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Cross-class 3D object synthesis guided by reference examples

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ABSTRACT

Re-combining parts of existing 3D object models is an interesting and efficient technique to create novel shape collections. However, due to the lack of direct parts' correspondence across different shape families, such data-driven modeling approaches in literature are mostly limited to the synthesis of in-class shapes only. To address the problem, this paper proposes a novel approach to create 3D shapes via re-combination of cross-category object parts from an existing database of different model families. In our approach, a reference shape containing multi-functional constituent parts is pre-specified by users, and its design style is then reused to guide the creation process. To this end, the functional substructures are first extracted for the reference shape. After that, we explore a series of category pairs which are potential replacements for the functional substructures of the reference shape to make interesting variations. We demonstrate our ideas using various examples, and present a user study to evaluate the usability and effectiveness of our technique.

1. Introduction

Creating large-scale man-made 3D shape collections is essential for modeling the virtual world. However, manually assembling such shapes would be tedious and extremely labor-intensive, especially when the target model to be designed is complicated in its structure and function.

Recently, several approaches [1–3] have been proposed to effectively synthesize 3D shapes of a single family through reusing existing object parts. In these approaches, a single-class shape collection is fed into the algorithm, which interchanges the parts among different 3D models to generate a large collection of novel shapes. However, although such approaches can achieve promising results in certain scenarios, the diversity of the synthesized shapes might be limited without attention to inter-class information. The challenge in cross-class 3D object synthesis is the lack of direct parts' correspondence: naively interchanging shape parts can easily destroy the shape plausibility. Moreover, for the probabilistic approaches [2,3], it is hard to collect enough cross-class models for training.

In this paper, we present an approach to synthesize shapes using parts from a variety of model families under the guidance of a reference shape. The reference shape is required to have composite man-made designs with multi-functional components and complicated structures. Given the reference shape and a database of pre-segmented shapes from multiple categories, we first summarize their part structures using *relation graphs*. For each part of the shapes, its structural context is then identified by considering the related parts which have a support relation. We denote the sub-graph constituted by a part as well as its structural context as a *substructure*. We notice that certain substructures are more critically related to the actual functionality of the models (e.g., a chair's seat and its support, a sunshade's awning and its support, etc.). Such a substructure is defined as the *functional substructure* of the shape. Then we use an *Harmonic Shape Descriptor (HSD)* based descriptor to match the substructures between the database shapes and the reference shape aimed to analyze the constituents of the reference shape (Section 4). The obtained correspondences could be leveraged for exploring potential component replacements based on a category suggestion algorithm for synthesizing novel shape collections (Section 5).

To validate the effectiveness of the proposed approach, we collect a database consisting of 15 model families, and conduct experiments on 9 complex reference shapes. The obtained results and an additional user study show that cross-class synthesis of novel 3D shapes could be effectively performed by reusing the composite design of a complex reference model.

2. Related work

Assembly-based modeling: Recently, as model collections grew, researchers have focused on data-driven content creation. Modeling

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by example [4] provided an approach to create new objects by cutting and compositing parts in a 3D database. Chaudhuri and Koltun [5] provided suggestions for 3D modeling benefited from customized examples that stimulate creativity. Shen et al. [6] presented an approach which converts scanning data to 3D models with labeled semantic parts. Tang et al. [7] presented a surface deformation method with local and nonlocal guidance, which supports mesh merging. In another approaches, probabilistic models were learned for shape synthesis [2,3]. Jain et al. [8] proposed a system to create new shapes by blending between shapes from a database. Smart variations [9] proposed a geometric approach based on substructure to create functionally plausible model variations. The above methods achieve impressive results in shape synthesis with in-class shapes, or shapes across the categories which have similar structures. While it is still a hard work for synthesizing the shapes from the categories with different structures and functions. We leverage the reference shape to inspire shapes from such categories synthesizing novel multi-function composite models.

Shape analysis: Various approaches have been proposed to extract high-level hierarchies of shapes. Wang et al. [10] introduced symmetry hierarchy of man-made objects to represent a 3D model by a symmetry-induced, hierarchical organization of the model's components. Semi-supervised learning method [11] used users' assists in the co-analysis by providing inputs iteratively to constrain the system. The survey [12] explored numbers of methods of extracting geometric symmetries and exploiting high-level hierarchies for a wide variety of geometry applications. In our work, we analyze the shape taking advantage of each component's structure context. Then we employ an analysis algorithm to recognize the functional substructures of the reference shape.

Exploring shape collections: With the fast growing of 3D databases that are available on the Internet, efficiently exploration of these shapes has becoming a new task for researchers. Attene et al. [13] proposed to perform segmentations and annotations of 3D surface meshes through ontology. Recently, more approaches have been extracted for organizing and exploring a collection of 3D shapes, such as deforming a base template [14], using fuzzy correspondences [15], and utilizing a qualitative analysis [16]. Besides, some works analyzed the relevancy between image and shape collection. For example, Averbuch-Elor et al. [17] proposed a distillation algorithm for image collections which supports 3D applications like the construction of a 3D abstract model. Zhou et al. [18] used a single image to model a 3D garment. Su et al. [19] added depth to an image of an object by exploiting a collection of aligned 3D models of related objects. Huang et al. [20] proposed to jointly analyze a collection of images of different objects along with a smaller collection of existing 3D models. In our work, we employ a category group suggestion algorithm to explore the matched shape categories, which can be used to replace the certain substructures of the reference shape to synthesize novel composite models.

3. Overview

As shown in Fig. 1, our method consists of an offline stage and an online stage. In the offline stage, we pre-analyze the 3D shape collections to facilitate computation. When online, an external reference shape is fed into our system with its design reused to synthesize novel composite models. We will briefly describe these two stages in the rest of this section.

3.1. Offline database pre-processing

The database of shape collections we use in this paper contains 15 categories (i.e., bathtubs, beds, benches, bikes, boats, chairs, dressers, cribs, lamps, pavilions, pianos, sofas, sunshades, tables and trolleys) collected from [21–23]. We assume that all the models in the database have been pre-segmented into meaningful parts. The state-of-the-art segmentation algorithms [13,11] work well for this purpose. Note that we do not require the semantic labels of parts or their correspondences be available.

Our approach requires that 3D models have approximately correct sizes as those presented in daily life. It is critical for our algorithm since some geometric features are deduced from the relative scales between parts. Besides, the method [24] is used to make sure that models have upright orientations. We also align the shapes globally to a common orientation to facilitate subsequent part synthesizing [9]. Finally, each shape is represented by a spatial relation graph, whose nodes and edges are formed by parts and their support relations, respectively. Note that the graph is directed since the support relations are not commutative.

3.2. Online shape synthesis

Given the input reference shape, the online shape synthesis consists of two main steps, namely, functional substructure matching and design reusing.

Functional substructure matching: This step aims at finding functional correspondences between the reference shape and a database shape. To this end, the input reference shape is first manually segmented into meaningful parts and represented by a relation graph as similar as in preprocessing database shapes. Afterwards, we seek for the substructures (i.e., components and their structural contexts) which are matched between the database shapes and the reference shape by a descriptor encoding shape geometry and support type. The matched substructures what we called *functional substructures* can be leveraged to describe the functional constituents of the reference shape, and establish the correspondences between the database shapes and the reference shape in part-level. The details of this step are summarized in Section 4.

Design reusing: After the correspondences between shapes are obtained, we reuse the design of the reference shape to inspire synthesis of novel cross-class models. Specifically, a suggestion algorithm is employed to encourage existing shapes from different categories to participate in synthesizing. Moreover, we adopt structure evolution to further diversify the created shapes. We refer the reader to Section 5 for more technical details.

4. Functional substructure matching

In this section, we introduce how to extract the functional substructures of the reference shape and database shapes with structural context descriptor, as well as establish their correspondences. We first add the support relation to the shape's related graph to get the each components structural context (i.e., the structurally related parts) and every substructure which consists of a component and its structure context. Then we use the structural context descriptor to analyze the shape and support type of each component, and match the similar substructure in shapes from the database to explore the functional substructure of the reference shape.

4.1. Functional substructure

For man-made shapes, some components are more critically related to the actual functionality of the models. Zheng et al. [9] leverage mutual (geometric) relations among different arrangements of shape parts to identify component-level compatible functional substructures. Since functionality is rarely explicitly