D computer game. He needs a number of 3D models, but it is impractical to create all of them from scratch. Hence, he connects to the Internet and visits a 3D model search engine. The search engine is based on content-based 3D model retrieval, and provides a friendly interface for users to draw 2D shapes for query. Soon, Vincent downloads plenty of 3D models retrieved from the search engine, and slightly modifies them before use. Subsequently, he needs to design a 3D trademark for a project. In the existing trademark laws of many countries, 3D shapes are allowed to form elements of a trademark. Therefore, during designing a 3D trademark, he uses the technique of 3D model retrieval to ensure that no other similar shapes are registered. A 3D trademark plays an important symbol for a project, and may be conceived and designed for a long time. Therefore, watermark was proposed to be embedded in the 3D trademark to protect the intellectual property [21]. One day, Vincent finds the same 3D trademark spread on the Internet for other use, and doubts that the trademark might be infringed by other companies. Therefore, he searches similar 3D models from thousands examples via the Internet using the 3D model retrieval for pre-filtering, and then applies watermark technique to find the infringed one.

At a later time, Vincent wants to buy a chair with a specific shape using electronic commerce (E-commerce) via the Internet, and then visits a shopping center, which includes many shopping sites. When he queries by the keyword "chair", it's very difficult to find what he wants since too many models are retrieved from the text-based search engine. Fortunately, the shopping center also provides content-based 3D model retrieval system. With the help of the content-based retrieval system, Vincent found the chair in a shopping site soon. Then, he visits an art sculpture museum on a web site, which contains many sculptures digitized by a 3D scanner, such as David by Michelangelo [17]. Vincent wants to review a sculpture, but he forgets or never knows the name of that. Therefore, he finds the sculpture using the 3D model retrieval technique, and learns more about it. Since Vincent is interested about the specific shape of the work, he uses the 3D model retrieval system to get more sculptures, which share similar 3D shapes, and investigates among them.

Main applications described above include 3D model search engines, verification of 3D trademarks, pre-filtering for 3D watermarks, and user interfaces for E-commerce and sculpture museum. Other possible applications of the 3D model retrieval are 3D object recognition, multimedia editing, education, digital libraries, functional labelling in 3D medical images, and molecular biology, etc. In this paper, one of the kernel applications, a 3D model search engine, is proposed in Section 5.

1.2. Objectives and challenges

The general objective of an information retrieval system is to minimize the overhead of a user locating needed information. Overhead can be expressed as the time a user spends in all of the steps leading to reading an item containing the needed information (e.g., query generation, query execution, and scanning results of query to select items to read, reading non-relevant items) [26]. To minimize the overhead, one of the most important issues is to increase the retrieval precision when designing a 3D model retrieval system. Therefore, the purpose of 3D model retrieval is to search relevant 3D models efficiently and correctly by querying from a database. One straightforward way is matching the input 3D model to each one in the database, and ranking by matching similarity. The key point is the way to define the similarity between two 3D models according to human perception. In general, representative features are extracted for each 3D model, and then matched among these models. Therefore, the problem of 3D model retrieval should be focussed on how to define features for representing 3D models and distance metrics for matching the features.

Several characteristics of matching 3D models make differences for other related problems. For example, recognizing objects from 2D images or range images is a traditional problem in computer vision [22, 23]. The difficulty of the problem lies in different projections, illuminations, shadows, reflections, segmentations, clutters, occlusions and partial matching. Most of these problems don't exist in 3D model retrieval. However, 3D model is in higher dimension than images, and usually representing irregularly sampled points. Another related problem is in molecular biology [24]. One of the problem focuses on partial matching in order to find the common active site among proteins. Note that there is no scaling problem in molecular biology, since the distance between two binding atoms, say, oxygen (O) and hydrogen (H), is a constant value.

In 3D model retrieval, there are many challenges when designing representative features, including extracting and matching among the features. The main challenges are listed in the following.

(1) Automation: Feature extraction should be automatic for dealing with large number of 3D models, which are collected from the Internet. In addition, when querying by uploading a 3D model, the features of the 3D model should also be automatically extracted.

(2) Efficiency: Both feature extraction and matching should be efficient, especially in feature matching. Therefore, the size of features should be small for quick comparison.

(3) Scope: Feature extraction and matching should work well in various kinds of 3D models.

(4) Robustness: The features should be robust against geometric processing, such as similarity transformation (translation, rotation and scaling), connectivity changes (remeshing, sub-division and simplification), model degeneracy (missing, wrongly oriented, intersecting, disjoint and

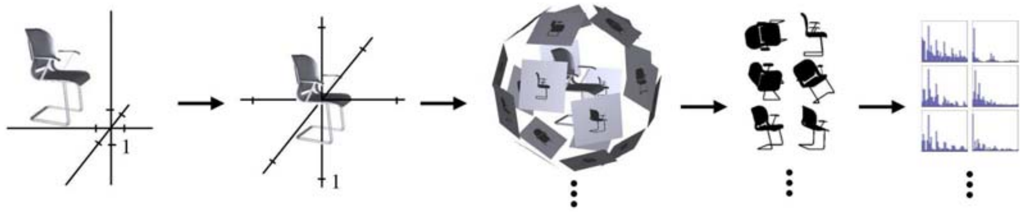

Figure 1: *Steps of extracting the LightField Descriptors for a 3D model*

overlapping polygons), random noise, smoothing, deformation, and posture changing, etc.

(5) Discrimination: The features should be sensitive to preserve important distinctions among 3D models. In addition, by ensuring that similar 3D models will have similar features, small changes in 3D models should lead to small changes in features.

2. Previous works

The technique of 3D model retrieval and matching is an important research topic in many research organizations from all over the world, such as Princeton [2,3], CMU [12], Berkeley, Stanford, Brown and Texas University in USA, Tokyo [4] and Yamanashi [6] University in Japan, National Research Council [5] in Canada, University of Konstanz [7] in Germany, Aristotle University [8] in Greece, and HP Laboratories [11] in Israel, etc. However, since the software and hardware environment for 3D models comes to maturity just recently, the research topic is a new challenge for all researchers. There are many experimental systems available, however, up to now, only two 3D model search engine systems are relatively "complete" on the Web for usage all over the world: one is built by Funkhouser et al. in Priceton University and the other one is developed by us. The search engine built by Funkhouser et al. is published in *ACM Trans. on Graphics* in Jan, 2003 [2], and our approach will be published in *EUROGRAPHICS 2003* that is also published in *Computer Graphics Forum* in Sep, 2003 [1]. Different methods of 3D model retrieval are used for each system: the former is geometry-based approach and the latter is image-based. According to the experimental results [1], the retrieval precision (precision-recall diagram) of our approach is 42% higher than that of method proposed by Funkhouser et al. That is, the retrieval results of our approach will be closer to human perception than that of method proposed by Funkhouser et al.

Previous works of 3D model retrieval can be broadly classified into two categories: geometry-based and image-based approaches. Geometry-based approach matches 3D models according to geometric distribution, and image-based approach does according to the similarity of rendered projection. One advantage of geometry-based approach is in the use 3D characteristics, such as topology structure [4,9] and curvature of a patch [10]. However, higher dimension and irregular sampled points make the analysis more difficult. Moreover, invisible polygons will damage matching results in geometry-based approach. For example, 3D models created by modelling tools usually possess invisible polygons especially in articulation, but 3D models digitized by scanning tools do not. On the other hand, one advantage of image-based approach is easiness of processing since images are in lower dimension and in regular sampled points. Besides, unlike still images, the rendered images are well segmented and easily matched. Nevertheless, image-based approach might lose 3D information and misplace the corresponding rendered images between two 3D models.

3. Feature extraction for 3D model retrieval

The steps of extracting the *Lightfield Descriptors* [1] for a 3D model are shown in Figure 1, and detailed in the following.

(1) Since each model has its own coordinated system, translation and scaling are applied first in order to ensure that a model is entirely contained in each rendered image. The input 3D model is translated from the center of the model to the origin of the world coordinate system, and then scales the axis of maximum length to be 1. The translation $T = (T_x, T_y, T_z)$ assigns the middle point of the whole model to be the new origin:

$$T_i = \frac{MaxCoor_i + MinCoor_i}{2}, \quad i = x, y, z \qquad (1)$$

where the $MaxCoor_i$ and $MinCoor_i$ are the maximum and minimum coordinate value of i axis, respectively. The scaling is isotropic, and normalizes according to the maximum distance from x, y and z axes of the whole model:

$$S = \frac{1}{\min_{i=x,y,z}(MaxCoor_i - MinCoor_i)} \qquad (2)$$

Although the stages cannot get the exact translation and scaling between two 3D models, the image metric of our approach is robust against translation and scaling.

(2) Render images from the camera positions of the light

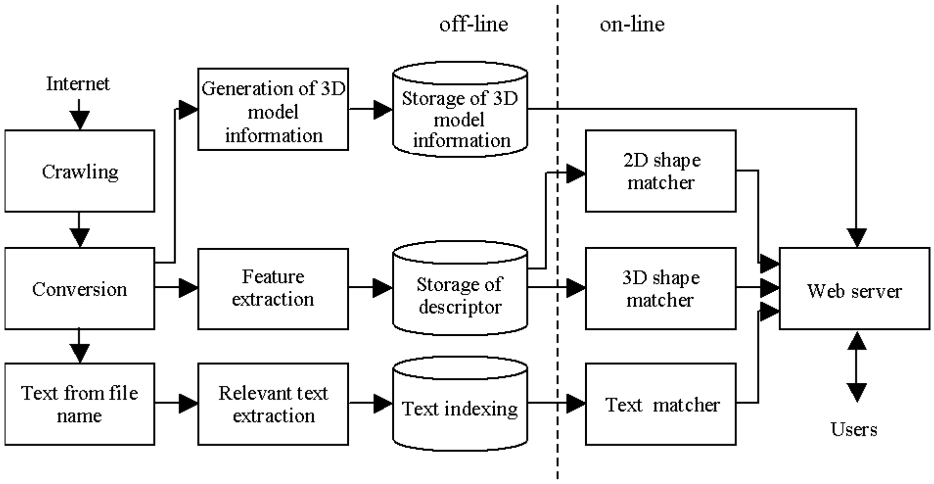

Figure 2: *Overflow of the search engine system*

fields, which is on the surface of a larger sphere. There are 10 light fields for each 3D model, and the camera positions of each light field are set at the 20 vertices of a regular dodecahedron. The camera at each viewpoint is directed towards the center of the sphere, and the up-vectors of cameras are placed uniformly. If two 3D models are of different orientations, their proper corresponding viewing images will have different rotational angles. It doesn't matter, since the image metric of our approach is also robust against rotations.

(3) We use an orthogonal projection in order to reduce the size of descriptors. Therefore, in a descriptor of light field, there are 10 images represented from 20 viewpoints. For a 3D model, 10 descriptors of light fields are created, so there are totally 100 images that should be rendered and extracted for features.

(4) Extract Zernike moment and Fourier Descriptor [13] from each image. Descriptors for a 3D model are those features from the 100 images.

4. 3D Model Search Engine Overview

The search engine system for 3D models consists of off-line pre-process and on-line retrieval process, as shown in Figure 2.In the off-line pre-process, a crawling is executed for downloading 3D models from the Internet first. File conversion is then applied for getting raw data of 3D models, including un-compression and graphics file format conversion. Now, there are 10911 3D models in our database after the conversion. For content-based retrieval, features of 3D models are extracted and stored in about 6 seconds on the average using a PC with Pentium III 800 CPU. For text-based retrieval, relevant texts are extracted according to file name of 3D models using WordNet [25] and indexed by RainBow [27] toolkit. In addition, thumbnails and other related information of 3D models are generated and stored for user browsing later.

In the on-line retrieval process, keyword search is available for text-based retrieval by using RainBow toolkit. For content-based retrieval, a user friendly interface of drawing 2D shapes is also provided to retrieve 3D models easily even for a novice. Querying by a retrieved 3D model interactively and iteratively allows user to get 3D models more similar and specific. The retrieval is down in a PC with two Pentium IV 2.4GHz CPUs. Only one CPU is used for the query at one time, and the retrieval takes 2 and 0.1 seconds with a 3D model and two 2D shapes as the queried keys, respectively. Several implementation details are listed in the following:

(1) Crawling: The 3D models collection is built by crawling from the Internet. However, it's not easy to collect 3D models from the Web since there are many different file formats for 3D models, and, what is worse, they are usually compressed in different compressing formats. The crawling process focuses on several web sites containing high quality 3D models. The crawling is executed in UNIX using command "wget" in shell. The downloaded files are saved in folder named after the downloaded path in order to avoid overlapping among files with the same name. For example, a file "xxx.zip" downloaded from "http://www.3dcafe.com/models/xxx.zip" will be saved to "http/www.3dcafe.com/models/xxx.zip".

(2) Conversion: As mentioned above, many 3D models are compressed and in different graphic file formats. In this conversion stage, three steps are applied in a PC with Windows 2000. First, in order to avoid repetition of the same file name after un-compression in a fold, for each downloaded

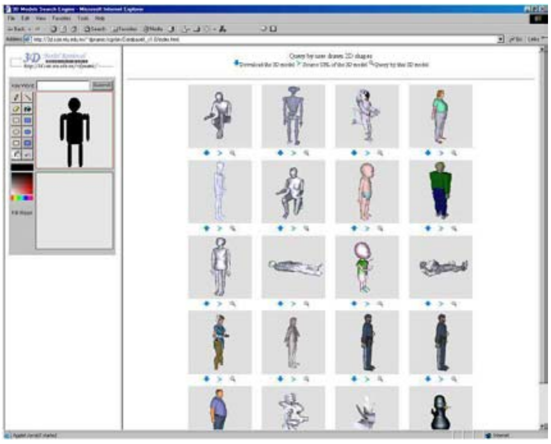

Figure 3: *Retrieval results from user drawn 2D shapes*

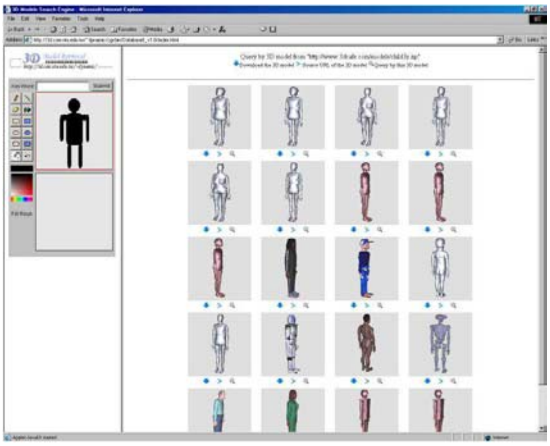

Figure 4: *Retrieval results from selecting a 3D model*

file, a folder is created according to the file name and then the file is moved to the folder. At the same time, the directory is also recorded where the model comes form. Second, PowerArchiver Command Line (PACL) [34] is adopted in our un-compression tools in command line, and can deal with many compression formats, such as zip, rar, lha, etc.

Third, Deep Exploration 2.0 [33]is used for converting graphics file formats since the software can convert batch from a folder, and can process many different graphics file formats, such as 3ds, wrl, obj, max, etc.

Thus, the file name of each 3D models is appended a number to avoid repetition and copied to a folder, and then copy the converted file format back after removing the added number. The file format of Wavefront OBJ [30] file (*.obj) is adopted in our implementation, and the material is save as another file (*.mtl). As a result, for example, a 3D model "yyy.3ds" is un-compressed from "xxx.zip", and the converted file will be put in "http/www.3dcafe.com/models/xxx.zip/yyy.obj". Note that, the conversion may be failed in un-compression or graphic file format conversion. Therefore, valid 3D models are checked and listed after measuring in several criteria, such as polygon number and vertex number.

(3) Feature extraction and storage: The approach of feature extraction for content-based retrieval is proposed in Section 3. The features are extracted in a PC with a Pentium III 800MHz CPU and GeForce2 MX video card in windows 2000. On the average, each 3D model with 7,540 polygons takes 5.7 seconds to extract features, and the average time of rendering and extracting a 2D shape takes about 0.06 seconds. Extracting features of 3D models is also suitable for both 3D model and 2D shape matching. No extra effort should be done for 2D shapes. When saving the features, coefficients of one image metric for all models are saved in a file. For each 3D model, the *LightField Descriptors* are saved sequentially, and are in a pre-defined order. For each *LightField Descriptor*, rendered images are also in a pre-defined order for storage. For each image metric, coefficients are saved in a pre-defined order if more than one coefficient is in the image metric. For each coefficient, only 8 bits are saved. For retrieval from database with large number of models, each coefficient of Zernike moment is also saved for 4 bits in another file. As a result, the features are 37.5MB and 18.7MB for Zernike moment, 10.4MB for Fourier Descriptor and 1.0MB for Circularity, whereas the raw data of all 10911 3D models is about 9GB.

5. Experimental results

Figure 3 shows a typical example of querying by user drawn 2D shapes of "human" model. Many "human" 3D models are retrieved. Figure 4 shows the interactive search by selecting a "human" 3D model from Figure 3. As we can see, after the iterative querying, retrieval results will return more human models with similar shape.

Our search engine with 10911 3D models has been publicly available on the Web since Jan. 2003. Up to now, the search engine has been improved for many times. The usage of the search engine is only listed on querying by 2D shapes and 3D models from "Find Similar" button or browsing. From Jan. 4, 2003 to May 20, 2003, the search engine served 3,475 queries (not counting queries from our lab by removing IP address 140.112.29.xxx), including 2144 query by 2D shapes and 1331 query by 3D model. Those queries come from 418 unique hosts, and in at least 27 different countries (Domain name can only be found in 309 IP addresses). The countries include Australia (.au), Belgium (.be), Brazil (.br), Canada (.ca), Switzerland (.ch), Czech Republic (.cz), Germany (.de), France (.fr), Greece (.gr), Hong Kong (.hk), Croatia/Hrvatska (.hr), Israel (.il), Italy (.it), Japan (.jp), Republic of Korea (.kr), Malta (.mt), Mexico (.mx), The Netherlands (.nl), Poland (.pl), Portugal (.pt), Singapore (.sg), Turkey (.tr), Taiwan (.tw), Ukraine (.ua), United Kingdom (.uk), Yugoslavia (.yu), and USA (.edu). The educational institutions in USA (.edu) include UMN, Princeton, TAMU, CMU, Washington, Purdue, Dratmouth, Arizona and MIT, etc. Other domain names include .com, .gov, .mil and .net.

6. Conclusion and future works

In this paper, the work for creating a 3D model search engine is introduced. *LightField Descriptors* are extracted for matching similarity among 3D models. Users can query 3D model by text, 2D shape and 3D shape. Other possible applications and design issues are also described in this paper.

Several future works are listed in the following. First, automatic crawling 3D models in all format is an important step for a 3D model search engine. Then, query interface also need to be improved in the future. Next, browsing is also an important issue for a content-based search engine [28]. Therefore, better browsing tools can be built automatically for a 3D model search engine.

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