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Natural lines inspired 3D shape re-design

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ABSTRACT

We introduce an approach for *re-designing* 3D shapes inspired by natural lines such as the contours and skeletons extracted from the natural objects in images. Designing an artistically creative and visually pleasing model is not easy for novice users. In this paper, we propose to convert such a design task to a computational procedure. Given a 3D object, we first compare its editable lines with various lines extracted from the image database to explore the candidate reference lines. Then a parametric deformation method is employed to reshape the 3D object guided by the reference lines. We show that our approach enables users to quickly create nontrivial and interesting re-designed 3D objects. We also conduct a user study to validate the usability and effectiveness of our approach.

1. Introduction

Reshaping the existing 3D objects enables interesting shape variations. However, designing an artistically creative and visually pleasing reshaped model remains challenging, since it always requires creativity and inspiration of the human artists or designers. Some artists specialize in finding inspiration from nature. For example, the wings of butterfly are popular elements in the design of jewelry, handbag or even chair. This motivates us to study how to use natural elements for easy re-design of 3D shapes.

In recent years, extracting 3D objects from a single image or sketch has been an active research topic [1,2]. Shapes generated by such approaches are based on 3D editable primitives (e.g., cylinder, cuboid). Reshaping such editable primitives is able to produce various novel designs only if appropriate deformation targets are given. Some techniques aim to leverage images or sketches as the targets to reshape the existing models [3,4]. We observe that, rather than directly using the target of the same kind, various cross-class natural objects can also provide proper targets for novel designs. As shown in Fig. 1, a 3D lamp model is re-deigned inspired by a pear and a pagoda. In the other example, a folding fan and a snake guide a 3D chair model to create a novel shape design.

We propose an approach to explore proper lines (i.e., the contours and the skeletons) in nature from the photographs of various kinds of objects, and then to utilize such lines for the re-design of 3D shapes. In this process, an image database which consists of various natural objects provides the contours and the skeletons. For an input 3D shape, we first extract its editable lines (i.e., axis, outline and cross-section) of its primitives. Aiming at exploring the proper lines to guide the primitive reshaping, a suggestion mechanism is then employed to suggest both the lines similar to the editable lines and the lines which are diverse, namely, dissimilar but also suit for reshaping guidance. In this manner, certain natural lines are suggested and then used to establish the point-to-point correspondence with the editable lines in the 3D primitives. Finally, a parametric deformation method is employed to produce novel 3D objects inspired by the suggested natural lines.

We provide an easy-to-use interactive tool to assist the user for re-designing existing 3D models. The user only needs to choose the editable region in the 3D object, and

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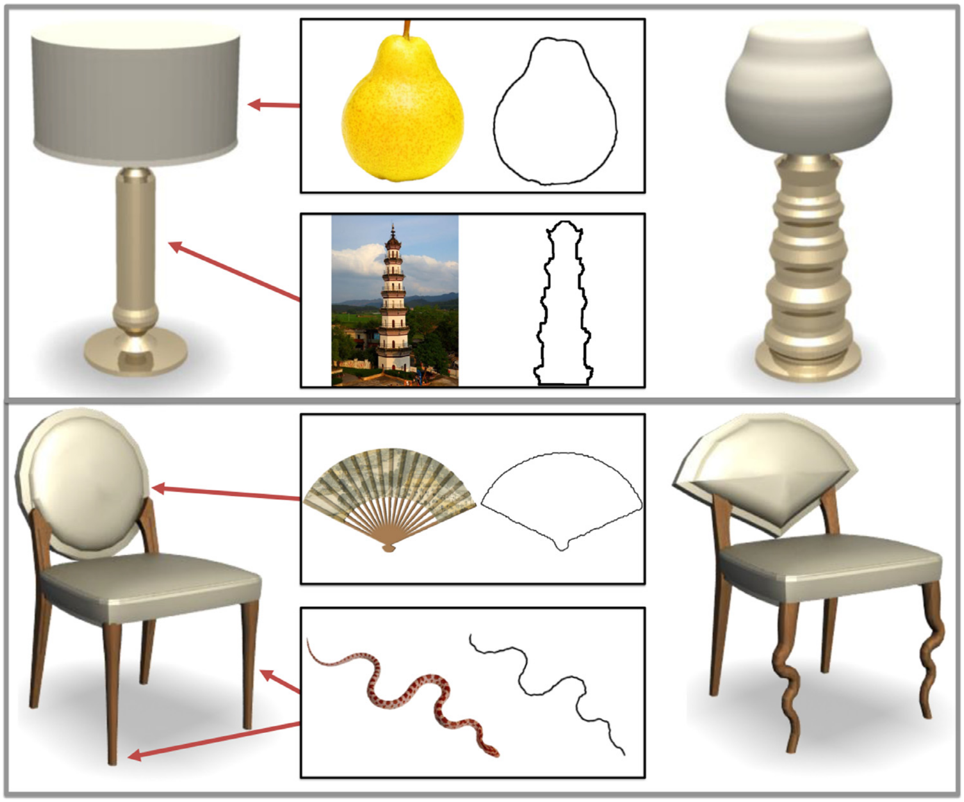

Fig. 1. 3D shape re-design. Given a 3D shape, the candidate images are suggested based on the editing parts. Lines extracted from the images provide inspirations for reshaping the corresponding parts to enable novel shape variations.

selects one of the suggested candidate images that provide the reference lines. Then the re-designed object is produced within less than one minute. We demonstrate the effectiveness of our approach by conducting experiments on various common 3D objects and an image database, leading to various interesting, nontrivial re-designed shapes.

2. Related work

In this section we first review the existing works on sketch interpretation. Then we examine the relevant works on sketch based modeling and shape editing techniques.

2.1. Sketch interpretation

Several approaches have been developed in recent years to automatically or interactively extract a sketch from an image. The state-of-the-art edge detectors (e.g., [5]) automatically produced contour from the image. To interactively extract the sketch, *ShadowDraw* [6] was proposed to guide the freeform drawing of objects. *EZ-Sketching* [7] provided an image-guided drawing interface using a tracing paradigm and automatically corrected sketch lines roughly traced over an image. Besides, other works focused on the sketch segmentation [8] or retrieval [9] inspire us to explore the proper lines for shape re-design. In our work, we use salient object detection to extract lines from the images, and explore the appropriate lines based on a metric distance which balances the similarity and diversity of the suggested lines.

2.2. Sketch based modeling

Sketch based modeling is an easy-to-use technique for novice users to model a shape. Xie et al. [4] presented an interactive *Sketch-to-Design* system, where the user sketches prominent features of parts to combine. Zou et al. [10] proposed to reconstruct polyhedral objects from single-view line drawings. Zhou et al. [11] utilized single images to model 3D garments with the contour as the constraint. Besides, sketches can also be used for scene modeling. For example, *Sketch2Photo* [12] is able to compose a realistic picture from a simple freehand sketch annotated with text labels. *Sketch2Scene* [13] automatically turned a freehand sketch drawing inferring multiple scene objects to semantically valid, well arranged scenes of 3D models.

Our work is inspired by [1] and [2], which presented interactive techniques for modeling and manipulating simple 3D objects from sketches. Their works provide editable 3D models which can be used for shape re-design in our approach. In our work, we focus on how to use the suggested natural lines to make shape variations, and we also provide a tool for 3D shape re-design.

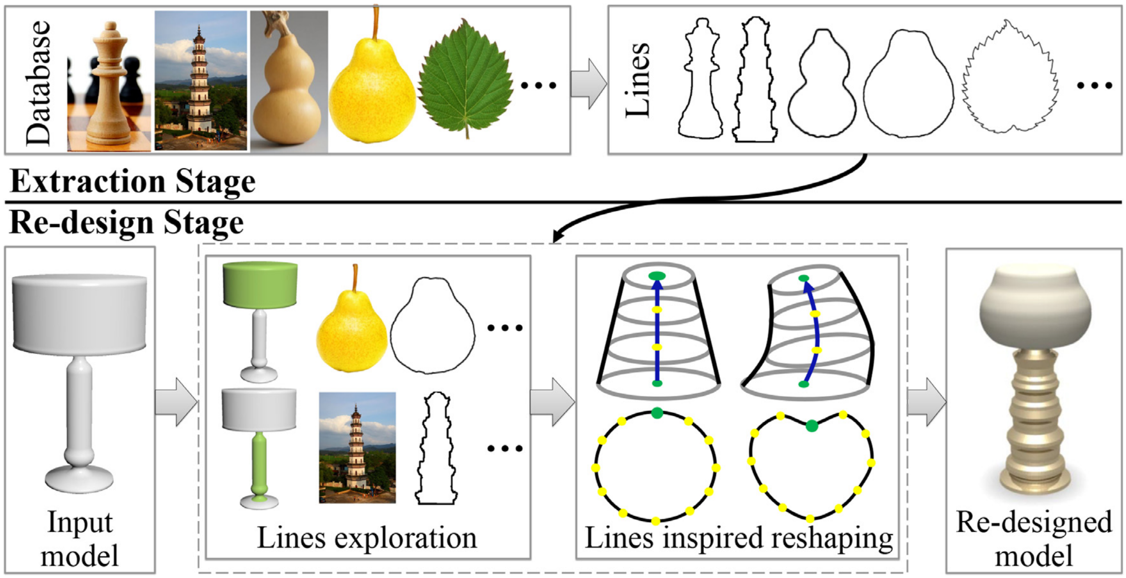

Fig. 2. An overview of our approach.

2.3. Shape editing

Shape editing has been widely studied to create shape variations. The analyze-and-edit approaches [14,15] used the relations between shape parts and features to constrain the shapes during editing. Lin et al. [16] proposed structure preserving retargeting of irregular 3D architecture models by decomposing the input model into a set of 1D structures. Tang et al. [17] leveraged the local and nonlocal guidance as the constraints for 3D shape surface deformation. Sweep-based deformation methods (e.g., [18]), which use the sweep surface for shape deformation by editing the axis and cross-section, are similar to our parametric deformation method. In our work, we focus on how to leverage the suggested lines for reshaping by editing the sweep-based primitives. Besides the axis and cross-section, our method can also reshape the outline of the 3D shape to produce more interesting variations.

3. Overview

As illustrated in Fig. 2, our approach comprises an off-line extraction stage to get the contours or skeletons from the image database, and an on-line re-design stage to explore proper natural lines and then reshape the input objects.

Our current image database consists of various natural objects such as animals, plants, etc, and be easily expanded. It also contains some man-made constructions, foods, etc. In the extraction stage, we first employ the salient object detection method [19] to segment the foreground objects. The segmented objects are then classified into two groups based on their symmetry. After that, the objects which are reflectively or rotationally symmetrical provide their contours, while the asymmetrical ones provide their skeletons.

Afterwards, we extract the axis, outline and cross-section of the editable primitives from the input shape (see Fig. 3), and then use these lines to explore the matched contours or skeletons from the database. A suggestion mechanism is employed in this stage, to insure both the similarity and diversity of the suggested lines (Section 4.2). Finally the suggested reference lines are used to guide parametric deformation for generating the re-designed object.

4. Our method

In this section we give more details about our shape re-design approach, and map the guidelines summarized in the overview into computational procedures.

4.1. Lines extraction

We collected an image database from the web. Most of the images are natural objects, and some man-made shapes are added as supplementary. These photographs are able to provide interesting and artistic lines for shape re-design. For simplicity we assume that the object in each image is salient and not occluded. Then the foreground object of each image is segmented by employing the salient region detection technique [19], which first detects the salient object and then uses the grabcut [20] to segment the saliency map (see Fig. 4).

We observe that the outline and cross-section of many artistic designs are reflectively or rotationally symmetrical, which is also one of essential characteristics of both natural and man-made shapes. The designs which are not symmetrical are mainly caused by their asymmetrical axes. With the above observations, we classify the objects segmented from the image database into two groups based on the symmetry detection algorithm [21]. The objects which are symmetrical provide their contours for reshaping the

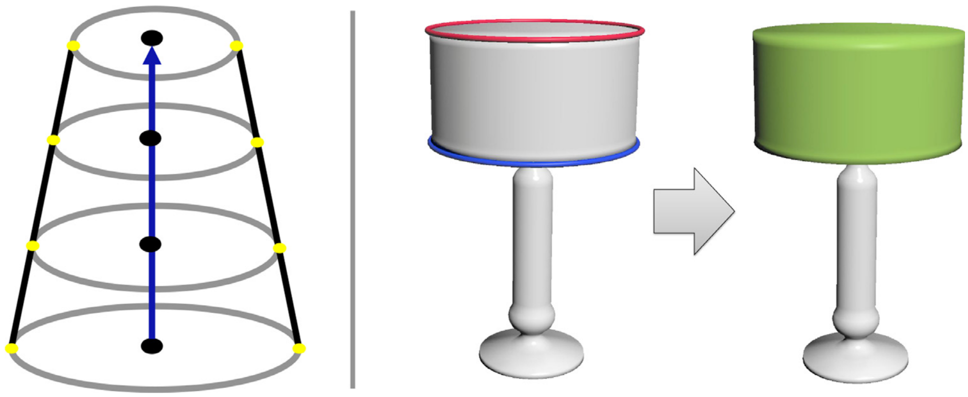

Fig. 3. *Left:* The editable 3D primitive includes axis (blue arrow), outline (black lines) and cross-section (gray circles). *Right:* The user selects the top layer (red circle) and the bottom layer (blue circle) to choose the editable part (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

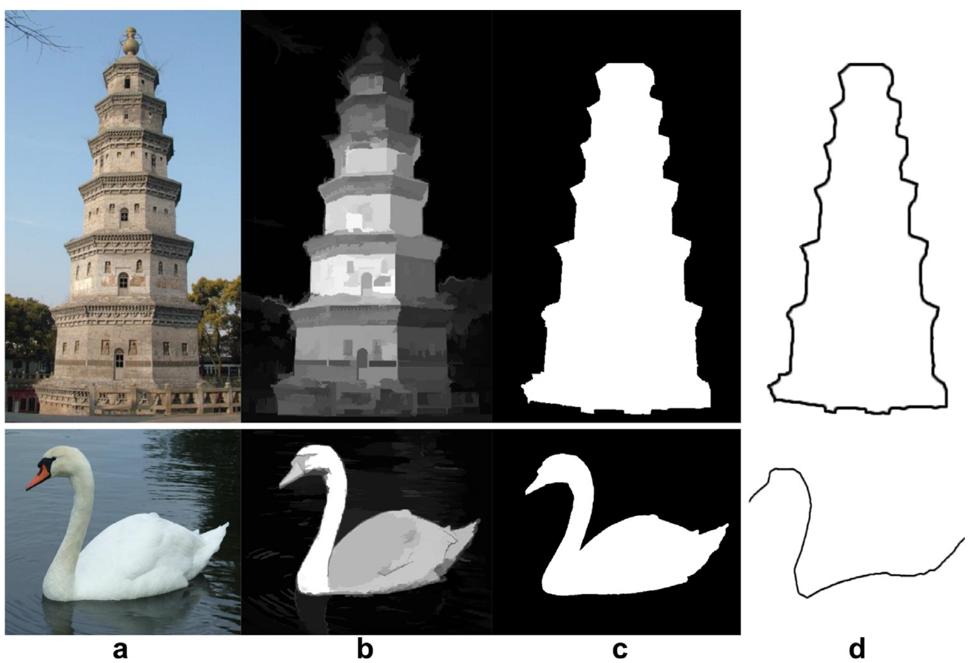

Fig. 4. Lines extraction: (a) Database images; (b) saliency maps; (c) object segmentation; (d) extracted lines (contours of the symmetrical objects and skeletons of the asymmetrical objects).

outlines and cross-sections of 3D shapes, while the objects which are asymmetrical provide the main skeletons (i.e., the longest line of the skeleton) for the axes of the 3D shapes (see Fig. 4). To obtain more various curves, we also use half of the symmetrical objects' contours as the candidate lines for exploration.

In this manner, we obtain a circle set with N contours, denoted as $\mathcal{C} = \{c_1, \ldots, c_N\}$, and a curve set with M skeletons and half of contours, denoted as $\tilde{\mathcal{C}} = \{\tilde{c}_1, \ldots, \tilde{c}_M\}$. Given a 3D shape which is generated by the editable primitives, we also extract the axis l_a, outline l_o and cross-section l_s of each primitive as shown in Fig. 3. Since the 3D objects can be reshaped by handling these lines, we explore the matched lines from the database to facilitate the re-design procedure.

4.2. Lines exploration

Generally, there exist more than one natural objects which are appropriate for re-designing a 3D shape. The similar lines benefit the reshaping without causing too much distortion. On the other hand, some lines which are dissimilar but have similar configurations to the editable 3D lines can also be proper for shape re-design and enable more interesting shape variations. Hence, our lines suggestion mechanism intends to balance the similarity and diversity between the reference natural object and the target 3D shape. To this end, for two lines l_i and l_j, we introduce the following distance metric to evaluate whether they are matched:

$$D(l_i, l_j) = (1 - \omega)SC(l_i, l_j) + \omega||p(l_i) - p(l_j)||_2^2, \quad (1)$$

Fig. 5. Given the outline of a lamp (top: green part) and the cross-section of a disk (bottom), six images are suggested in each turn of exploration with the weight from $\omega = 0$ (leftmost) to $\omega = 1$ (rightmost).

where $SC(l_i, l_j)$ is the distance of shape context [22] between l_i and l_j, measuring the similarity of two lines. $p(l)$ describes the configuration of line's oriented bounding box (OBB). We use the long axis D_l and short axis d_l of the line's OBB to construct a vector, and then normalize the vector to obtain $p(l) = \frac{(D_l, d_l)}{||(D_l, d_l)||}$. In this manner, we can adjust the weight ω to balance the similarity and diversity of the suggested lines. Note that, the above metric is applied to both the contours and the skeletons. In the exploration step, the user chooses what kind of 3D lines should be edited. For the axis l_a of the shape, we calculate $D(l_a, \tilde{\mathcal{C}})$ to seek for the proper curves, and for the outline l_o and cross-section l_s, we search the proper circles by calculating $D(l_0, \mathcal{C})$ and $D(l_s, \mathcal{C})$, respectively.

To encourage more appropriate lines for user selection, we employ the following suggestion mechanism. The weight set $\omega = 0, \ldots, 1$ is an arithmetic progression with n elements ($n = 6$ in our experiment). In each turn of suggestion, we use such a weight set in Eq. (1), and select n lines from the database which have the shortest distance to the target line in the 3D editable primitive with respect to each weight. Then in the next turn, we suggest another different n lines. Fig. 5 shows two lines exploration results, in each case, the leftmost one whose weigh $\omega = 0$ is the most similar to the target line, while the rightmost one whose $\omega = 1$ has a similar configuration of OBB to the target line, but can be more various. We have also conducted a user study to demonstrate this characteristic in Section 5.

4.3. Lines inspired reshaping

The suggested lines are then used to inspire shape redesign by reshaping the 3D primitives. Cylinder is a typical editable primitive, which can be discretely represented by two endpoints and multi-layer circles that have the same number of vertexes. The vertexes in different layers constitute a longitude (see Fig. 3). Such a primitive can be deformed to sphere, cube, tetrahedron and other diverse shapes by editing its axis, outline and cross-section. Some 3D modeling methods [1,2] fit the editable primitives to match the image or the sketch guidance, and many existing 3D shapes or their parts can be represented by such editable primitives via shape deformation [23].

To guide the reshaping of the editable primitive, we first establish the correspondence between the suggested reference line and the editable target line, and then employ a parametric deformation to reshape the primitive. In this process, we align the symmetry axes of the circles and the lines between each pair of endpoints of the curves, to align the orientations between the reference and target lines. Note that we allow the user to symmetrically turn the reference image to obtain the symmetric reshaping results (see the snake-like chair legs in Fig. 1). Assume V and V' are two sets of vertexes in two lines, and v_1 and v'_1 are the endpoints in two curves or the middle and topmost vertexes as the endpoints in two circles (see Fig. 6 top left). Since the vertexes of all lines are in order, we use the proportional relation of length to find the corresponding vertexes, namely, for a vertex v_n, its corresponding vertex v'_m is calculated as follows:

$$\arg\min_{v'_m} \left\| \frac{d(v_n, v_1)}{L(V)} - \frac{d(v'_m, v'_1)}{L(V')} \right\|_2^2, \quad (2)$$

where $d(v_n, v_1)$ is the length of the partial line between vertex v_1 to v_n, and $L(V)$ is the length of the whole line which consists of the vertex set V. The vertex correspondences are then used to guide the 3D object reshaping, in which a parametric deformation step is employed. As illustrated Fig. 6 (top), we use the vector from the endpoint to each vertex in the line as the deformation parameter $dp(v)$. The reference line is able to guide the target line by transferring the parameter of the corresponding vertex as follows:

$$p(v_n) = p(v_1) + dp(v'_m)\frac{l(v)}{l(v')}, \quad (3)$$

where $p(v)$ is the position of the vertex v, v_1 is the endpoint of the target line, v'_m and v_n are two corresponding vertexes in the reference and target lines, respectively. $\frac{l(v)}{l(v')}$ is a scale factor, where $l(v)$ is the distance between two endpoints for curve and the distance from the center point to the endpoint for circle. Fig. 6 (bottom) indicates that the

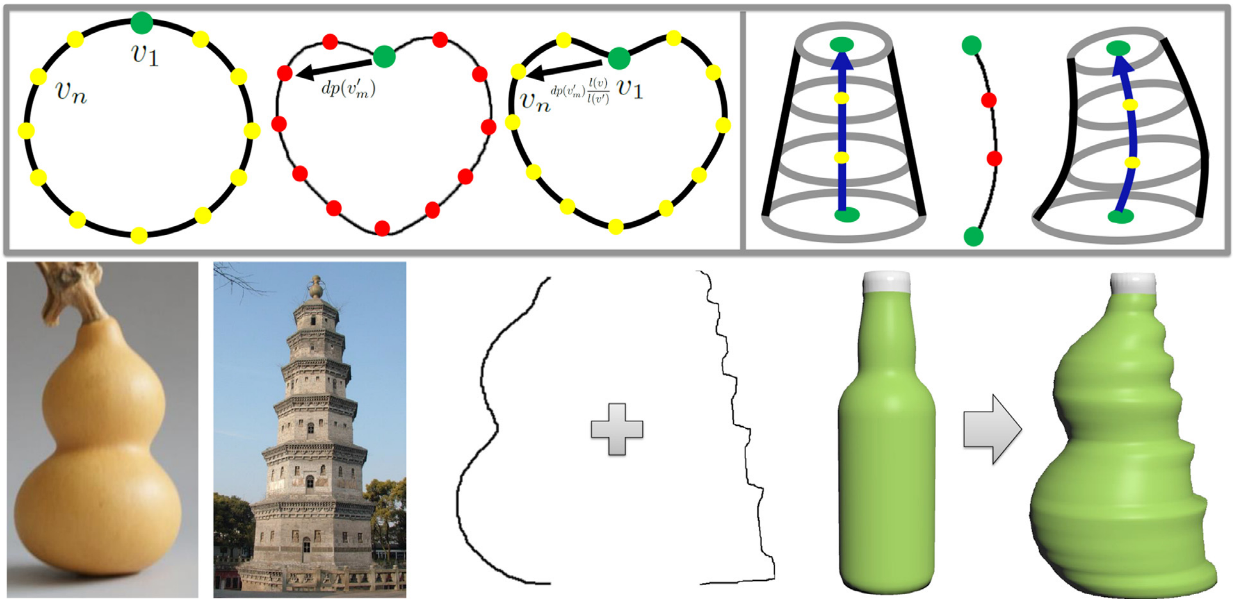

Fig. 6. *Top:* Lines inspired reshaping for circle (left) and curve (right). *Bottom:* Shape re-design inspired by multiple lines.

3D primitive can be reshaped by more than one reference line, broadening the scope of our approach to more interesting results. Editing the outline consisting of two opposite longitudes is more suited for the editable 3D primitive of the revolving shape. For other shapes, we edit the outline consisting of two longitudes which are symmetrical in a certain surface of the shape to preserve their original symmetry (see Fig. 7).

Although reflective symmetry with a straight axis is popular in the design of man-made shapes, there also exist some special-designed objects that may not have straight axes. We use the symmetric objects which have straight axes in the image database to provide their contours for reshaping the outlines of 3D shapes. As a result, for the 3D shapes with curved axes, directly using the contours from the database to guide outline reshaping might lead to distortion. To address this problem, as illustrated in Fig. 8, we first straighten the axis of the edited model, and then employ the above mentioned approach to reshape the model. Finally, we adjust the axis to the original status. Note that using the contours to reshape the cross-sections will not be influenced by the curved axes.

5. Results and discussion

In this section we show several re-designed objects, and present a user study to validate the usability of our lines exploration method for shape re-design.

5.1. Experiment results

We collected a database including 100 images of various natural or man-made objects. As mentioned in Section 4.1, the contours or skeletons are extracted from the database images. Then, with our shape re-design tool, the user chooses the editable region or part of the input 3D object, and our tool suggests several groups of candidate images based on the type of editable lines (axis, outline or cross-section) chosen by the user. Afterwards, the user selects the reference image(s) from the suggested candidate images and the re-designed object is soon produced. Such an interactive paradigm only needs slight user interaction. On average it took less than one minute for lines exploration and 10 s for shape re-design, tested on a PC with Intel Core i7-4790 3.60 GHz and 16 GB RAM.

Fig. 9 shows four simple 3D shapes and the corresponding re-designed results, where the images which provide the reference natural lines are automatically explored from the image database. Fig. 10 displays three complex re-designed examples. The top two examples illustrate that a shape can be re-designed via reshaping its parts inspired by different reference lines. The bottom example indicates that users can also provide their favorite reference lines to produce interesting re-designed objects with our approach, we use the same way shown in Fig. 6 (bottom) to produce this Tai Ji bottle.

5.2. User study

We also conducted a user study to assess the results of our method. The user study was conducted with 8 lecturers majored in art design. To prepare for the user study, we collected the first 5 turns of lines exploration results (6 images in each turn), which were suggested based on input 3D shapes in Fig. 9. Afterwards, we asked each participant to compare the input 3D shape and the suggested images to evaluate both the similarity and diversity of each suggested image, by giving a score in the range from 0 (poorest) to 100 (best). We told each participant about the evaluation criterion that similarity means the object in the suggested image is similar to the 3D shape, and diversity means the object in the image is dissimilar to the 3D

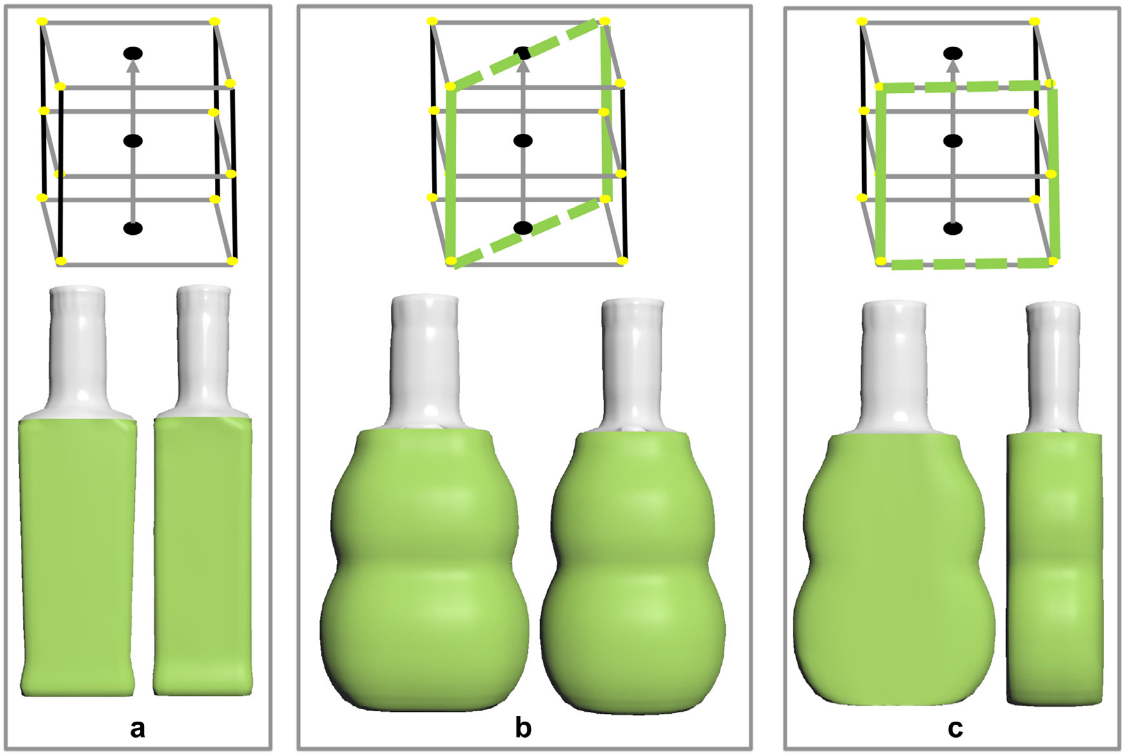

Fig. 7. (a) The input object; (b) reshaping the outline consisting of two opposite longitudes (green circle); (c) reshaping the outline consisting of two symmetrical longitudes (green circle). We show the front (left) and side (right) views of each model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

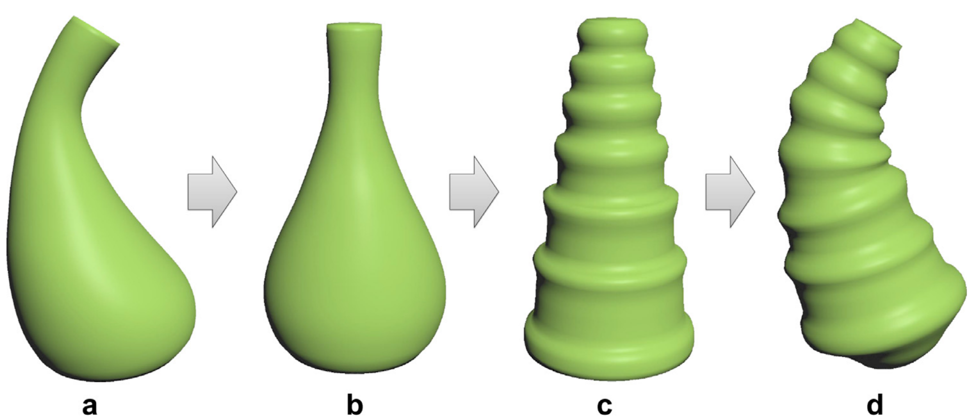

Fig. 8. Reshaping the outline of a shape with a curved axis. (a) The input object; (b) straightening the axis of the input object; (c) reshaping the outline; (d) adjusting the axis to the original status.

shape but still proper for re-designing the shape. We also asked each participant to evaluate each suggested image whether they would like to use it to re-design the input 3D model.

The evaluation results are summarized in Fig. 11. In the left, the *X*-axis represents the score of similarity and the *Y*-axis represents the score of diversity. The six points from left to right in Fig. 11 (left) are the average scores of the images suggested by Eq. (1) with $\omega = 1, 0.8, 0.6, 0.4, 0.2, 0$, respectively. It indicates that, the greater weight ω will suggest more diverse images, while the smaller weight ω will suggest the images more similar to the input 3D shape. Therefore, we can use the weight ω to balance the similarity and diversity of the suggested lines. The right of Fig. 11 shows the acceptance ratio of the first 5 turns of lines exploration results. It indicates that, in the first turn of exploration, more than 4 out of 6 suggested images on average were accepted by human designers, and our suggestion mechanism works well in first few turns to explore the proper lines for shape re-design.

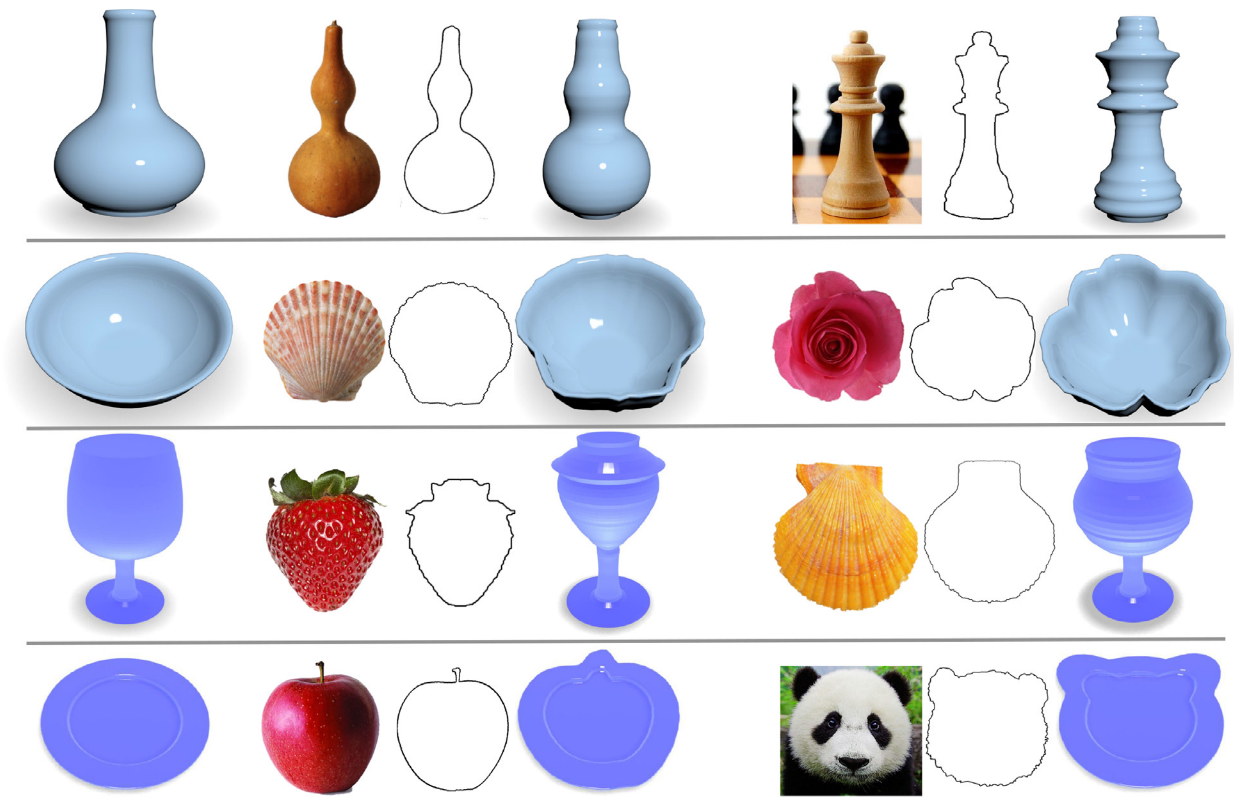

Fig. 9. Examples of shape re-design. In each case, we show two results inspired by lines extracted from different suggested images.

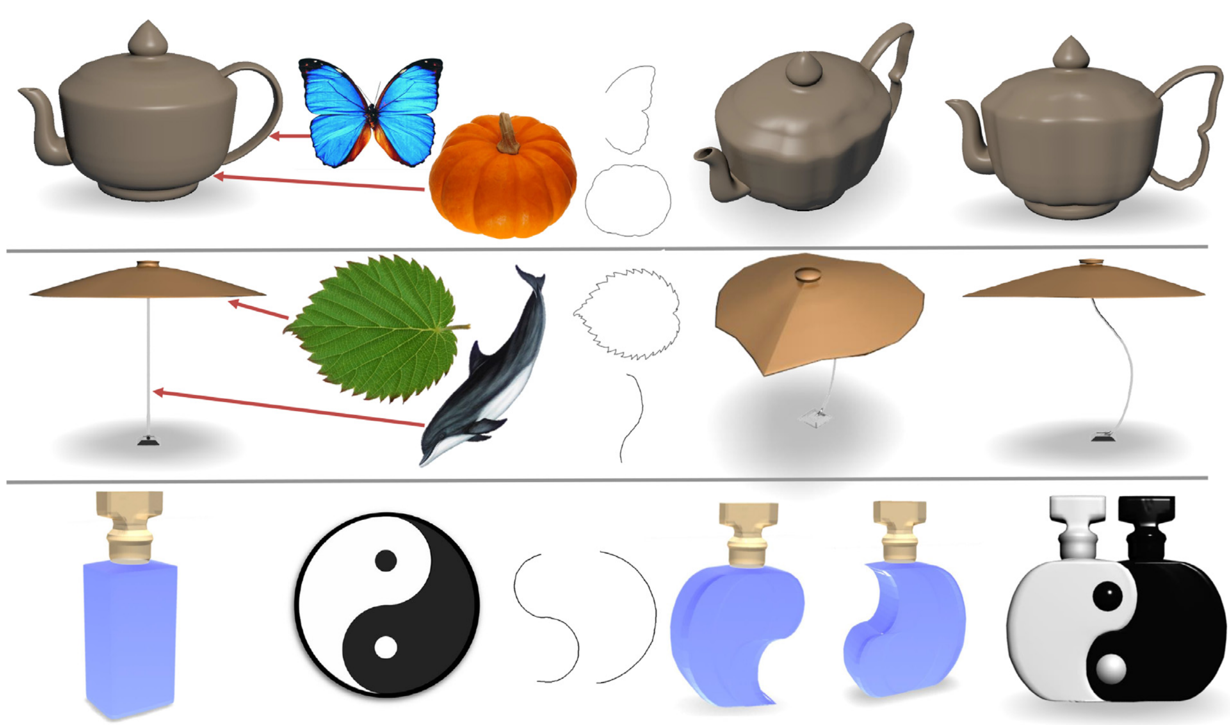

Fig. 10. Several complex re-designed examples produced by our approach.

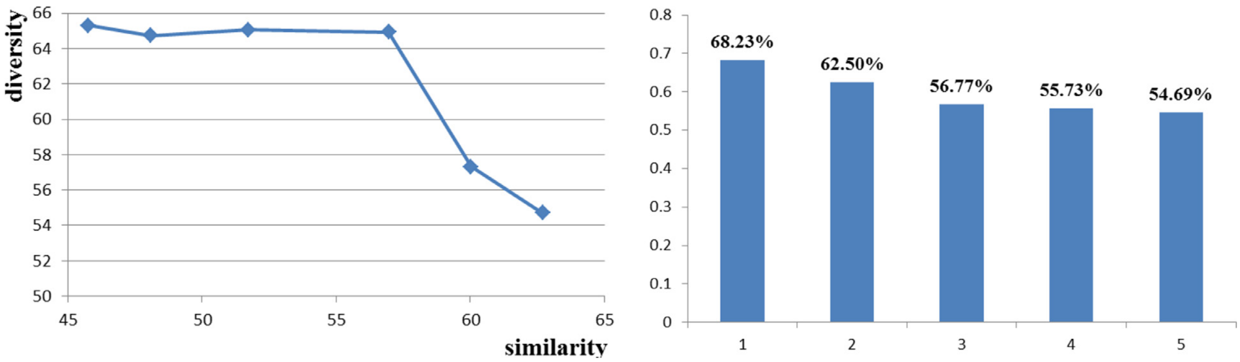

Fig. 11. The evaluation of the similarity and diversity (left) and the acceptance ratio (right) of the lines exploration results.

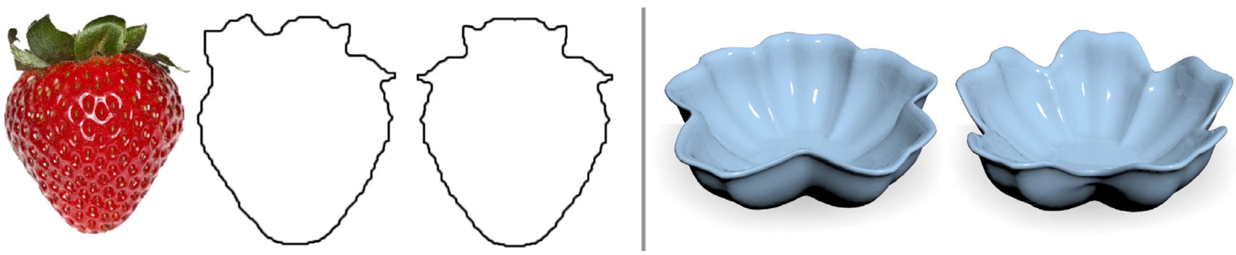

Fig. 12. *Left:* Refining the contour based on symmetry. *Right:* Guided by 2D lines, our approach can only produce a shape with planar cross-sections (left), it cannot generate a shape with non-planar cross-sections (right).

5.3. Limitations

Our current approach has several limitations. Firstly, the extracted lines of the single salient object in an image might also be distorted, because the perspective or the object itself is not strictly symmetrical. To obtain visually pleasing re-designed objects, we refine the contours based on symmetry (left in Fig. 12), and smooth the skeletons by spline curves. Moreover, since the depth of an object can hardly be extracted from the image, our method cannot produce a 3D shape whose editable primitive having non-planar cross-sections (right in Fig. 12). Similar to 3-Sweep method [2], another limitation is that the quality of re-designed objects depends on the 3D editable primitives (e.g., cylinders), while many shapes cannot be represented or decomposed into such primitives. Hence, these shapes cannot be reshaped by our approach. Besides, although we can adjust the axes of 3D shape to reshape the shapes with curved axes, shapes with non-planar axes may lead to distortion and would lose the characteristic of the reference natural object.

6. Conclusion

We have introduced a 3D shape re-design approach to leverage the natural lines to inspire the reshaping of 3D objects. With the contours and skeletons extracted from the image database, a series of natural lines are explored to guide the deformation of the 3D editable primitives to generate various interesting re-designed objects. We have evaluated our approach with several re-design results, and presented a user study demonstrating that our approach performed well to explore proper lines to inspire the shape re-design. In the future, we are interested in extending our approach to more types of natural elements, such as texture and structure. We believe that new opportunities will open up for 3D shape re-design with natural elements enabling novice users to design artistic works.

Acknowledgments

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.gmod.2016.01.002

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