An Integrated System for 3D Object Reconstruction and Recognition

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Abstract: - This paper presents and develops an integrated system for 3D object reconstruction and recognition, which contains three key functional subsystems: superquadric based structural description extraction, multipart object reconstruction and 3D object recognition. These three subsystems are relatively independent and also connected each other, which accomplish the conversion from 3D object data to virtual 3D model and interpretation. Some experiments and subsystem running interface are demonstrated.

Key-Words: - 3D object reconstruction, 3D object recognition, 3D model, superquadric

1 Introduction

3D object reconstruction and recognition are very important in many application and research areas, such as robotics, virtual reality and computer vision.

Volumetric part representation has been used popularly in computer vision [1,2,3] since it is viewpoint independent, insensitive to local variations and supported by extensive psychological evidence. In this paper, the superquadric based parametric description is implemented for representing the parts involved in 3D objects, which enables a more compact 3D object representation.

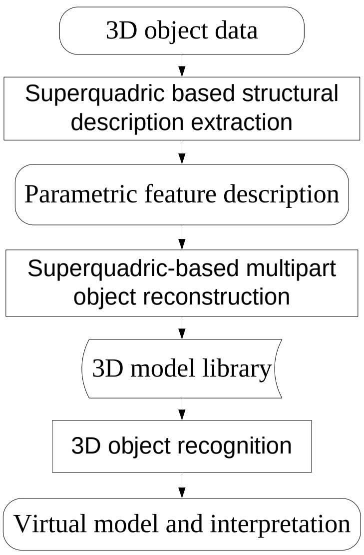

Fig.1 Integrated framework of 3D object reconstruction and recognition system

In the paper, an integrated 3D object reconstruction and recognition system is presented and developed, which is shown in Fig.1. The system is decomposed into three key functional subsystems: superquadric based structural description extraction, multipart object reconstruction, and 3D object recognition, which are described in detail in the following sections.

2 Superquadric based Structural Description Extraction

Superquadrics as a family of parametric shapes can describe a wide variety of relatively complex and realistic 3D primitive shapes effectively with compact parameters [4]. A basic superquadric surface may be defined by an implicit equation:

$$f(x,y,z) = \left(\left(\frac{x}{a_x}\right)^{2/\varepsilon_2} + \left(\frac{y}{a_y}\right)^{2/\varepsilon_2}\right)^{\varepsilon_2/\varepsilon_1} + \left(\frac{z}{a_z}\right)^{2/\varepsilon_1} - 1 = 0 \quad (1)$$

The modeling power of superquadrics is augmented by applying various deformation operations which include bending, tapering, etc [4] to the basic superquadrics.

The superquadric based structural description of 3D objects is implemented at two levels, geometrical level features describing the shape attributes of each object part and the topological level features reflecting the global connection structure among object parts.

2.1 Part shape features at geometrical level

- Superquadric parameters:

It has been known that a superquadric surface is defined by an implicit equation (1). At a first step toward fitting superquadric to 3D data, an inside-outside function is defined as follows:

$$F(x,y,z) = [\,f(x,y,z)+1]^{\varepsilon_1} \quad (2)$$

For a superquadric in general position and orientation with linear tapering and bending deformations, the inside-outside function may be written as an implicit function with 15 parameters.

$$F(X,Y,Z) = F(X,Y,Z;a_x,a_y,a_z,\varepsilon_1,\varepsilon_2,\phi,\theta,\psi,p_x,p_y,p_z;K_x,K_y;K_b,\alpha) \quad (3)$$

Given the 3D data is a set of points (x_i, y_i, z_i), $i = 1,2,\cdots,N$, which correspond to the description of 3D real object part. The goal of superquadric fitting is to change the 15 parameters to find the values for which most of the 3D points are close to the superquadric surface. The best fit may be obtained by searching for the minimum of the energy:

$$E = \sum_{i=1}^{N} \sqrt{a_x a_y a_z}\left[1 - F\left(x_i, y_i, z_i; a_x, a_y, a_z, \varepsilon_1, \varepsilon_2, \phi, \theta, \psi, p_x, p_y, p_z; K_x, K_y; K_b, \alpha\right)\right]^2 \quad (4)$$

where a_x, a_y, a_z are defined for the superquadric size; $\varepsilon_1, \varepsilon_2$ characterize the shape; ϕ, θ, ψ are defined for the orientation and p_x, p_y, p_z for the position in space; K_x, K_y are defined for the tapering deformation along Z axis and K_b, α for the bending deformation.

Through the nonlinear minimization of (4), the superquadric parameters describing 3D part data are obtained [4].

Based on the superquadric parameters of 3D object parts, many features can be defined and extracted as part shape features at geometrical level.

- Geon type FU_{geon}: It is the qualitative attribute of 3D object part. Based on the superquadric parameters, a set of discriminative features are derived; then, the geon classification is implemented utilizing SVM-based multi-class classifier that is trained by SMO (Sequential Minimal Optimization) algorithm and the qualitative attribute, geon type is achieved.
- 3D spherical harmonic descriptor FU_{sph}: This is a 3D rotation invariant describing volumetric part shape. The FU_{sph} extraction of volumetric part represented by superquadric is decomposed into three steps: first, sample regularly on superquadric surface along the longitudinal and latitudinal directions; second, construct spherical function describing superquadric surface based on the obtained samples; finally, implement fast spherical harmonic transform on the spherical function and obtain the 3D spherical harmonic descriptor [5].
- Volume rate FU_{Vrate}: The ratio of current part volume to the whole model volume, which reflects the part's spatial occupancy. Due to the clear equation of superquadric, it is simple to compute the part volume represented by superquadric [6].
- Elongations FU_{elong}: It consists of two elements $FU_{elong1} = \frac{a_{\max}}{a_{med}}$ and $FU_{elong2} = \frac{a_{med}}{a_{\min}}$, in which $a_{\max}, a_{med}, a_{\min}$ are the maximal, medium and minimal superquadric size parameters of volumetric part along X, Y, Z axis (among a_x, a_y, a_z) respectively.

2.2 Connection structure at topological level

- Part connection number FU_{Pnum}: It is the number of parts connecting with the current part.
- Connections $FB_{connect}$: This feature represents the connection relationship of one part with other parts of the model. The $FB_{connect}$ is denoted by a connection relationship matrix, where the row number is the part label and the elements in this row are the part labels connecting with the current part, other elements are assigned -1.
- Connection type $FB_{contype}$: It reflects the number of intersections between two parts, which corresponds to $FB_{connect}$.

2.3 Experiment on structural description extraction

Fig.2 shows one of some experiments on extracting the structural shape description of 3D objects, including the individual part shape features and the global topological structure.

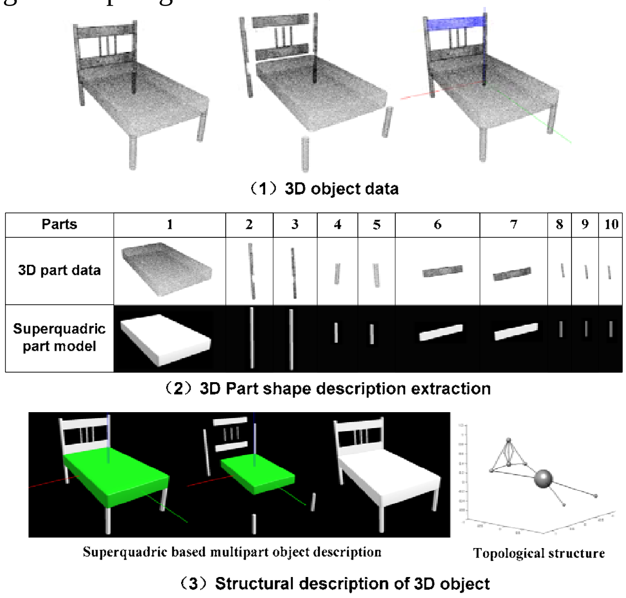

Fig.2 Structural description extraction of 3D object – bed

3 Superquadric based Multipart Object Reconstruction

A superquadric based visual multipart object reconstruction subsystem AVRMODEL is developed, on which 3D models with different part number and different part shape can be constructed in realtime and interactive manner. For the reconstruction subsystem, the left panel is for parameters control, and the right is the viewport of 3D model. As shown in Fig.3, first, the individual part is created and edited by inputting and adjusting parameters; then all the created parts are assembled together by adjusting the position and orientation parameters; finally, the realtime operation and interactive control can be implemented in 3D viewport. Additionally, the existing models can be read and reedited for fast creating new 3D models, which improves the modeling efficiency greatly.

Fig.3 is the running interfaces of the visual 3D model reconstruction subsystem; Fig.4 demonstrates some multipart object reconstruction instances.

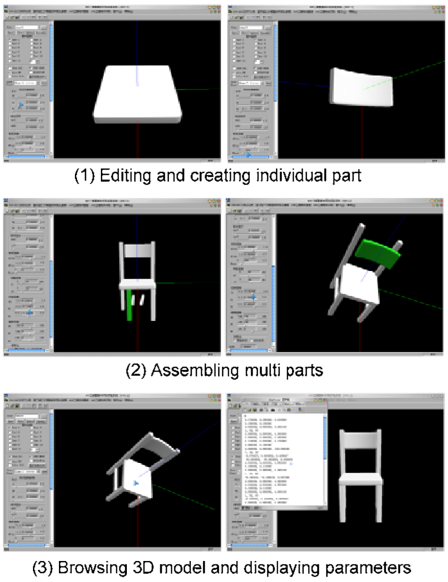

Fig.3 Running interfaces of multipart object reconstruction subsystem

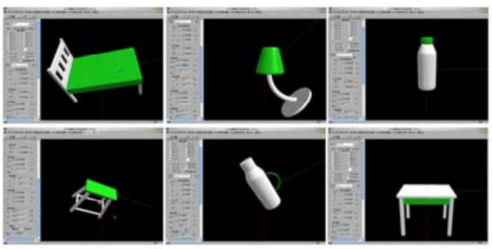

Fig.4 Instances of multipart object reconstruction

4 3D Model Library Construction and Organization

In order to implement 3D object recognition, a 3D model library is built in the paper. We construct a number of 3D models for each object class according to the actual diversity of the class, and the models within one object class are similar but still exhibit significant variation among exemplars. One object class is thus a set, in which each element is a 3D model denoted by a feature vector. For efficient 3D object recognition, 3D model library is organized hierarchically.

Fig.5 illustrates the hierarchical organization structure of 3D model library. This way of organization and management has many advantages: (1) the 3D model library's completeness and realities of representing object categories are improved greatly, which is not only efficient for recognition computing, but also closer to human perception on 3D objects in the real world; (2) inserting or deleting 3D model or object class in 3D library does not lead to any change of the recognition system structure; (3) it is potential and beneficial to the object recognition research based on statistical learning methods.

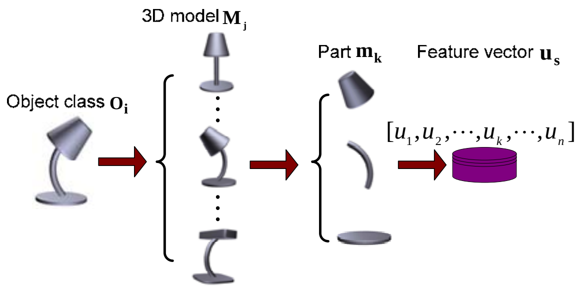

Fig.5 Hierarchical organization of 3D model library

5 3D object recognition

We are given a set of unknown object parts represented by structural description features, and also given a set of object classes, where each object class contains some prestored 3D models. In the paper, the recognition of 3D objects can be regarded as the match between unknown object and models, which can be formulated as determining the correspondences subject to certain matching constraints between object parts and model parts. One most well-known algorithm for high-level match in computer vision is the Interpretation Tree algorithm, which searches a tree for consistent model-to-data matching pairs.

The presented recognition method with improved interpretation tree in this paper consists of two stages, i.e. the improved constrained interpretation tree search and the shape similarity measure computation. In the tree search stage, both the efficient constraints forced by the features in Section 2 and the tree search rules are defined to fast find possible consistent interpretations between unknown object and 3D models.

Based on the obtained consistent interpretations and the presented structural shape features, a similarity measure computation algorithm is then developed to achieve matching results with similarity ranks. The algorithm consists of the following:

1) Similarity measure between parts of unknown object and 3D model.

2) Whole match and partial match: whole match focuses on the global shape similarity between unknown object and 3D model; while the part number of unknown object is less than that of 3D model, i.e. the object is superimposed on the model, there also exists partial match emphasizing the local accurate correspondence. In the whole match or partial match, the model similarity measures between unknown object and 3D models are computed.

3) Focus match with the labeled key parts: In focus match, the different key parts of the same unknown object may be labeled and all the models containing the corresponding key parts can be matched with the model similarity measures.

4) Classification: The unknown object is classified by the calculated model similarity measures in step 2) or step 3). First, select all the models with similarity measures higher than a predefined threshold, the class similarity measures are computed by averaging the model similarity measures between all the selected models of one object class and the unknown object; second, the unknown object will be classified into the object class that has highest class similarity measure.

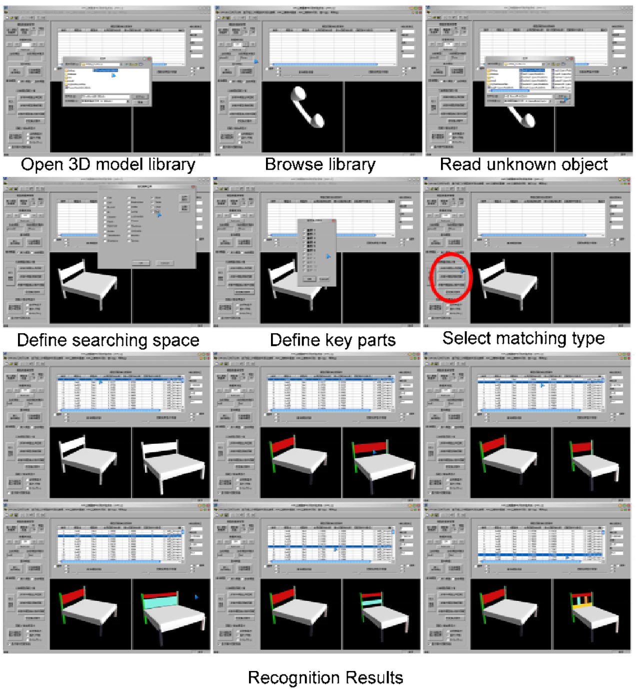

Fig.6 3D object recognition subsystem

Fig.6 shows the running interface and experiment of the developed 3D object recognition subsystem. The results contain three components: the shape similarity measure values and ranks between unknown object and 3D models in library, the object class that unknown object is assigned to, and the correspondences between the parts of unknown object and 3D model, which are denoted by different colors in two corresponding viewports.

6 Conclusion

In this paper, a superquadric based integrated 3D obejct reconstrucion and recognition system is described, where three key subsystem are developed and some experiments are carried out. The system can achieve the conversion from real 3D object data to virtual models and interpretation.

Acknowledgments:

This work is supported by the National Grand Fundamental Research 973 Program under Grant 2006CB303105, the University Research Foundation No.K06J0170, No.JS2005J0503, and the National Natural Science Foundation of China under Grant 60441002.

References:

[1] J. Krivic, F. Solina, Part-level object recognition using superquadrics, *Computer Vision and Image Understanding*, Vol.95, No.1, 2004, pp.105-126.

[2] H. Daniel, K.Anuj, et.al., Parts-based 3D object classification, *IEEE Conference on Computer Vision and Pattern Recognition*, 2004, pp. 82-89.

[3] I. Biederman, Recognition-by-Components: A theory of human image understanding, *Psychological Review*, 1987, pp.115-147.

[4] F. Solina, R. Bajcsy, Recovery of parametric models from range images: the case for superquadrics with global deformation, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.12, No.2, 1990, pp.131-147.

[5] W. W. Xing, W. B. Liu, B. Z. Yuan, Superquadric Similarity Measure with Spherical Harmonics in 3D Object Recognition, *Chinese Journal of Electronics*, Vol.14, No.3, 2005, pp.529-534.

[6] A. Jaklic, A. Leonardis, F. Solina, *Segmentation and recovery of superquadrics*, Kluwer Academic Publishers, 2000.