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Automatic generation of LEGO building instructions from multiple photographic images of real objects ☆

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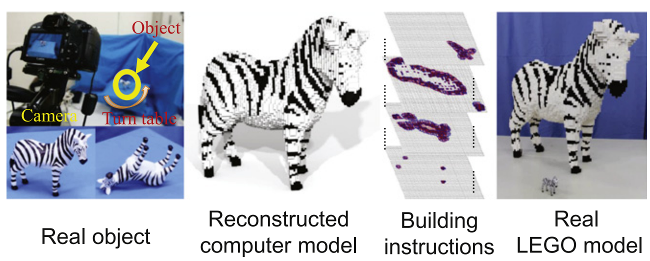
HIGHLIGHTS

- Even beginners are able to build realistic complex LEGO models.
- Our system allows reconstruction of portable large scale models with color information.
- Easy adjustment of the trade-off between model strength and the total number of bricks is possible.

GRAPHICAL ABSTRACT



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ABSTRACT

We introduce a system to reconstruct large scale LEGO models from multiple two dimensional images of objects taken from different views. We employ a unit voxel with an edge length ratio of 5:5:6 for the shape from silhouette method that reconstructs an octree voxel-based three dimensional model with color information from images. We then convert the resulting voxel model with color information into a LEGO sculpture. In order to minimize the number of LEGO bricks, we use a stochastic global optimization method, simulated annealing, to hollow the model as much as possible but keep its strength for portability. Several real complex LEGO models are provided to demonstrate the effectiveness of the proposed method.

1. Introduction

LEGO has attracted many people, as a toy, as a hobby, even as an educational tool for all generations all over the world. However, the design and construction of large scale LEGO models is not easy for beginners. Here we define "large scale" models as those consisting of 1000–10,000 bricks. The upper limit comes from the portability of the models. We present a method for reconstructing a LEGO model from several two dimensional (2D) images of a complex object taken from different views so that even beginners are able to build realistic complex models. The data acquisition system consists of a camera on a tripod and a computer-controlled turntable, as shown in Fig. 1. We employ the shape from silhouette (SFS) method that reconstructs an octree voxel-based 3D model with color information from images. In addition, we employ a unit voxel with an edge length ratio of 5:5:6, which is the ratio used for a unit LEGO brick, instead of the 1:1:1 ratio used in the traditional SFS method. The resulting solid voxel model, consisting of unit voxels with edge length ratios of 5:5:6, are then converted to a hollow LEGO model consisting of larger bricks with interior supports based on the stochastic global optimization method, simulated annealing (SA). The hollowed LEGO models are in average 30% lighter than the solid ones and have strength for portability.

This paper makes the following contributions:

- We introduce a novel system to reconstruct portable large scale LEGO models with color information from 2D images of

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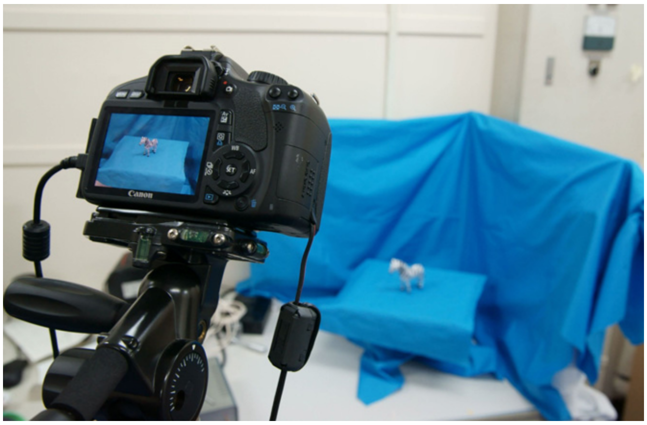

Fig. 1. Data acquisition system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

complex objects using SFS and by exploring the search space using SA.

- Our algorithm allows for easy adjustment of the trade-off between model strength and the total number of bricks used for construction. This leads us to design a lighter model without losing its strength for portability.

The remaining part of this paper is organized as follows. In Section 2, we review related work. In Section 3, we present a method to reconstruct a solid LEGO model consisting of unit LEGO bricks from several 2D images. The solid LEGO model is converted to a hollow model consisting of larger bricks using SA in Section 4. The energy functionals used in the SA are discussed in Section 5. In Section 6, we demonstrate the effectiveness of our method using some complex examples. Finally, we conclude the paper in Section 7.

2. Related work

Kim et al. [1] provided an excellent review of previous work on automated LEGO assembly construction. They reviewed the problem definition, formulation, and a variety of approaches to solve the problem. Readers are referred to the references therein.

Silva et al. [2] presented a method to voxelize surface models and then convert them to LEGO representations that are rendered using realistic graphics techniques. However, the connectivities between bricks were not presented.

Gower et al. [3] suggested six important factors related to the connectivity of bricks and discussed implementation strategies for several penalty functions that can be incorporated into SA; however, the ideas presented in the paper were not implemented but left for future studies.

Funes and Pollack [4] integrated a model of the physical properties of LEGO structures with an evolutionary process based on a genetic algorithm (GA) that freely combines different shapes and sizes into structures that are evaluated by how well they perform the desired function. Their focus was on buildable designs, and the method was applied to the construction of 2D bridges, scaffolds, and cranes.

Zijl and Smal [5] discussed the modeling of the LEGO construction problems using cellular automata with emphasis on efficient cluster evaluation. A cellular automaton is a collection of "states" on a grid of a specified shape that evolves through a number of discrete time steps according to a set of rules based on the states of the neighboring cells [6]. However, the method cannot handle colored models.

Testuz et al. [7] voxelize a 3D mesh, and merge the resulting voxels to form larger bricks. They then analyze and repair structural problems using a graph-based algorithm and finally output a set of building instructions. They also extended the system so that hollow models can be constructed while fulfilling the limits of the number of bricks of each size. However, hollowing the models, satisfying the brick type numbers, and the usage of colored bricks were not included in the optimization pipeline.

Ono et al. [8] applied the conventional scan line method to generate the voxel representation from the polygonal data, and then deleted the internal voxels. Finally, they adjusted the tree structure, which they refer to as a legograph, to convert the voxel representation into a LEGO brick representation based on the greedy algorithm. However, there are cases where the connection between bricks is not guaranteed.

Zometool models, which are different from LEGO models, are also recreational model assemblies for use at home. Zimmer et al. [9] introduced an algorithm that approximates 2-manifold surfaces with Zometool models. Starting from a rough initial approximation, the Zometool operators are iteratively selected within a stochastic framework guided by an energy functional measuring the quality of the approximation.

In summary, none of the previous work generates building instructions of portable, complex hollow LEGO models in color from multiple 2D images of real objects.

3. Reconstruction method

Most of the research on LEGO construction assumes that the triangular mesh model or the voxel model associated with color information is already given. However, this assumption may not always be applicable. In this paper, we employ recent advances in computer vision and geometric modeling techniques to facilitate the reconstruction of a voxel model from images of objects and generate building instructions for LEGO models.

3.1. Data acquisition system

Our data acquisition system consists of a camera (EOS Kiss X4) placed on a tripod and a computer-controlled turntable, which is considerably more cost-effective than a laser scanner. We use the SFS method [10–12], which constructs an octree voxel-based 3D model from silhouette images of an object captured during rotation on the turntable. The camera is fixed, so it can only capture information in the scene that is visible to the camera during the rotation of the object. Thus, complete object information has to be acquired by inverting the object, which is then recaptured via another round of rotations [13]. Using the two sets of object silhouette images collected during rotation (see Fig. 2(a)–(c)), we can reconstruct a complete voxel model, as shown in Fig. 2(d).

We have improved the method by Nanya et al. [13], which integrates the two incomplete voxel models by reducing the errors in the system, namely, camera calibration errors, silhouette extraction errors, and errors caused by the iterative closest point, so that we can simply apply the set intersection of the two voxel models to integrate them into a single voxel model.

3.2. Scaling effect

The relation between the voxel size and LEGO unit brick size can be determined as follows. Let us denote the characteristic linear dimension of an object as L. If we denote the length of the root-voxel as L, and the octree depth in SFS as k, then the length of the smallest unit voxel is $L/2^k$. If the side length of a unit LEGO is h, then the reconstructed LEGO model has a size of $2^k h$. Fig. 3 shows a zebra model with three different octree depths ($k = 6, 7$, and 8). Because the horizontal length of the unit LEGO brick is $h = 8$ mm, the horizontal length of the zebra model will be approximately 512, 1024, and 2048 mm. Because our method is based on the SFS method, all