Kinetic Sculpture Design Using the Dynamic Cage

Xinwei Zhang 1, Jin Wang 1*, Yu Liu 2, Guodong Lu 1, Xusheng Zhang 2

1 State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou, China
2 College of Computer Science and Technology, Zhejiang University, Hangzhou, China
dwjcom@zju.edu.cn.

Abstract. Kinetic sculptures are attractive for periodic dynamic deformation effects. Designing such a sculpture is not easy considering the holistic shape versus many part details. To provide an easier design process, we propose a top-down framework for kinetic sculpture design. The system converts several input sketch curves to a dynamic cage, which shows the deformation of the sculpture's holistic shape in motion. The user can manipulate the sculpture's shape by dragging on the cage at any moment in motion. After that, a group of skeletons is generated from the cage. The user can adjust their shapes for detailed unit model generation. Experimental results show that with our system, designers can concentrate on the shape and motion effects, significantly promoting the orientation and speed of design.

1. Introduction
The kinetic sculpture [1] is a special kind of sculpture, which comprises many rotating units installed on an axle (Figure 1). Hence, such sculptures show periodical dynamic deformation effects as the units rotate. The complex structures and effects make the design of the sculpture professional and time-consuming. Most existing kinetic sculptures are designed by experts or teams [2].

Figure 1. Kinetic sculptures with many rotating units.

Visual effects and aesthetics of shapes and structures are more stressed in the design of installation art, compared with functional machine design. In static art, many researchers proposed excellent methods of shape modeling [3,4]. While in kinetic art, most existing studies are on their dynamics [5] and controls [6]. The shape modeling of dynamic effects is less studied. In 3D design, the sketch is friendly guidance and driver for novices [7]. There are many studies on the mesh generation [8, 9], and animation [10], offering easier ways for designers to get complex models. But for the collaborative modeling and assembly of many parts, sketch-based methods need to be more studied; they are quite promising. Thanks to the development of CAM technologies such as 3d printing [11,12], designers have
more choices to process complex installation artwork at a lower cost. However, existing studies cannot tackle the problems in the design of kinetic sculptures: (a) It is hard to take dynamic effects into account all the time during the design process. (b) Designers need more focus on the holistic shape rather than part details. (c) Professional CAD tools are hard for novices.

In this paper, we proposed a top-down design framework of kinetic sculptures. We use sketch curves as the rough shape of the sculpture, and propose the dynamic cage for the user to visualize and manipulate the sculpture’s shape deformation effects. We use skeletons built from the cage to drive the unit shape modeling. Even novices can build a digital model of a kinetic sculpture easily and fast.

2. Methodology

2.1. Dynamic cage construction and deformation simulation

Our framework starts with input sketch curves that indicate the holistic shape of the sculpture. Such sketch curves can be free-form splines or regular parametric curves such as the helix, ellipse, etc. Among all the sketch curves, the user needs to choose one as the axis around which all units will rotate. Note that the sculpture’s shape is dynamic, deforming all the time during the sculpture’s revolution, so static sketch curves are not enough to represent sculpture’s holistic shape. We propose the dynamic cage to enable the user to see and manipulate the dynamic shape.

A dynamic cage is a group of dynamic curves. Given an axis a, a group of sketch curves \( \{c_1, c_2, \ldots, c_m\} \), below is the algorithm of constructing a dynamic cage (see an example in Figure 2):

1. Sample the axis to get a list of sampling points \((p_1, p_2, \ldots, p_n)\), then build a normal plane at each sampling point to get a group of normal planes \((P_1, P_2, \ldots, P_n)\).

2. For each sketch curve \(c_j\) \((j < m)\), get its intersecting points with all normal planes. If it has multiple intersecting points with \(P_i\), keep the closest one to \(p_i\). Then \(c_j\) is discretized as a list of intersecting points \((p_{j1}, p_{j2}, \ldots)\). Each intersecting point corresponds to a sampling point.

3. Consider \((p_{j1}, p_{j2}, \ldots)\) as control points, and build an interpolation curve \(c_j'\) \((j < m)\) to connect them. All \(c_j'\) construct the dynamic cage.

After the dynamic cage is constructed, the original sketch curves \(\{c_1, c_2, \ldots, c_m\}\) will be replaced by dynamic curves \(\{c_1', c_2', \ldots, c_m'\}\). To see the sculpture’s dynamic shape formed by the cage, the user can assign each dynamic curve with rotation speed. Each control point of a dynamic curve will rotate around its corresponding sampling point based on the tangent vector at the sampling point. Therefore, all dynamic curves are updated in real-time by the rotating control points, as shown in Figure 2.

![Figure 2. Auto-construction and updating of the dynamic cage.](image)

2.2. Interactive cage editing

To edit the dynamic cage’s shape, the user can drag a control point of the dynamic curve. But such operation has very low efficiency when adjusting many control points. For easier and faster cage morphing, we propose 3 types of cage deformation (see in Figure 3) for users to choose. Suppose that dragging a control point \(p_{ji}\) applies a transformation \(T\) to it, then the 3 types of cage deformation are:
(1) **Tangent deformation.** All control points on the same normal plane with \( p_{ji} \) will change with \( p_{ji} \). For such a passive control point \( p_{di} \), it will execute a transformation

\[
T \left[ x_1 y_1 1 \right] \left[ x_2 y_2 1 \right]^T / ||p_{ji} - p||^2,
\]

where \((x_1,y_1) = p_{di} - p, (x_2,y_2) = p_{ji} - p, p\) is \( p_{ji} \)'s corresponding sampling point on the axis curve.

(2) **Axial deformation.** The other control points on the same dynamic curve with \( p_{ji} \) will change with \( p_{ji} \) gradually. For such a passive control point \( p_{jk} \), it will execute the transformation

\[
kT/i, (k < i), \text{ or } (M - k)T/(M - i), (k > i), \text{ where } M \text{ is the number of control points on the dynamic curve.}
\]

(3) **Neighbor deformation.** \( p_{ji} \)'s neighbor control points will change with \( p_{ji} \). For a neighbor control point \( p_{dk} \) on the same normal plane with \( p_{ji} \) or \( p_{jk} \), respectively, it will execute an angle-degraded transformation

\[
((2\theta/\pi)^2 - 1)^2 \Delta T, \text{ where } \theta \text{ is the angle between } p_{ji} \text{ and } p_{di} \text{ or between } p_{jk} \text{ and } p_{dk}.
\]

![Figure 3. Three types of cage deformation when dragging a control point.](image)

2.3. **Unit generation based on skeletons**

After the cage shape manipulation, the sculpture’s holistic shape is determined. We propose deformable skeletons constructed from the cage to drive unit shape modeling. Given the number \( N \) of requiring units, the axis is sampled again to build \( N \) normal planes to intersect with the cage. Each normal plane will have several intersecting points with the cage curve. We provide 3 types of skeletons based on the points on a normal plane (see in Figure 4) for the user to configure. The free-connected skeleton is drawn manually by connecting points. The skeleton shape is also editable. Each line segment in a skeleton is a spline with middle editable 2 control points.

![Figure 4. Skeleton shape of different types.](image)

Once a skeleton’s shape is determined, a unit can be generated from it. For the polygon skeleton, the unit is generated by extrusion with configurable bead size and depth. For the radial and free-connected skeletons, the unit is generated by sweeping with configurable section shape and size, and unit decorations such as balls and plates.

The configuration of one skeleton can be propagated to other normal planes for batch generation of skeletons and unit models. The propagated data includes the skeleton type, the relative positions of the middle 2 control points concerning 2 endpoints of each spline segment, and the skeleton shape configurations. The user can also build different skeletons for different normal planes to get more diverse unit models if they like.
3. Experiment
To evaluate our framework, we developed a prototype system (see the user interface in Figure 5(a)). The user can draw curves, simulate and manipulate cages, configure skeletons, and refine units. We recruited 2 experienced designers and 2 novices for experiments.

3.1. Design cases
We spent 30 minutes teaching them how to use our system and gave them another 30 minutes to get familiar with it. Then we asked them to design some kinetic sculptures in 20 minutes. Each participant can operate the system fluently and designed several sculptures (selected results are shown in Figure 5(b)). The average time for designing a kinetic sculpture is less than 10 minutes. While in traditional tools, as described by the 2 experienced designers, it always takes hours because they cannot skip a lot of part details, and have to rework due to the lack of overview control of the sculpture effects. Our system enables the designer to manipulate the sculpture’s holistic shapes first, significantly reducing the rework compared with traditional tools where detailed parts must be modelled to see motion effects.

![Figure 5](image1.png)
(Figure 5). The user interface of the kinetic sculpture design system and some selected design results.

3.2. Fabrication
We selected a design result with a straight axis for easier fabrication. All units are refined in CAD software (adjust hole sizes, add beads, etc.) and 3D printed, and the sculpture axle is steel. We used motors for more feasible motion driving and used bevel gears to realize the inverse rotation of units. Figure 6 shows the fabricated kinetic sculpture and the photos at some moments in its revolution. The sculpture’s holistic shapes executed periodical dynamic deformation effects.

![Figure 6](image2.png)
(Figure 6). A fabricated sculpture and its revolution moments.

3.3. Limitations
There are also some limitations. First, our system has not included dimensions and 3D models of standard machine parts, such as the bearings. If they can be integrated into our system, the machine design flow will be more seamless with fabrication. Second, aiming at shaping for novices, our system does not have physical analysis or auto-optimizations, such as friction, stress, and dynamics. Such
analysis has to be done in other software by professional engineers currently. The integration of design, analysis, and optimization will make the whole process a closed loop.

4. Conclusion and future work
In this paper, we propose a top-down design framework for the kinetic sculpture. Novice designers can build a digital prototype of a kinetic sculpture from sketches interactively without any barriers. We have made the following contributions:

- We are the first to propose the top-down design framework of the kinetic sculpture, including sketching, cage simulation and editing, skeleton configuration and unit model refinement. Such a framework meets the requirement of visual effects in the design of the kinetic sculpture.
- We proposed a shape modeling and manipulation method for the holistic shape of many rotating parts based on the dynamic cage. Designers can manipulate the sculpture’s holistic shape’s dynamic effects without modeling any part details first.
- We proposed the skeleton-driven unit shape modeling configurations for the kinetic sculpture, carrying the skeleton prototype forward to 3D assembly models and practical fabrication.

In the future, we plan to study the integration of physical analysis, such as stability, dynamics, kinematics, motor-driven mechanisms, materials, and motion-transmissions, and the auto-optimization process to realize the closed loop of kinetic sculpture design. Besides, the bottom-up design methods and interactions in kinetic sculpture design are also interesting research topics.

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