Study of the Digital Design Method on Tubular Steel Chair

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Abstract: In order to reduce the repeat design work of designers of furniture manufacturing industry and improve the application frequency of the 3D models, the article analyzes the character of tubular steel chair and presents a digital design method of it based on RhinoScript. With the parameterization of ergonomics sizes and exterior categories based on key curves, surfaces and points, the design work of tubular steel chair especially for the exterior of repeat texture partly can be finished by program, which can raises the efficiency of design and makes the evaluation among the products of different parameter values more convenient. In the last, the design process of a kind of tubular steel chair testified the method.

Key words: Rhinoceros, tubular steel chair, digital design

INTRODUCTION

From 1925 when Marcel Lajos Brever designed Wassily chair which is the first tubular steel chair in the world, tubular steel chairs have become a necessity to our life. Because of their material's character, they are durable with simple and beautiful appearance.

Common design process of industrial product is shown in Fig. 1. The chair of large production should have many proposals with different exterior to match human's body size and meet persons' preference. Therefore, standardized and digital design program is needed to make the design process of such chairs more simple and more fast (Liu and Sun, 2009).

The powerful and innovative 3D modeling software called Rhinoceros, or Rhino for short, is good at NURBS modeling. It can create, edit, analyze and translate NURBS curves, surfaces and solids in Windows (Acheson and Hardin, 2003). As one of the mainstream industrial design software, it has powerful modeling functions and simple interface. There are many plug-ins for it, such as Grasshopper, EasySite, Alibre Design, Tech3Gems and so on. They are parametric modeling tools for different industries to meet their design requirements.

The study on this 3D modeling software is still at a preliminary stage in domestic research. Dai et al. (2004) realized design and implementation of two-dimension, three-dimension transformation with Rhino3D developer platform based on V^{**}. Pan and Jiang (2007) developed modeling system of Tiffany lamp-chimney based on Rhino with VC. Su and Liu (2010) use Rhino.Net SDK (Software Development Kit) to develop ship design system based on Rhino. Su and Liu (2010) realized the rapid design techniques of crystal light based on Rhino using VB.

According to previous studies, there are four ways for secondary development of Rhino commonly: (1) Command Scripts. This is the easiest way for custom of Rhino with just inputting the script in the command line. (2) RhinoScript. RhinoScript is a scripting language based on VB, simple and easy to understand. (3) Rhino C++ SDK. It is based on the Microsoft Visual C++ platform and can directly generate the plug-in program or dynamic link library for users by the software development package provided by Rhino C++ SDK and (4) Rhino.Net SDK. This approach is similar to the former one. But it can use any kind of net 2.0 languages (Sun, 2010).

METHOD OF DIGITAL DESIGN ON TUBULAR STEEL CHAIR

RhinoScript is the parametric editing script provided by Rhino. Similar to VB, it can develop functional module for special design demand with the parametric

Fig. 1: Present design method of products

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modeling functions provided by Rhino quickly and simply. As RhinoScript is good at avoiding the repeat modeling work, it is chosen to realize the tubular steel chairs' digital design. In this way, the design program could easily generate series of proposals with control parameters changed in less time. The basic aspects of the digital method could be seen in Fig. 2.

The working steps in the process are as follows: (1) Determine the shape of the tubular steel chair and analyze the styling feature. Extract the key curves and surfaces and determine the key points to create them. (2) Do parametric analysis in ergonomic and appearance style and determine the control parameters. Find the location of the key points based on the control parameters. (3) Program to create model. (4) Change the control parameters to obtain a series of products. (5) Evaluate the products in the views of ergonomics, aesthetics, engineering mechanics and so on to get the optimal one.

**Appearance analysis of the tubular steel chair:** There are varieties of tubular steel chair (Fig. 3) and in general it can be classified into four parts which are foot tube, seat tube, backrest tube and link tube. Curve is the key element in its modeling according to the feature of its exterior. Therefore, the key curves are chosen to summarize the chair's styling feature in this article.

As there are many types of geometric curve (Fig. 4) (Rutten, 2004) and the difficulty of creating them is different, simple curve should be chosen to be key curve.
The extraction of the key curves must be in accordance with the following principles:

- **The principle of saving:** The key curve should be simple, such as line, arc and NURBS curve with fewer control points.
- **The principle of full performance:** The key curve should be fully express the chair’s styling features.
- **The principle of segmenting according to geometric characteristics:** At the place having obvious geometric feature (such as vertex, inflection point, cuspidal point, tangent point, etc.), segment the curve and avoid choosing the polyline to be key curve. Ensure that each curve has continuous curvature (except for the key curve of straight line) (Liu et al., 2012).

Besides the key curves, it also needs to determine some key surfaces to help modeling, such as the seat surface and backrest surface. RhinoScript provides a lot of functions to create surface which are Surface from 2, 3 or 4 Edge Curves, Loft, Extrude Straight, Patch, Sweep and so on. Different function need different auxiliary curve. We should choose the easiest way to create and select auxiliary curve based on the way. Then choose the auxiliary point to create the curves and determine their coordinates (Wang et al., 2008).

**Determination of the control parameters**:

Control parameters of human scale:

- The main control parameters according to ergonomics.
- Human’s body scale is the main sources to determine the basic data of the chair. The main data are shown in Fig. 5, including that the depth of the seat d, the width of the seat w, the height of the seat h, the width of the backrest b, the height of the backrest e, the backrest’s angle f and the curvature of the seat g (Ding, 1997; Li and Shi, 2013; Wang et al., 2013).

In order to guarantee the comfort of the seat, the data all refer to the adults’ body scale in ergonomics to determine each of the control parameter’s range.

**Establishment of the coordinate system:** The origin (0, 0, 0) is the center of the circle based on the endpoints of the foot tubes’ bottom with the vertical direction as the Z-axis, the horizontal direction as the X-axis, the front-rear direction as the Y-axis (Fig. 5).

**To determine the coordinates of the key points**:

Determine the coordinates of the key points based on the control parameters of the ergonomics such as the depth of the seat d, the width of the seat w, the height of the seat h, the width of the backrest b, the height of the backrest e, the backrest’s angle f and the curvature of the seat g. Among them, there are absolute coordinates and relative coordinates. Absolute coordinate is directly related to the data of ergonomics and can be determined based on the control parameters of the ergonomics. Relative coordinate is related to modeling and should be determined based on absolute coordinate (Tang et al., 2004).

**Control parameters of appearance style:** When the scale of the chair is ensured, the surface’s texture of backrest and seat is the main content of the appearance style. The backrest and seat surface, as key surfaces, can be seen as a NURBS surfaces with control points \(d_i, (0 \leq i \leq n)\) and its rational fraction is expressed as:

\[
p(u, v) = \frac{\sum_{i=0}^{n} \sum_{j=0}^{m} \omega_i \omega_j \, N_{i,j} (u) N_{i,j} (v)}{\sum_{i=0}^{n} \sum_{j=0}^{m} \omega_i \omega_j \, N_{i,j} (u) N_{i,j} (v)}
\]  

(1)
The surface could be divided into a grid in the direction of U and V and get the location of each node according to the positive operation and inverse of NURBS curves and surfaces (Wang et al., 2000). Then the control parameters of U and V could be changed. And use the nodes \( \text{Pt}_k \) \((k = 0, 1, \ldots, u; l = 0, 1, \ldots, v)\) to create the key curves of texture (Zhou et al., 2006; Li and Wang, 2005) (Fig. 6).

The style of the curves in cell is used to describe the pattern style of the chair. The styles could be classified into four categories: Horizontal straight line, vertical straight line, diagonal slash, and arc. And horizontal straight line is classified into two categories: The upper one and the lower one. Vertical straight line is classified into two categories: The left one and the right one. Diagonal slash is classified into two categories: The one with left lower and the one with right lower. And arc is classified into four categories: The one with center of lower right, the one with center of upper right, the one with center of lower left and the one with center of upper left (Fig. 7).

With the control parameter U and V constant, the combinations of the ten categories of patterns above are as follow:

When select one from the ten categories, the number of combinations A1 is (Table 1):

\[
C(10,1) = \frac{10!}{9!} = 10
\]

When select two from the ten categories, the number of combinations A2 is (Table 1):

\[
C(10,2) = \frac{10!}{2!8!} = \frac{10 \times 9}{2} = 45
\]

When select three from the ten categories, the number of combinations A3 is (Table 1):

\[
C(10,3) = \frac{10!}{3!7!} = \frac{10 \times 9 \times 8}{3} = 120
\]

When select m \((m \leq 10)\) from the ten categories, the number of combinations Am is:

\[
C(10,m) = \frac{10!}{m!(10-m)!}
\]

Above all, the number of combinations of cell is:

\[
A = \sum_{m=1}^{10} C(10,m) = 2^{10} - 1
\]

The number of cell is U x V. As each cell could have different pattern style, the total number of combinations of the surface is:

\[
B = A^{\frac{v}{u}} = (2^{10} - 1)\frac{v}{u}
\]

Some combinations of the entire grid's style are shown in the Fig. 8.

When \(U\) and \(V\) change, there could be more categories. In the situation above, make \(V\) double, the categories of the pattern style could be as the ones in Fig. 9. Above, after parameterization, the appearance of the backrest and seat could vary according to a certain rule.

**Digital design expression:** With the control parameters all determined, the design proposals I can be expressed as:
Fig. 8: Some combinations of the entire grid’s style

\[ I = [S_{ex}, S_{xx}] \]

\[ S_{ex} = (E_p, E_o, E_r, E_d, E_m, E_e) \]

\[ S_{xx} = (E_y, E_v, E_d) \]

\[ E_x = \{E_x, E_{x2}, \ldots, E_m\} \ x = a, b, c, d, e, f, g, u, v, p, a \]

(when X takes different values, Xn differ).

\( S_{ex} \) is ergonomic parameters set. \( S_{xx} \) is appearance style parameters set. \( E_x \) is the categories set of control parameters, \( x \) including the depth of the seat \( a \), the width of the seat \( b \), the height of the seat \( c \), the length of the backrest \( d \), the height of the backrest \( e \), the backrest’s angle \( f \), the curvature of the seat \( g \), \( u \), \( v \) and pattern types \( p, a \). I would be changed by \( S_{ex} \) and \( S_{xx} \). \( S_{ex} \) and \( S_{xx} \) are controlled by \( E_o, E_p, E_r, E_d, E_m, E_e \) and \( E_y, E_v, E_d \), respectively. Therefore, with the parametric relationship, there could be a lot of different designs.

Programming: According to the control parameters, the logic of the modeling is as follows:

- Define the control parameters
- Determine the parametric relationship among key parameters, surfaces and points based on the control curves
- Create the structure curves of the chair’s steel tube
- Re-divide the seat and backrest surfaces’ UV grid
- Set points on the nodes of each cell in the grid
- Create the pattern in the cell based on the nodes
- Set the radius of the pipe and create pipe for each structure curve

The program, following the VBScript’s rules, should combine with the functions of RhinoScript to model. Key curves are created by the function of AddLine, AddCurve, AddArc in Curve Methods. The point, curve and surface are selected by the function in Selection Methods. The functions in View and Construction Plane Methods could be used to define working plane. The objects could be edited with the functions in Object Methods. At the same time, some new function should be defined to realize some specific work. For example, the function piperd (crv) which is used to create pipe with rounded end (Wang, 2011):

```
Function piperd (crv)
    Dim strline, piperd, strline
    strline = crv
    piperd = 1
    strline = "t_Pipe _SelID " &strline & "_Cap = Round " &piperd &"
    _Enter _Enter"
    Call Rhino.command (strline)
End Function
```

Table 2: Values of each control parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (mm)</td>
<td>400</td>
<td>490</td>
</tr>
<tr>
<td>b (mm)</td>
<td>300</td>
<td>390</td>
</tr>
<tr>
<td>c (mm)</td>
<td>340</td>
<td>450</td>
</tr>
<tr>
<td>d (mm)</td>
<td>300</td>
<td>390</td>
</tr>
<tr>
<td>e (mm)</td>
<td>510</td>
<td>640</td>
</tr>
<tr>
<td>f (°)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>g (°)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>h (mm)</td>
<td>5</td>
<td>(e-c+0.26)</td>
</tr>
</tbody>
</table>

DESIGN CASE OF DIGITAL DESIGN ON TUBULAR STEEL CHAIR

Take this kind of chair as an example. Figure 10 it is made of front foot tube, back foot tube, seat tube, backrest tube, back link tube and fixed tube. Extract the key curves and surfaces based on its characteristic and then choose the key points of the lines (Fig. 10).

According to ergonomics, determine the corresponding position of the control parameters in this model and establish the corresponding size model. The control parameter values are as shown in the Table 2.

After that, establish modeling coordinate system and make sure of the position of key points. Take the back link tube of left side as an example (Fig. 11).

The line from P1 to P2 is the key line named as Line22 (line). The line controlled by P2, P3 and P4 is the key line named as Line21 (arc). And the line from P4 to P5 is the key line named as Line21 (line). The coordinates of P1 and P5 are absolute coordinates which are related to the control parameters of ergonomics directly. The coordinates of P2, P3 and P4 are relative coordinates related to P1 and P5. They make sure that Line21 and
The coordinates of key points are as follows.

\[
P_1 = (-d/2, a/2 + 0.0155 / \sin(95/180) \times b, e) \\
P_2 = (-d/2, a/2 + 0.05, c - 0.06) \\
P_3 = (-d/2, a/2 + 0.055, c - 0.26) \\
P_4 = (-d/2, a/2 + 0.035, c - 0.33) \\
P_5 = (-d/2, 0.00, c - 0.3)
\]

Then, ensure the appearance style. Take the backrest as example. Its style is the combination of cross slashes. The backrest surface is divided into a grid of four lines and four columns. And each node in the grid are key points. Figure 12 shows the grid of backrest.

After the parameter determined, programming begins. The number of each size parameters inputted should between the max and min which determined before. Part of the program is as follows:

```plaintext
a = Rhino.GetReal("input a number of the depth of seat (40<=a<=49, unit:cm")
If (40<=a) And (a=49) Then
ElseIf a=40 Then
   Rhino.Print "The number is too small"
Else
   Rhino.Print "The number is too big"
End If
```

Then use RhinoScript to create key curves with the coordinates of key points. When create key surface, we need to use the surface functions, for example, use the function named AdvLofSrf to create the seat surface. At first, create the upper and lower edges named strMScurve1 and strMScurve2.

Then create the seat surface by Loft. Part of the program is as follows:

```plaintext
Rhino.AddCurveArray (Array (b/2, (a/2), c), Array (0.00, - (a/2), (c-1)), Array (b/2, -(a/2), c))
strMScurve1 = Rhino.LastObject
Rhino.AddCurveArray (Array (b/2, -(a/2)+a, c), Array (0.00, - (a/2)+a, (c-1)), Array (-b/2, -(a/2)+a, c))
strMScurve2 = Rhino.LastObject
'create the auxiliary curve for seat surface
Rhino.AddLayer("surf")
Rhino.CurrentLayer("surf")
'select working layer
Rhino.AddLofSrfArray (strMScurve1, strMScurve2)
strSurfaces = Rhino.LastObject
'create seat surface
```

In the stage of creating pattern, the UV surfaces of seat and backrest should be redefined. And create pattern in each cell of the UV surface. Part of the program is as follows:

```plaintext
Const Objecttype = 8 'define the type of selection
secu = 4
secv = 4
'define the value of the surface's UV direction
Redim collet (secu, secv)
'define an array of U and V
Dim strsurfaceAs, strsurfaceA, arpoints, secu, secv
Dim Udomain, Vdomain, Uparam, Vparam, i, j
'define the names of the variables
strsurfaceAs = Array (strsurface, strSurfaceB)
'select a surface
For Each strsurface As string
   If IsNull(strsurfaceA) Then Exit Sub
   Udomain = Rhino.SurfaceDomain (strsurfaceA, 0)
   Vdomain = Rhino.SurfaceDomain (strsurfaceA, 1)
   For i = 0 To secu
      For j = 0 To secv
         Uparam = Udomain (i) + i * ((Udomain (1)-Udomain (0))/secu)
         Vparam = Vdomain (j) + j * ((Vdomain (1)-Vdomain (0))/secv)
         redefine the surface in the direction of U and V
         arpoints = Rhino.evaluateSurface (strSurfaceA, Array (Uparam, Vparam))
         collet(i, j) = arpoints
      Next j
   Next i
```

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