Computer-Aided Design 74 (2016) 45–54

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Assembly-based conceptual 3D modeling with unlabeled components using probabilistic factor graph☆

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ARTICLE INFO

Article history:
Received 20 October 2014
Accepted 26 October 2015

Keywords:
Conceptual 3D modeling
Factor graph
Assembly-based modeling

ABSTRACT

This work presents a novel and intuitive assembly based 3D modeling interface to support conceptual design exploration activities. In the presented modeling interface, unlabeled segmented components of the objects are assembled to create new 3D models. The development of the interface is motivated by two aspects. First, the focus is on novice users since they stand to gain the most from intuitive interfaces. Second, the intent is on creative reuse of a growing number and variety of 3D models available on vast online repositories like Turbosquid and Trimble 3D warehouse. Specifically, we have devised an automated component suggestion algorithm based on a probabilistic factor graph. This algorithm helps the user to easily browse and select components from a database that are most compatible with the current state of 3D models being assembled. The component suggestion algorithm incorporates various aspects such as shape similarity, repetitions of shapes, and adjacency relationships. Our new suggestive interface overcomes several limitations of traditional CAD interfaces by helping the users to quickly create and explore new conceptual designs. We present results on the conceptual design of several products.

1. Introduction

Computer Aided Design (CAD) is omnipresent in multipleindustrial domains such as automotive and aerospace. In terms of market size, the CAD market is one of the established, largest, and growing areas in software markets with a market cap of $7 billion in 2011 [1]. CAD is used for representation, knowledge management, communication, and visualization of design information at various stages of engineering design process. CAD plays a significant role in all the stages of design process. If the past is prologue, the role that CAD tools play in the engineering design value chain will likely to grow in scope, scale, and complexity. Although, the currently available CAD tools allow significant degree of control in 3D shape creation by requiring the user to specify exact shape parameters in a structured manner, they are not well suited for early conceptual design exploration and ideation activities.

For conceptual design, the current CAD systems have two major disadvantages: (1) inability to reuse existing design solutions as inspiration and (2) assumption that users know exact parameters and geometric details of the 3D model. Conceptual design exploration process is a creative and open-ended process in which designers initially do not have a clear mental picture of what their design looks like. They only have a rough idea of the design and through unexpected changes of direction during the generation of solution components they come up with the final solution concept. Another observation in conceptual design is that users usually derive inspiration from elements of existing designs and combine them with some new ideas to generate innovative concepts. Deriving inspiration from existing design accelerates the design process and enhances the creativity of the users. Therefore, CAD systems for conceptual design exploration should not only allow easy and intuitive (unexpected change in goal) exploration of possible design space but also enable one to reuse existing solutions as inspiration. Additionally, such interfaces should be simple to interact with and should not rely on the user providing geometrically accurate information.

In this paper, we present an assembly based modeling interface for conceptual design exploration. A key advantage of assembly based modeling system is that users focus on component selection and assembly rather than the creation of new geometry from

☆ This paper has been recommended for acceptance by Hayong Shin.

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http://dx.doi.org/10.1016/j.cad.2015.10.002
0010-4485/

scratch. The modeling interface suggests the modeler with possible additional components for the current shape through an unsupervised component suggestion algorithm. The component suggestion algorithm is based on probabilistic factor graph and leads to considerable speedup in conceptual shape synthesis. We used shape similarity, size, repetition, and adjacency relation to define factors for the factor graph. These factors help to determine plausible components from a repository of models that could then be assembled to create designs. The marginal probability distribution computed from the factor graph is used to score and rank components. The ranked component list is provided to the user within the interface as sources of suggestions for faster, intuitive, and easy shape synthesis.

Overall, this paper makes following contributions:

1. A probabilistic factor graph based model that encapsulates the relationship between unlabeled components in a shape database.
2. An unsupervised dynamic component suggestion algorithm that guides the user by suggesting most relevant components at a given stage of assembly.
3. Development of a novel assembly based CAD modeling interface to guide a user to perform conceptual design assemblies.

In next section, we discuss related works on component suggestion algorithms and assembly based design systems. A brief overview of the whole approach is given in Section 3. Section 4 describes processing steps on database 3D models to compute various attributes and relationships. In Section 5, the factor graph is described in detail. Experimental results are presented in Section 6. Finally, possible future applications and limitations of our approach is discussed in Section 7.

2. Related work

The techniques pertinent to assembly based design systems and design suggestion algorithms are briefly reviewed below.

Assembly based design systems

Many research papers focus on reusing existing 3D models to synthesize new models. Kreavoy et al. [2] developed a system that can swap similar components of different models in a point-and-click way using precomputed compatible segmentation. However, this approach is restricted to models with similar shape or structure. Kanai et al. [3] described techniques for manually inserting arbitrary components into a target surface by: (1) first cutting a suitable hole in the target, (2) aligning the component with the hole, (3) defining a boundary correspondence, (4) and then finally blending the two surfaces. Funkhouser et al. [4] tried to automate the aforementioned steps via "intelligent scissor" cutting, ICP alignment, and automatic generation of smooth fillet surfaces. Various methods based on Poisson [5,6] and bi-Laplacian [7,8] are proposed to generate smoother transitions and handle differences in scale.

Another type of method proposed by Hassner et al. [9] uses graph cut based tool to combine components from different models. To increase user's participation, SnapPaste interface [10] can automatically "snap" a component to a suitable target hole where the user would like it to be. A soft-ICP alignment parameterized by the cursor speed is used to drive the snapping, and a smooth blend surface is geometrically obtained. Note that, for each of aforementioned tools, the user must specify a global orientation for the component to be inserted as well as the target hole. Similarly, MeshMixer system [11,12] adopts a "drag-and-drop" type interactive tool to automatically perform global orientation using a parameterization of the component boundary, which is then projected onto the target surface via local parameterization. As all the computations are efficient, the user can interactively drag the component across the target surface with real-time visual feedback. *In our implementation, we use CGAL library* [13] *with Boolean union operation for component assembly interface*. Note that the users have the freedom to save the assembled models as a set of disconnected components, or they could also choose to use Boolean union operation to merge the components into one unified model.

Component suggestion algorithms

An important step in assembly based modeling is the selection of relevant components to be assembled into a user specified base model. A key challenge in this task is to select relevant and plausible components from a given repository of shapes, usually with thousands of 3D models. To address this problem, component suggestion algorithms have been proposed. These algorithms speed-up component selection process by suggesting components with high probability based on certain criteria.

As a pioneer of assembly based 3D modeling, Funkhouser et al. [4] proposed an example based modeling approach allowing the user to search a model library and assemble desired models from segments of retrieved shapes. Their method requires users to search for the particular component they would like to add. Talton et al. [14] presented a data-driven approach that supports open-ended 3D modeling. The key aspect of their method is that it requires the existence of a parametric space from which models are drawn. Other research works similar to ours are [15–18]. In 2010, Chaudhuri and Koltun [15] proposed a data-driven approach that gives suggestions for additional component based on model's current geometrical attributes.

Chaudhuri et al. [16] improved the results of their previous work by introducing Bayesian network to represent semantic and stylistic relationships between components. Kalogerakis et al. [17] further improved the results by adding consideration of latent variables in the probabilistic graphical model. Chaudhuri et al. [18] described a modeling system that achieve high-level design goal by using semantic attributes expressed in linguistic terms. *Although, the aforementioned approaches provide useful suggestions, the major disadvantage of these methods is that they require labeled segmented components.* The component labeling in a supervised framework becomes very tedious in the case of a database with high numbers parts and shapes. Label-based methods have scaling disadvantages. In case of large databases, labeling is a significant overhead. In our paper, we address this disadvantage. Additionally, a labeling based framework will require a user to label an alien/new part for which user wants to generate a suggestion list. A novice user without the knowledge of labeling schema might label the part wrong! In such cases, the labeling based approach could have additional disadvantages. In this paper, we propose a factor graph based component suggestion algorithm that does not require labeled components to generate suggestions and the user is free to interact with the system to create conceptual designs.

3. Overview

Using a diverse set of 3D models in the database, our method generates component suggestion list to guide users during assembly based modeling process. Users can interactively combine components from the suggestion list in the developed modeling interface (Fig. 1). Our interface allows users to add components from any alien source as well. The suggestion list automatically updates every time a component is added to the assembly.

We propose a probabilistic factor graph approach to identify most relevant components in the database to generate the overall