Copy-and-paste operation of planar polygonal shapes*

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Abstract A 2D polygonal shape copy-and-paste method is proposed which is based on a multiple planar shapes blending algorithm. First sub-shapes are specified and selected, which correspond to user-defined visual features on the input shapes. Then they are copied and pasted with contribution weights to generate new shapes via a modified intrinsic 2D shape blending algorithm. User can edit the generated shape intuitively and interactively by adjusting the contribution weights. The proposed method fills the gap in the object modeling methodology based on the copy-and-paste operation. Besides the static 2D copy-and-paste operation, the proposed method can also be applied to 2D metamorphosis among multiple planar shapes.

Keywords: copy-and-paste, 2D shape blending, metamorphosis.

A shape blending is a visually smooth transformation between a source shape and a destination shape, either in 2D or 3D space[1—4]. It is an important technique for special effects generation in computer animation and computer game, and is also widely applied to pattern matching, geometric modeling, etc. Based on the shape blending technique, graphical object copy-and-paste operations are developed and are drawing more and more attention. Among them Lee's work is regarded as a powerful 2D image copy-and-paste operation[5]. Recently such an operation is being extended to 3D mesh as an intuitive geometric model generation tool[6—11]. Using the copy-and-paste operation, users can reuse the existing models to create the new ones, which greatly improves the geometric modeling efficiency.

A 2D copy-and-paste operation has been mentioned in Ref. [12]. But to our knowledge there is not a method which is specifically designed for the 2D polygonal shape copy-and-paste operation yet. The challenges in such an operation are how to join copied portions on the generated shape naturally and how to edit the generated shape intuitively and interactively.

Similar to its 3D counterpart, a 2D copy-and-paste operation is also closely related to the 2D shape blending technique. The 2D shapes blending can be divided into two steps: vertex correspondence[13—15] and vertex interpolation path[2,16—20,21]. The first one is to establish the vertex correspondences between the source shape and the destination shape, and the second one is to compute the vertex moving trajectories of the in-between shapes via an interpolation along the predetermined path.

In this paper, a weighted 2D polygonal shape copy-and-paste operation is proposed. First the sub-shapes on the input shape are specified interactively, which correspond to the user-defined visual features. Then the sub-shapes are selected, copied, blended and attached with the contribution weights on a frame polygon to create a new shape via the intrinsic multiple 2D shapes blending algorithm. Thus a new 2D polygonal shape is generated with the mixed visual features of the input polygonal shapes. In the proposed method the new shape can be edited locally and globally by adjusting the contribution weights. Moreover, the metamorphosis sequence among the new polygonal shapes can also be generated straightforwardly where the in-between shapes are non-uniform blending of the input polygonal shapes' visual features.

The rest of paper is organized as follows. The visual feature decomposition is introduced first. Then the 2D copy-and-paste operation is described in detail. Some examples and discussions are given before the conclusions are drawn finally.

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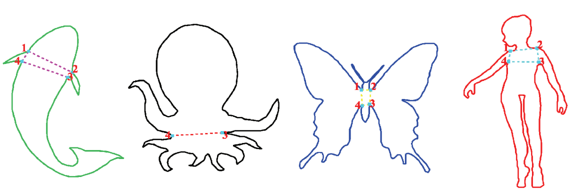
1 Visual feature decomposition of 2D input shapes

The visual feature decomposition is a preprocessing step of the 2D copy-and-paste operation. It defines and extracts the visual features from the 2D input shapes (i.e. the 2D planar polygons) interactively. For the convenience of the user's interaction, the concept of feature decomposition vertex (abbreviated as FDV) is introduced. In Fig. 1, each FDV is labeled with a natural number, and each specified visual feature is delimited by two successive FDVs. For example, in Fig. 1(d), the successive FDVs 1 and 2, 2 and 3, 3 and 4, 4 and 1 delimit the girl's head, right arm, body, left arm respectively which are distinctive features on the girl shape, namely, sub-shapes in this paper. Obviously a sub-shape is represented by an open sub-polygon.

The polygon formed by all FDVs on an input polygonal shape is called an frame polygon, shown as the dashed line polygons in Fig. 1. As a special case, if the frame polygon is not a close loop, it is called a degenerated frame polygon. The frame polygon in Fig. 1(b) is a degenerated example. The frame polygon can be regarded as a low-resolution version of the original polygon. Each edge of a frame polygon is related with a sub-shape. The edge determines the local position and orientation of its corresponding sub-shape.



(a) Fish (b) Octopus (c) Butterfly (d) Girl

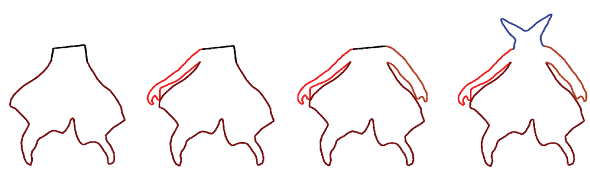
Fig. 1. Visual feature decomposition of the polygonal shapes.

When multiple polygonal shapes are given, the visual feature decomposition process is applied to each of them. The correspondences among the sub-shapes can be established by the FDVs. As shown in Fig. 1, the head parts of the fish, the girl and the butterfly are the corresponding sub-shapes because they are delimited by the same FDVs: 1 and 2. In addition, the non-degenerated frame polygons are defined as equivalent frame polygons if they have the same FDV labels. In Fig. 1, the frame polygons in (a), (c) and (d) are equivalent frame polygons except for that in (b). As a special case a non-degenerated frame polygon can also be an equivalent frame polygon itself (see the following).

All of the sub-shapes can construct a 2D visual feature warehouse. The users can select the desirable ones to create a new shape via the 2D copy-and-paste operations. The next section will describe the 2D copy-and-paste operation in detail.

2 Weighted copy-and-paste operation via multiple 2D shapes blending

In the 2D copy-and-paste operation process, the user selects the sub-shapes and assigns the weights to them interactively. Then the corresponding sub-shapes are blended with their weights to generate a new sub-shape. In addition, a blended frame polygon is computed as the weighted average of the equivalent frame polygons. The new shape is generated by attaching the blended sub-shapes on the blended frame polygon smoothly. The shape can be further edited locally and globally by adjusting weights of the selected sub-shapes and the scaling coefficients of the equivalent frame polygons respectively. Fig. 2 illustrates a full copy-and-paste operation process.



(a) Step 1 (b) Step 2 (c) Step 3 (d) Step 4

Fig. 2. A copy-and-paste operation. (a) 50% octopus body + 50% girl body is attached; (b) 100% left arm of girl is attached; (c) 1/3 right arm of fish + 2/3 right arm of girl is attached; (d) 10% girl head + 10% fish head + 80% butterfly head is attached.

The last step in Fig. 2(d) for generating a new head sub-shape is further illustrated in Fig. 3. In this step, the user selects the head sub-shapes and assigns weights to them for generating the desirable head sub-shape. For convenience of the user's interaction, the weight is represented as a percentage. For example, in Fig. 3(a), the girl's head sub-shape is selected and automatically assigned a default weight of 100% since it is the unique sub-shape pasted on the new shape. In Fig. 3(b), the fish's head sub-shape is selected and assigned a weight 50%. Then it is blended with the current head sub-shape to generate a new head sub-shape (i.e. 50% girl head + 50% fish head). In Fig. 3(c), the butterfly's head sub-shape is selected and assigned a weight 80%. The final head sub-shape is a weighted average of 20% current head sub-shape in Fig. 3(b) and 80% butterfly head sub-shape (i.e. 10% girl head, 10% fish head, 80% butterfly head respectively).

In the following subsections, an intrinsic multiple 2D shapes blending algorithm is introduced first. Then these 2D shapes are tailored to the weighted equivalent frame polygons blending and the weighted sub-shapes blending respectively.

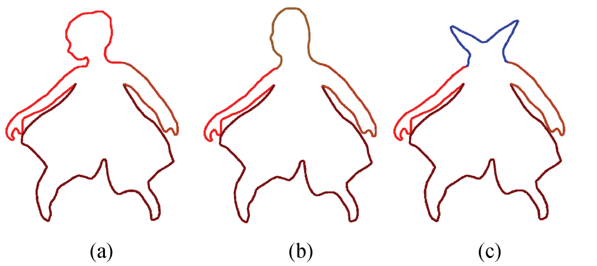


Fig. 3. The copy-and-paste operation step in Fig. 2(d) for the new head sub-shape generation. (a) 100% girl head; (b) 50% head in (a) + 50% fish head; (c) 20% head in (b) + 80% butterfly head.

2.1 Intrinsic blending of multiple 2D shapes

In this section, the intrinsic 2D shape blending method based on the turtle geometry[2] is extended to a multiple-shape case. Let $\{\boldsymbol{P}^k\}(k=1,2,\cdots,m)$ be m planar polygons whose vertex correspondences have been established already. Each polygon is denoted as $\boldsymbol{P}^k = \{p_0^k, p_1^k, \cdots, p_{n-1}^k\}$. Its intrinsic parameters are p_0^k, $\{L_i^k\}_{i=0}^{n-1}$, α^k, $\{\theta_i^k\}_{i=1}^{n-1}$, which are anchor point, edge lengths, signed angle between the first edge and angle line, vertex angles respectively (illustrated in Fig. 4). In the turtle geometry the anchor point and the angle line determine the position and orientation of the polygon.

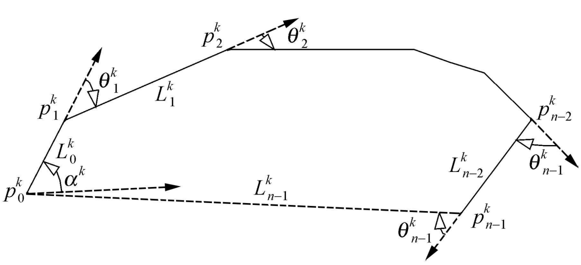


Fig. 4. Intrinsic parameters of a polygon.

Let w^k be the weight assigned to the intrinsic parameters of the k-th polygon $\boldsymbol{P}^k$. The intrinsic parameters interpolation among m polygons can be computed as follows:

$$p_0 = \sum_{k=1}^{m} w^k p_0^k / T \quad (1)$$

$$\alpha = \sum_{k=1}^{m} w^k \alpha^k / T \quad (2)$$

$$\theta_i = \sum_{k=1}^{m} w^k \theta_i^k / T \quad (i = 1,2,\cdots,n-1) \quad (3)$$

$$L_i = \sum_{k=1}^{m} w^k L_i^k / T \quad (i = 0,1,\cdots,n-1) \quad (4)$$

$$T = \sum_{k=1}^{m} w^k \quad (5)$$

Similar to the method in Ref. [2], the interpolated shape will be subject to some blending constraints, i.e., close constraint and vertex coincidence constraint in this paper. To satisfy these constrains, the edge length L_i should be adjusted after the blending interpolation. Let S_i be the adjusted length for L_i in (4), so the blending edge length should be modified as:

$$L_i = \sum_{k=1}^{m} w^k L_i^k / T + S_i \quad (i = 0,1,\cdots,n-1) \quad (6)$$

Intuitively, S_i should be proportional to the variance of the i-th edge lengths of m polygons, namely $\tilde{L}_i$, which is defined as:

$$\tilde{L}_i = \sqrt{\frac{\sum_{k=1}^{m} (L_i^k - \bar{L}_i)^2}{m}} \quad (i = 0,1,\cdots,n-1) \quad (7)$$

where $\bar{L}_i$ is average length of the i-th edge of m polygons. Then objective function is min $\{f(S_0, S_1, \cdots, S_{n-1})\}$ and it can be solved by using the Lagrange multiplier solver. Finally the blended polygon is obtained by converting the intrinsic parameters to Cartesian coordinates.

Now we describe how to define the objective functions for two types of the blending constraints, i.e., close constraint and vertex coincidence constraint. The close constraint forces the head vertex and tail vertex of the blended polygon to be coincident such that the blended polygon is close. The objective function for such a constraint is defined as:

$$f(S_0, S_1, \cdots, S_{n-1}) = \sum_{i=0}^{n-1} \left(\frac{S_i}{L_i'} \right)^2 \quad (8)$$

which is subject to

$$\phi_1(S_0, S_1, \cdots, S_{n-1}) = \sum_{i=0}^{n-1} (L_i \times \cos\alpha_i) = 0 \quad (9)$$

$$\phi_2(S_0, S_1, \cdots, S_{n-1}) = \sum_{i=0}^{n-1}(L_i \times \sin\alpha_i) = 0 \tag{10}$$

where L_i' is max $\{\tilde{L}_i, 0.0001 \times \max_{[0,n-1]} \tilde{L}_i\}$ for avoiding division by zero, α_i the angle from angle line to each edge vector, which is $\alpha_i = \alpha_{i-1} + \theta_i (i = 1, 2, \cdots, n-1)$.

The vertex coincidence constraint forces the tail vertex of an open polygon to be coincident with a pre-specified position. It will be applied to attach a sub-shape on a frame polygon without gap. Letting the pre-specified position be (x_p, y_p), the corresponding objective function is defined as:

$$f(S_0, S_1, \cdots, S_{n-2}) = \sum_{i=0}^{n-2}\left(\frac{S_i}{L_i'}\right)^2 \tag{11}$$

which is subject to

$$\phi_1(S_0, S_1, \cdots, S_{n-2}) = \sum_{i=0}^{n-2}(L_i \times \cos\alpha_i) = x_p \tag{12}$$

$$\phi_2(S_0, S_1, \cdots, S_{n-2}) = \sum_{i=0}^{n-2}(L_i \times \sin\alpha_i) = y_p \tag{13}$$

where L_i' and α_i are defined as the same as those in the close constraint case.

2.2 Weighted equivalent frame polygons blending

In this section, the intrinsic multiple shapes blending algorithm is applied to the equivalent frame polygons interpolation. Supposing that there are m equivalent frame polygons, each of them has n vertices. Their weights $\{w^k\}$ $(k = 1, 2, \cdots, m)$ can be computed as follows. Let $w^k_{\text{sb}_i}$ $(i = 0, 1, \cdots, n-1; k = 1, 2, \cdots, m)$ be the weight of the i-th sub-shape on the k-th equivalent frame polygon, then $w^k = c^k \times \sum_{i=0}^{n-1} w^k_{\text{sb}_i}$. The c^k is called scaling coefficient (abbreviated as SC), and can be interpreted as the k-th frame polygon's contribution factor to the blended frame polygon. Its default value is set to 1. Since the frame polygon is close, the blended frame polygon can be computed by Eqs. (1)—(5), (8) with the close constraints (9) and (10).

As we know in Section 1, each edge of the frame polygon is related with a sub-shape. In the 2D copy-and-paste operation, the blended sub-shape will be attached to the corresponding edge of the blended frame polygon with the vertex coincidence constraint. The sub-shapes blending method will be introduced in the next section. If the frame polygons are directly blended as above, the attached blended sub-shape may stretch or shrink greatly since it is subject to the vertex coincidence constraint. An example is shown in Fig. 5. The scaling coefficients of the girl frame polygon in Fig. 1(d) and the fish frame polygon in Fig. 1(a) are 0 and 1 respectively, which means the fish frame polygon is chosen as the blended frame polygon. When the girl's head sub-shape is selected and attached to the fish frame polygon, it will stretch greatly since the girl's head sub-shape size does not match the corresponding edge length of the fish's frame polygon. In order to avoid such a warp of the attached sub-shape, the corresponding edge length of the frame polygon should be adjusted as closely as possible to the blended sub-shape size. This can be accomplished as follows. Let L^i_{sub} be the length of the head and tail vertices of the blended sub-shape to be attached to the i-th edge of the frame polygon, Eqs. (4) and (6) for the equivalent frame polygons blending should be modified as:

$$L_i = L^i_{\text{sub}} \quad (i = 0, 1, \cdots, n-1) \tag{14}$$

$$L_i = L^i_{\text{sub}} + S_i \quad (i = 0, 1, \cdots, n-1) \tag{15}$$

By replacing Eqs. (4) and (6) with (14) and (15) respectively, the edge length of the blended frame polygon will approximate the corresponding sub-shape size, i.e. L^i_{sub}. The improved result is shown in Fig. 5(c) by using the above improvements. It partially alleviates the large warp of the girl's head sub-shape attached to the blended frame polygon. The blending result seems better than that in Fig. 5(b).

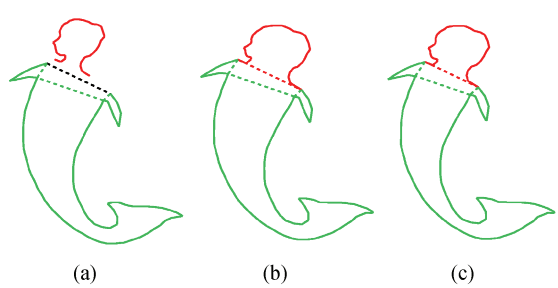


Fig. 5. Adjusting the edge length of the blended frame polygon. (a) The girl's head sub-shape and the fish's frame polygon; (b) the attached girl's head shape has large warp; (c) alleviating the large sub-shape warp.

Now we explain how the SCs $\{c^k\}$ $(k = 1, 2, \cdots, m)$ influence the blended shape globally. Since the modified edge length interpolation is independent of the weights $\{w^k\}$, the SCs have impact on the angle interpolation. In turtle geometry, the angle represents the orientation. Thus the SCs have impact on the blended frame polygon edge's orientation. Because the edge vector of the blended frame polygon will determine orientation of the corresponding attached sub-shape, the SCs have final impact on the orientation of the sub-shape. The larger the SC of an equivalent frame polygon, the more closely the orientations of the blended sub-shapes will follow those of the equivalent frame polygon. Thus the scaling coefficient can be used to adjust the orientation of the blended sub-shape relative to the frame polygon. An example is shown in Fig. 6. The orientations of the head and the left arm of the girl, the right swing of the butterfly and the fish body on the new polygonal shape vary according to the different SCs of the equivalent frame polygons. As the example in Fig. 6 (c), the configuration of the blended shape is much close to that of the fish shape when the SC of the fish frame polygon is much larger than the SCs of other frame polygons.

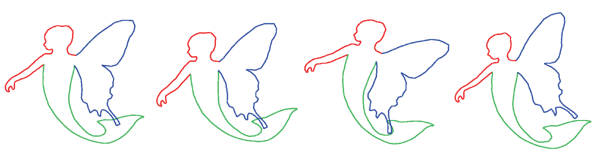


Fig. 6. Edit the new shape globally through adjusting the SCs: (a) Three SCs are default value 1; (b) the SC of the butterfly frame polygon is magnified to 10, while two others are 1; (c) the SC of the fish frame polygon is magnified to 10, while two others are 1; (d) the SC of the girl frame polygon is magnified to 10, while two others are 1.

2.3 Weighted 2D sub-shapes copy-and-paste operation

2.3.1 Sub-shape representation in the local coordinate system

Unlike other 2D shape blending methods performed in a global manner, the proposed sub-shape interpolation is decomposed into two parts: rigid body motion interpolation and flexible motion interpolation. Before the sub-shape blending, each sub-shape is transformed into a local coordinate system. During the blending step, the rigid body motion interpolation determines the local coordinate system, and the flexible motion interpolation is the sub-shapes blending performed in the local coordinate system. Therefore such a local coordinate system should satisfy the following two properties: (i) The local coordinate systems of the different sub-shapes are independent; and (ii) the local coordinate system fully determines the position and the orientation of the corresponding sub-shape.

According to the proposed visual features decomposition in Section 2, each edge vector of the frame polygon determines the local position and orientation of the associated sub-shape. Thus in the proposed algorithm the frame polygon edge vector is adopted to construct the local coordinate system of the corresponding sub-shape. Let $\boldsymbol{P}_{sb}$ be a sub-shape whose vertices are $p_0^{sb}, p_1^{sb}, \cdots, p_{M-1}^{sb}$. Obviously the head and tail vertices p_0^{sb}, p_{M-1}^{sb} are two successive FDVs. Let $\boldsymbol{u}^{sb}$ be the normalized vector of $\overrightarrow{p_0^{sb} p_{M-1}^{sb}}$ and $\boldsymbol{v}^{sb}$ the unit vector by rotating $\boldsymbol{u}^{sb}$ 90° counterclockwise. Combining with the head vertex p_0^{sb}, the triple $(p_0^{sb}, \boldsymbol{u}^{sb}, \boldsymbol{v}^{sb})$ define the local coordinate system of the sub-shape $\boldsymbol{P}_{sb}$. Each vertex p_i^{sb} of the $\boldsymbol{P}_{sb}$ can be represented as the local coordinates (u_i^{sb}, v_i^{sb}) by the following equation:

$$p_i^{sb} = p_0^{sb} + u_i^{sb}\boldsymbol{u}^{sb} + v_i^{sb}\boldsymbol{v}^{sb} \tag{16}$$

After the sub-shapes are transformed into their corresponding local coordinate systems, the weighted sub-shapes blending is implemented for their local coordinates.

2.3.2 Weighted multiple 2 D sub-shapes blending

In the 2D copy-and-paste operation, the selected sub-shapes are blended with the assigned weights. Similar to the classical 2D shape blending, the vertex correspondence and the vertex path interpolation problems are involved. In the proposed algorithm, the vertex correspondences are established through the arc-length parameterization and topological merging since the corresponding sub-shapes have the similar visual features. The blended sub-shape is mainly influenced by the vertex path interpolation among multiple sub-shapes. Thus the vertex path interpolation algorithm should meet the following criteria: (i) The algorithm could be implemented in real-time; (ii) the blended sub-shapes should suffer from little distortion, and manifest the weight effect; (iii) the blended sub-shape is attached to the blended frame polygon without the gap. The 2nd and 3rd criteria sometimes conflict. However the 3rd criterion is more important for the natural and smooth 2D copy-and-paste operation (see an example in Fig. 7).

Many methods were proposed to blend multiple

2D or 3D shapes[22—25], or to blend the local features of 3D shapes[6,26]. However they cannot be applied to the multiple 2D sub-shapes blending in the context of the 2D copy-and-paste operation because either they cannot be extended to 2D case straightforwardly or they do not satisfy the above criteria. The modified intrinsic multiple shapes interpolation in Section 2.1 is chosen as the blending algorithm because it is simple and fast and can meet the criteria above. Combining with the vertex coincidence constraint in Section 2.1, the blended sub-shape can be attached to the blended frame polygon without gap, which meets the 3rd criterion. The example in Fig. 7(b) illustrates the result without gap.

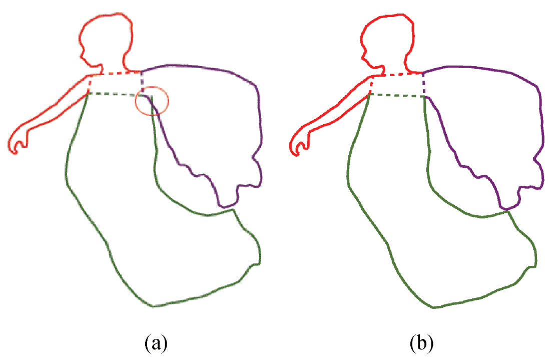


Fig. 7. The effect of the vertex coincidence constraint: (a) Without the constraint, there is a gap in the final result; (b) with the constraint, the blended sub-shape is attached to the blended frame polygon without the gap.

In the proposed algorithm, the sub-shapes blending process is divided into two steps. The first step is to blend the intrinsic parameters of the sub-shapes by using (1)—(5) without any constraints. At this step, a temporary sub-shape is generated. Its size is defined as the length between its head and tail vertices. The size of temporary sub-shape will be used to determine the corresponding edge length of the blended frame polygon by using (14) and (15). After this step, a new blended frame polygon is obtained as described in Section 2.2. In the second step, the intrinsic parameters of the sub-shapes will be blended again with the vertex coincidence constraint such that the tail vertex of the blended sub-shape can be coincident to the second vertex of the corresponding edge of the blended frame polygon. Then the blended sub-shape can be joined on the new shape without gap.

3 Implementation results and discussion

The proposed method has been implemented on a PC with Pentium IV CPU and 512M memory. The algorithms described are integrated into a 2D copy-and-paste prototype system. The examples in the paper are generated in real-time using the system. The example in Fig. 8 can be considered as a cut-and-paste operation because the sub-shapes are selected from the input polygonal shapes and attached to a frame polygon directly. The visual feature decompositions for the input polygonal shapes are shown in Fig. 8(a), (b), (c), (d) and (f). The equivalent frame polygon is the tree frame polygon itself in Fig. 8(d) or (f). The two different Christmas trees are generated through the two different feature decompositions of the tree shape.

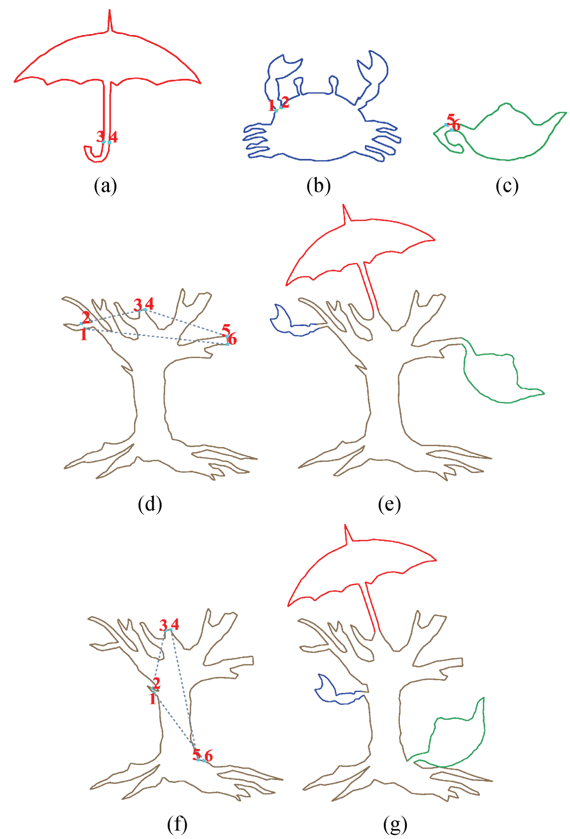


Fig. 8. Christmas trees in (e) and (g) generated by 2D cut-and-paste operations.

The proposed method can also generate the metamorphosis sequence among the multiple 2D polygonal shapes with non-uniform contribution weights. As described above, the 2D copy-and-paste operation is based on the multiple 2D shapes blending algorithm, each generated polygonal shape is a blending result among the input shapes. Therefore the metamorphosis sequence can be generated through key-frame technique by setting the parameters of the blended polygonal shapes as the key values and by constructing in-between polygonal shapes through the above techniques. It is called multiple planar shapes blending[25]. Fig. 9 is an example of a metamorphosis sequence of input polygonal shapes in Fig. 1.

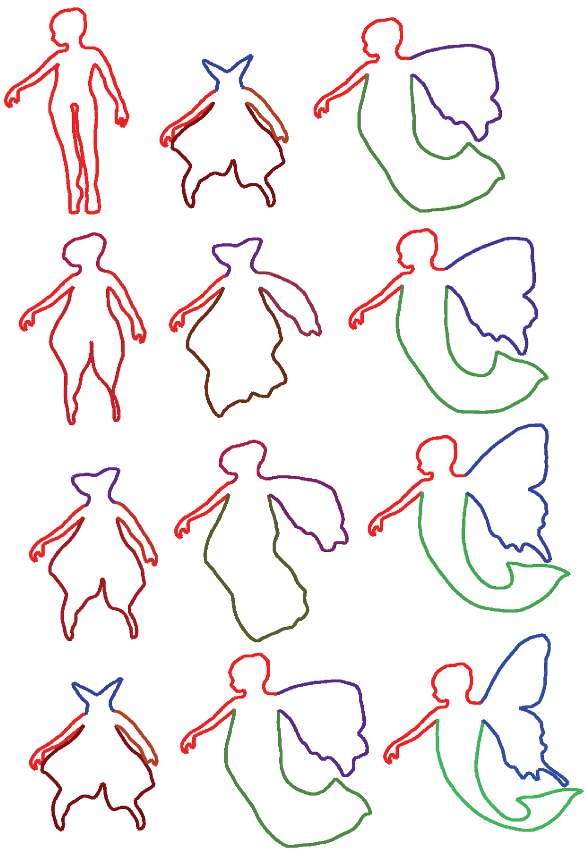


Fig. 9. Multiple polygonal shapes morphing. The first and last shapes at each column are key frames, which are generated by the proposed 2D copy-and-paste operation.

4 Conclusions

In this paper, a novel 2D copy-and-paste operation is proposed to reuse the sub-shapes or common parts of the input polygonal shapes to generate new polygonal shapes. The operation is based on an intrinsic multiple shapes blending method. It enriches the copy-and-paste modeling methodology in computer graphics. Besides applying to the new planar shapes generation, the method can also generate metamorphosis sequence among multiple 2D polygonal shapes, i.e. multiple planar shapes blending. The new polygonal shapes generated by the proposed copy-and-paste operation are smooth and aesthetic in this paper. The user can edit the generated shape by adjusting the weights. However, how to assess the generated polygonal shape is not addressed in the paper. It is an aesthetic problem and difficult to describe by an analytic formula.

The future work is to extend the proposed method to the 3D case. It includes how to define the 3D frame polygon and to attach the 3D sub-shapes to the 3D frame polygon; and to extend the method to the multiple 2D shapes blending with different topologies.

References

1 Alexa M. Recent advances in mesh morphing. Computer Graphics Forum, 2002, 21(2): 173—196
2 Sederberg TW, Gao P, Wang G, et al. 2D shape blending: an intrinsic solution to the vertex path problem. ACM Computer Graphics, 1993, 27(4): 15—18
3 Lerios A, Garfinkle C and Levoy M. Feature-based volume metamorphosis. ACM Computer Graphics, 1995, 29(3): 449—456
4 Wolberg G. Digital Image Warping. 1st ed. California: IEEE Computer Society Press, 1990, 241—242
5 Lee S, Wolberg G and Shin S. Polymorph. An algorithm for morphing among multiple images. IEEE Computer Graphics and Applications, 1998, 18(1): 58—71
6 Kanai T, Suzuki H, Mitani J, et al. Interactive mesh fusion based on local 3d metamorphosis. In: Proceedings of Graphics Interface. Kingston, Ontario, Canada, June 2—4, 1999, 148—156
7 Singh K and Parent R. Joining polygonal objects using implicitly defined surfaces. The Visual Computer, 2001, 17(7): 415—428
8 Biermann H, Martin I, Bernardini F, et al. Cut-and-paste editing of multi-resolution surfaces. ACM Trans on Graphics, 2002, 21(3): 312—321
9 Museth K, Breen DE, Whitaker RT, et al. Level set surface editing operators. ACM Trans on Graphics, 2002, 21(3): 330—338
10 Fu H, Tai C and Zhang H. Topology-free cut-and-paste editing over meshes. In: Proceedings of Geometric Modeling and Processing. Beijing, China, April 13—15, 2004, 173—184
11 Yu Y, Zhou K, Xu D, et al. Mesh editing with Poisson-based gradient field manipulation. ACM Trans on Graphics, 2004, 23(3): 644—651
12 Sorkine O, Cohen-or D, Lipman Y, et al. Laplacian surface editing. In: Proceedings of the Eurographics/ACM SIGGRAPH Symposium on Geometry Processing. Nice, France, July 8—10, 2004, 179—188
13 Sederberg TW and Greenwood E. A physically based approach to 2D shape blending. ACM Computer Graphics, 1992, 26(2): 25—34
14 Zhang Y. A fuzzy approach to digital image warping. IEEE Computer Graphics and Applications, 1996, 16(4): 34—41
15 Liu L, Wang G, Zhang B, et al. Perceptually based approach for planar shape morphing. In: Proceedings of Pacific Graphics. Seoul, Korea, October 6—8, 2004, 111—120
16 Shapira M and Rappoport A. Shape blending using the star-skeleton representation. IEEE Computer Graphics and Applications, 1995, 15(2): 44—50
17 Carmel E and Cohen-or D. Warp-guided object-space morphing. The Visual Computer, 1997, 13(9—10): 465—478
18 Gotsman C and Surazhsky V. Guaranteed intersection-free polygon morphing. Computers & Graphics, 2001, 25(1): 67—75
19 Surazhsky V and Gotsman C. Controllable morphing of compatible planar triangulations. ACM Trans on Graphics, 2001, 20(4): 203—231

20 Che W, Yang X and Wang G. Skeleton-driven 2D distance field metamorphosis using intrinsic shape parameters. Graphical Models, 2004, 66(2): 102—126

21 Alexa M, Cohen-or D and Levin D. As-rigid-as-possible shape interpolation. In: Proceeding of SIGGRAPH. New Orleans, Louisiana, USA, 2000, 157—164

22 Chen S and Parent R. Shape averaging and its applications to industrial design. IEEE Computer Graphics and Applications, 1989, 9(1): 47—54

23 Rossignac J and Kaul A. Agrels and bips: Metamorphosis as a Bézier curve in the space of polyhedra. Computer Graphics Forum, 1994, 13(3): 179—184

24 Michikawa T, Kanaai T, Fujita M, et al. Multi-resolution interpolation meshes. In: Proceeding of Pacific Graphics. Tokyo, Japan, 2001, 60—69

25 Johan H and Nishita T. Blending multiple polygonal shapes. In: Proceeding of Pacific Graphics. Alberta, Canada, 2003, 434—439

26 Alexa M. Differential coordinates for local mesh morphing and deformation. The Visual Computer, 2003, 19(2—3): 105—114