Rapid Prototype Design of the Kinetic Sculpture Based on Sketches and Skeletons

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Abstract—The kinetic sculpture is an important aspect of modern urban landscapes and installation art. However, designing such a sculpture needs much time, imagination, engineering knowledge and even rework, which restrains iterations of design and imagination of artists. To allow designers to have a holistic perspective in design, and to simplify and accelerate the design process, we proposed a system to assist designers to build kinetic sculpture digital prototypes from sketches rapidly. The system simplifies the design pipeline as sketch processing, skeleton generation, unit assignment, and motion simulation. Different from other design tools, our system liberates designers from detailed modeling and animation. Therefore, they can focus on perfecting visual effects. User cases show that our system can spark the creativity and accelerate design process both for professional and inexperienced designers, and can generalize the pipeline to other kinetic applications.

Index Terms—sketch-based design, kinetic sculpture, prototype design, installation art

I. INTRODUCTION

The kinetic sculpture combines the beauty of engineering and art to provide a richer aesthetic experience for modern society. Numerous works of this type have been created by artists\textsuperscript{1} since the early 20th century. The kinetic sculpture with a large number of rotating units is a very attractive genre (see in Fig. 1) because of its highly repetitive structure and the periodic dynamic effect. The dynamic curves in motion effect are realized by the shape and spatial layout of units, making the design process relatively more abstract than other products, which is hard to imagine and modeling.

Most existing artworks are designed by interdisciplinary experts or teams\textsuperscript{2} after a long time of trial and error. There have been a study on 3 Dimensional (3D) dynamic simulation for kinetic sculptures\textsuperscript{3}. But the operation of the software in this kind requires certain technical thresholds, for which professional engineers are competent. Thus it is apparently not suitable for designers to perform concept iterations in the early stage. Designers need faster, more parametric and intuitive design tools.

II. RELATED WORK

Kinetic sculpture design. With the rapid development of CAD technology, more and more design tools for the interface of art and technology are being developed\textsuperscript{4},\textsuperscript{5}. While research on the kinetic sculpture is really rare. Furuta \textit{et al.}\textsuperscript{3} developed a CAD system for the design of kinetic sculpting based on rigid body simulations. However, their objective kinetic sculpture consists of several parts that are connected and swing freely, which is very different from the rotating kinetic sculpture. Corker-Marin \textit{et al.}\textsuperscript{6} combines multiple projections of 4 Dimensional (4D) space-time into 3D space to create facets and local distortions and create static and kinetic Cubist-style sculptures. Related product designs include designers like Raine\textsuperscript{7} who, on the basis of dynamics, explored the design laws that maintain the similarities between static and dynamic states when sculptures were transforming. There has not been a systematic design method on kinetic sculptures with rotating units. We proposed a top-down design method for it using sketches.

Sketch-based design. Sketch is the simplest auxiliary design method. People are used to conveying geometric
shapes and psychological images through sketches [8]. In computer-aided design, researchers have introduced a series of 3D freeform design systems based on 3D curves [9], [10]. Liu et al. [11], [12] proposed a three-dimensional modeling method with an editable plane curve as the core, which further simplifies the designer’s work. The above research effectively promoted the design of complex product forms, which, however, mainly focused on the static shape of the product or mesh generations. Our work enriches the research on dynamic product design.

III. DESIGN FLOW

This paper focuses on the rotary type of kinetic sculptures. Such a sculpture comprises a straight or curved axis, and a rotary unit array installing on the axis. Units rotate around the axis uniformly or independently, depending on different structures and powers, forming orchestrated dynamic visual effects. To get a universal design pipeline, we carried out a pilot study on designing such sculptures.

A. Pilot Study

Five Students majoring in industrial design with a good mastering of Cinema 4D (C4D) are invited to this pilot study. We provided them with a series of pictures and video materials of kinetic sculptures of different artists before the experiment for familiarity. Then they are asked to design kinetic sculptures freely with C4D. In the design process, 2 kinds of design approaches emerged.

- The first one is top-down: designing from sketches. Curves in the sketch are used as the axis and contours of the sculpture. Common axes are generally 2D straight lines, circles, and arcs. Contours represent the connecting curve of outermost points of all required units. Then units are arranged and modeled based on them.

- The second one is bottom-up: designing from the rotary units. All units are modeled first, then an axis is modeled. After that, units are arranged and deformed to compose a holistic sculpture shape.

The 2 approaches are inverse. We found that the sketch-based method is more generalized. When a sculpture is in regular shape (straight/circle axis, identical units), both approaches can build such sculptures. But when the sculpture’s shape becomes irregular, such as ones with curved axis and diversified units, sketch-based approaches provides a more holistic perspective for participants. While designing from units lacks a holistic perspective, making it more likely to encounter tedious try and error.

Then, each participant was asked to reproduce a similar kinetic sculpture with the sketch-based approach to record and analyze the design flow details. The ideal sequence is sketching, modeling the simplified prototype, and making a simulation animation. Blueprints recording participants’ designs are shown in Fig. 2.

We recorded the operation time of each participant, as shown in Fig. 3 The time proportion on modeling and animation is the largest in a design iteration, with an average ratio of 87.2%. After the experiment, most participants said that the prototype design of kinetic sculpture was a challenge for designers. A summary of their feedback is as follows.

- Making animations is very time consuming, which hinders subsequent changes of the designer.
- In the early stage, designers need to pay more attention to the overall visual effects. It is acceptable to ignore shape details, only keeping basic skeletons to guide later modeling.

B. Design Pipeline

After the pilot study, we concluded 5 participants’ feedbacks and discussed with them to build a universal design pipeline for a more automated process reinforced with Computer Graphics (CG) and CAD technologies.

Our final design pipeline of the kinetic sculpture includes the following steps, as shown in Fig. 4.

1) Sketching. Draw a axis and contours for a kinetic sculpture. Considering the aesthetics and manufacturing, the axis should be smooth. Contours can be 2D/3D.
2) **Skeleton generation.** The system solves the skeletons of each unit automatically. A skeleton comprises several radical lines starting from the axis and ending on the contours. Skeletons will be used in unit assignment.

3) **Unit assignment.** Units are generated automatically based on the previous step's skeletons. The user can get varied unit shapes by selecting different types before generation, or import unit modeled with other software.

4) **Motion simulation.** The user assigns rotation speed controls of all units and simulate the motion to see the dynamic visual effect.

### IV. METHODOLOGY

In this section, we show the details of each step in the design pipeline, and how they are reinforced and automated by CAD/CG technologies.

#### A. Sketch Processing

It is not difficult for most designers to draw 2D curves with CAD tools such as Rhino. However, the outline of a kinetic sculpture is usually a smooth continuous space curve, such as a spring line. We use the following steps to transform a 2D sketch curve to a 3D curve by projection:

1) **Projection surface generation**

This step is to determine the projection surface for the 2D sketch. After drawing an axis curve, the user can adjust a radius parameter to make the system automatically generate a tube-like geometry using curvilloft, or assign other geometries from the library, as the projection surface. Then the user can proceed to draw contours.

2) **Projection**

This step is to generate various 3D contours for users to refer to. Project a 2D contour in the direction perpendicular to its base plane on the projection surface. The projection may generate points where the projection surface has a normal almost parallel with the contour's base plane. If it is the most parallel within a neighbor region, set it as the tangent point. The tangent points are special points where the projected contour can go to the other side of the surface. So the user can select a contour segment between 2 tangent points and decide which side it is projected on. Two different projections with the same contour and surface are shown in Fig. 5.

#### B. Skeleton Generation

A unit's skeleton is some lines starting from the origin of a unit and ending on the contours. The origins of units are on a point of the axis curve. A skeleton rotates around its Z-axis which is aligned with the tangent of the axis point. So, the skeletons can be generated by intersecting normal planes, which are located at sampling points on the axis curve, with these contours.

A parametric axis curve \( a = (x, y, z) \) is indicated as:

\[
\begin{align*}
  x &= \phi(t) \\
  y &= \psi(t) \\
  z &= \alpha(t)
\end{align*}
\]

Therefore, the tangent of a sampling point is \( T = (\phi'(t), \psi'(t), \alpha'(t)) \). The sampling normal plane family \( P_s = (x, y, z) \) is indicated as

\[
(x - \phi(t))\phi'(t) + (y - \psi(t))\psi'(t) + (z - \alpha(t))\alpha'(t) = 0
\]

So, given a contour \( c_i = (\phi_i(t), \psi_i(t), \alpha_i(t)) \), its intersecting points can be computed by solving the simultaneous equations of its parametric formula and (2). For an intersecting point \( p_i \) on the sampling point \( p_s \), then a skeleton line \( l = p_s p_i \) is obtained.

To provide precise control on getting intersecting points, a distance threshold \( d \) is employed. Given a sampling point \( p_s \) on the axis curve and a detected intersecting point \( p_i \), if \( ||p_s p_i|| > d \), the intersecting point will be ignored. This can exclude far intersecting points. For example, given 2 concentric circles as the axis and contour, the generated skeletons are as shown in Fig. 6a rather than Fig. 6b. The threshold is set by the user. Similarly, intersecting points too near to sampling points will also be ignored.

To generate all units’ skeletons, the user needs to set a sampling number \( n \) (\( n > 3 \)). The system will generate an equidistant array of \( t \) for sampling the axis. For an open curve of axis, the array is \( (0, 1/n-1, 2/n-1, ..., 1) \). While for the closed curve of the axis, the array is \( (0, 1/n, 2/n, ..., 1) \). When computing intersecting points, specific contours can be selected. This allows the user to build several sets of skeletons which will be used for different motions later. The user can use an additional bias factor \( b \) to stage these skeletons, as shown in Fig. 6c.

The bias factor will be added to each element in the \( t \) array to change their values, where \( 1 < b < 1/(n-1) \) for the open curve axis and \( 1 < b < 1/n \) for the closed curve axis.

![Figure 5](image-url)  
**Figure 5.** Different results of converting a 2D circle to a 3D contour using projection.

![Figure 6](image-url)  
**Figure 6.** Threshold and bias in the skeleton generation.
C. Unit Assignment

After all units' skeletons are obtained, our system provides some shape types for the user to select. Then all units' 3D models can be generated based on the shape type and skeletons. Generated units are parametric models so they are easy to modify. The provided shape types are (a) straight, (b) curved, (c) rigid. Given a skeleton \( S=\{l_1, l_2, \ldots\} \), different shapes are generated with the following methods, as shown in Fig. 7.

- **Straight.** Use a circle to sweep along each skeleton line \( l_i \) to get rod-like geometries.
- **Curved.** Generate rod-like geometries and bending them in tangent directions. The user can assign the bending degree.
- **Rigid.** Build a polygon by connecting all ends of lines in \( S \). Then extrude the polygon to generate geometries. The user can assign the radius of circular beads at each end.

The user can attach additional geometries at the ends of straight or curved shape units to intensify the visual effect.

![Figure 7. Three types of automated unit model generation. a. skeleton. b. Straight unit. c. Curved unit. d. Rigid unit.](image)

Besides automated generation, the user can also build more complex models with other professional modeling software and import it in our system. The assigning and deforming steps are:

1) **The user assigns the imported model's rotation axis.**
2) **The user assigns one point on the imported model with the end of a skeleton line.**
3) **The system clones, rotates, and radical scales the imported model to fit all skeletons.**

After the unit assignment, the digital prototype of a kinetic sculpture is obtained. All units are in a required layout based on the axis and contours.

D. Motion Simulation

To reduce time spending in simulation animation, we build the motion simulation model for the system to enable users to easily get diversified controls on unit rotations. Our system provides 3 types of motion configurations.

- **Unified speed.** All units rotate around the axis at a constant speed.
- **Grouped speed.** Each group of skeletons can have its velocity, as shown in Fig. 8. This configuration can build differential or cross rotating effects.
- **Varied speed.** Since all units rotate around the axis, they will form a tube-like envelope in motion. In this configuration, the system will show this envelope to the user. The user can draw new contours on the envelope and assign corresponding time to set each units rotation speed during the motion, as shown in Fig. 9.

![Figure 8. Grouped speed control of units.](image)

Figure 9. Varied speed control by envelopes and additional contours. Units will rotate from the red marks to blue marks with different speeds.

V. EXPERIMENTS

A. Design Case

We conducted a user study including 6 students majoring in design and having no prior experience in designing kinetic sculptures, and 3 experienced designers having modeled several kinetic sculptures before.

We showed the 9 participants some videos of kinetic sculptures, and explained what axis and contours were, and how they can express the structure of a kinetic sculpture through skeletons. Then they were taught the basic operations of our system. Participants were asked to sketch the design on paper and then create their prototypes and animations in 20-30 minutes. While in our pilot study, an experienced designer may need more than an hour.

![Figure 10. Design results of kinetic sculptures with our system](image)
All participants created objects based on their ideas, and Fig. 10 shows some of the results they achieved. In the design process, many novice users were gradually capable of finishing a creative design with their styles from the initial imitation towards existing kinetic sculpture.

B. User Feedback

Representing the structure of the kinetic sculpture with sketches is very clear to the designer's ideas. Under the guidance of the interface, all participants have no difficulty in the design process. This design approach helps designers start with a vague idea and gradually improve it. After the completion of the first design, many users have released more styling ideas through the modification. To quote a novice user, "This design process not only saves time for modeling and simulation but also helps me achieve more ideas. I am willing to try different outlines and units in the design process." An experienced designer says, "Creating a kinetic sculpture was a heavy work for me in the past, which limits designers' design iteration. This tool helps me save a lot of time on modeling and making animations so that I can try more design directions." In short, the feedback shows that our system does it can help novice designers create a rich kinetic sculpture prototype without barriers.

C. Extending to other Applications

Our design pipeline and automated methods can also be extended to wider design fields and accelerate the process.

Interactive arts. The need for new forms of interaction in artworks is an inevitable trend. While the spatial order and dynamic visual effects of kinetic sculpture are born for various interactive art. Wave is a kinetic sculpture that combines wind speed sensors. The speed of wave motion changes with wind speed. Through this application, we intend to demonstrate how can users to guide the design of dynamic products in the early stages. First, we draw sketches on the paper (Fig. 11a), secondly, we got the prototype’s model and simulation (Fig. 11b). After the prototype achieved a desirable effect (Fig. 11c), based on the original model’s data, a detailed model and finally processing production will go on (Fig. 11d).

Dynamic architectures. Artists may use movement to attract attention, to intensify old ideas, to transmute the visible world or to construct new architectonic forms [13]. With a straight axis and the rigid unit generation, we can use our system for the conceptual design of such dynamic buildings (Fig. 12).

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a sketch-based design method for rapid digital prototyping of the kinetic sculpture. We have made the following contributions.

- We proposed a novel pipeline and related automated methods to design prototypes for kinetic sculptures. Designers can build digital models of a kinetic sculpture concisely and rapidly.
- We proposed the sketch processing method to convert 2D sketches to space 3D curves. Many variants can also be generated, effectively sparking the designers' imaginations for later design.
- We proposed the rapid skeleton generation method, which can build skeletons for rotary units along the axis according to sketch curves. Designers do not need to spend much time in arranging and adjusting unit positions and orientations.
- Our system provides compatible unit assignment and motion configurations, allowing designers to get and test sculpture's 3D model conveniently. The pipeline can be generalized to wider applications.

In the future, we plan to study prototype design based on an array of sketches, in which each sketch represents a shape contour of the sculpture at some time point in motion. In addition, 3D sketch input with virtual reality devices, mechanisms related to fabrication, and light effects design in motions are also interesting research directions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Xinwei Zhang and Jinsong Xiao did the methods, coding and writing; Jin Wang and Guodong Lu...
conducted the research; Yu Liu and Xusheng Zhang did experiments and drawing; all authors had approved the final version.

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REFERENCES


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