



Sketch-based Computer-Aided Design Tool for Configuration Design of Automobile Instrument Panel

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ABSTRACT

This paper presents two geometric operations--constrained curve beautification and polygonal mesh scissoring--for a sketch-based Computer-Aided Design (CAD) tool for the configuration design of automobile instrument panels. Using the proposed sketch-based CAD, industrial designers and mechanical engineers can work together closely to perform the early-stage configuration design efficiently by drawing candidate sub-panel boundaries on the laser-digitized data of a clay model or a rough CAD model from design sketches. The proposed system supports two geometric operations essential to the collaborative work between industrial designers and mechanical engineers: (1) the beautification of hand-drawn curves, and (2) the scissoring of the instrumental panel to partition it into a set of sub-panels. Although similar geometric operations are available in current commercial CAD packages, they are not targeted toward early-stage collaborative work and are cumbersome and time-consuming to use. The proposed constrained beautification takes as input a free-hand sketch stroke and beautifies it by snapping the stroke to an existing geometric feature, an offset of the geometric feature, or a predefined geometry such as a line, circular arc, or elliptic arc. Once a set of beautified strokes is connected to form a loop, the inside of the loop can be cut out using the polygonal mesh scissoring operation. The effectiveness of the proposed sketch-based CAD is demonstrated by applying the system to several test cases.

Keywords: configuration design, instrument panel, mesh scissoring, sketch.

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1. INTRODUCTION

Automobile instrument-panel design starts when the engineering division receives from the design studio a clay model and its laser-digitized data and/or a preliminary surface CAD model. Fig. 1 shows an example of the early-stage design process of an automobile instrument panel. The initial clay model and the preliminary CAD model show the overall geometry, but they do not indicate how the surface should be partitioned into a set of injection-moldable components, or how other functional components, such as air-conditioning ducts and audio/visual modules, should be attached to the panel. These tasks of configuration design, also known as layout design, need to be performed by the engineering division in close collaboration with the design studio.

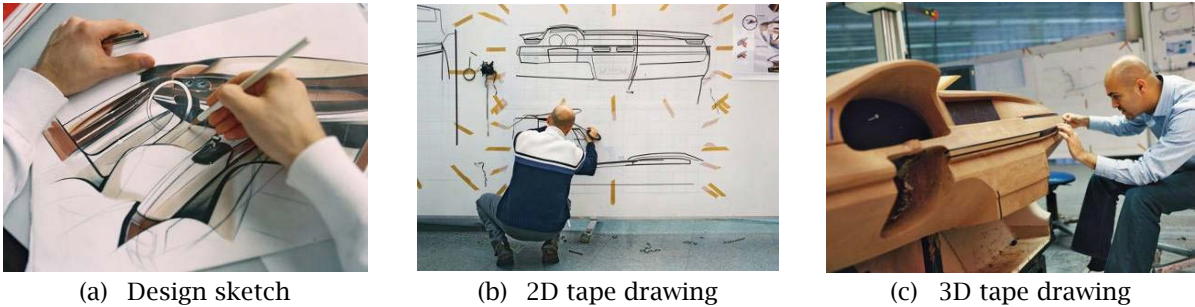


Fig. 1: Early-stage design process of an automobile instrument panel.
(Adapted from: <http://www.bmwblog.com/2008/08/08/behind-the-design-of-the-bmw-7-series/>)

In such an early-stage configuration design, industrial designers of the design studio and mechanical engineers of the engineering division must collaborate closely to perform various design tasks. One of the key tasks in this process is to determine the partitioning of an instrument panel into sub-panels based on Design for Manufacturing (DFM) and Design for Assembly (DFA) considerations. Engineers need to consider other factors such as the choice of fastening methods between sub-panels, structural soundness of the sub-panels, and the cost of manufacturing.

These early-stage design tasks for configuration/layout design need to be completed prior to the detailed geometric modeling of sub-panels, structural ribs, fastening mechanisms, and internal mechanisms, typically performed by using commercial 3D CAD packages. Since there are no specialized and convenient computational tools for these early-stage conceptual and layout design tasks, the industrial designers and mechanical engineers have to hold many face-to-face meetings and communicate their ideas using hand-drawn diagrams and sketches on a sheet of paper or a whiteboard.

The goal of the proposed sketch-based CAD system is to offer a new digital tool to mechanical engineers and industrial designers so that they can freely sketch their ideas on 3D polygonal mesh data created by laser-digitizing a clay model or created as a preliminary CAD model based on idea sketches. Using the system, designers and engineers can express their ideas freely and instantly by drawing with a digital stylus directly on the instrument panel rendered on a tablet computer screen. They can draw the boundary of a sub-panel quickly and cut out the sub-panel to see whether a proposed design idea works or not. The designers can then check the aesthetics of the instrumental panel immediately, while the engineers consider a potential fastening mechanism along with its DFM and DFA issues. The proposed sketch-based CAD serves as an intuitive communication tool, similar to paper and pencil used in the traditional design process, but also offers more realistic visual feedback to designers and engineers, accelerating their thinking and communication process.

This paper focuses on the two geometric operations, constrained curve beautification and polygonal mesh scissoring, for sketch-based CAD for the configuration design of automobile instrument panel. The proposed constrained beautification takes as input a free-hand sketch stroke and beautifies it by snapping it to an existing geometric feature or an offset of the geometric feature. The system will also snap a hand-drawn stroke to a predefined template geometry such as a line, circle, or ellipsis. Once a set of beautified strokes is connected to form a loop, the inside of the loop can be cut out using the polygonal mesh scissoring operation to create a hole or removable sub-panel. The effectiveness of the proposed sketch-based CAD is demonstrated by applying it to several test cases.

2. PREVIOUS WORK

There has been a significant amount of research work published on sketch-based geometric modeling techniques, primarily by researchers from the computer graphics and geometric modeling communities. As part of the functionality, most of the previous work used a version of de-noising, or beautification, methods for free-hand strokes. Among these systems is Igarashi et al.'s Teddy [1], which was built for modeling a free-form 3D shape using gesture-based interfaces and 2D free-hand strokes as well as various practical functions for 3D modeling. Owada et al. studied the design of internal

structures by using a sketch system [2]. Tsang et al. proposed an image-guided pen-based suggestive interface for sketching 3D wireframe models [3]. This system requires an image for each viewport as it uses 2D images as input. Kara et al. presented a usability study with interfaces of sketch-based modeling systems to derive an interface favored by users [4]. Kara and Shimada proposed a template-based automobile exterior design system that can be used to derive car designs rapidly [5-7]. Igarashi et al. applied the concept of interactive beautification to the rapid construction of geometric diagrams [8]. Schmidt et al.'s Shapeshop includes several sketch-based operations for cutting holes, oversketched blending, and adding surface detail [9]. While some of the commercial packages, for example AliasStudio of Autodesk, offer some sketching functions, they are primarily 2D sketch plane-based functions.

Although many previous studies have proposed a variety of techniques on the beautification of free-hand strokes, most of them are limited to beautifying strokes by smoothing out the noises, or undesired wiggles, of a hand-drawn stroke. Unfortunately these methods alone are not sufficient in our specific target application of configuration/layout design of the instrument panel design, which needs to satisfy additional geometric constraints.

Another area of research that is closely related to our sketch-based CAD is the surgical simulator that allows a surgeon to virtually cut and edit a polygonal mesh model [10-12]. Most existing studies on mesh cutting use raw sketch strokes without beautifying them. In our proposed sketch-based CAD system, we use a mesh cutting operation similar to ones used in these surgical applications, but only after the strokes are beautified based on the geometric constraints imposed by the industrial designers and mechanical engineers, yielding a more aesthetically pleasing scissoring result.

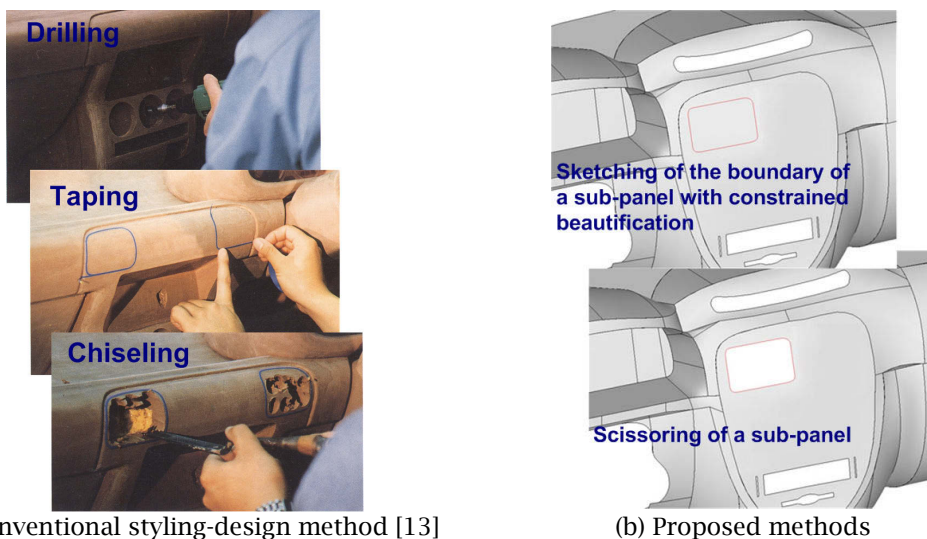


Fig. 2: Comparison between conventional and proposed modeling method.

The unique aspect of our work proposed in this paper is the sketching and mesh cutting based on aesthetic and functional considerations in the early stage design of the automobile instrument panel. The way free-hand strokes are beautified in our system mimics the clay modeling methods currently used in the design studio. These methods include drilling, taping and chiseling operations shown in Fig. 2(a) [13]. Our system enables designers and engineers to perform similar operations on a digital model using two geometric operations, constrained curve beautification and polygonal mesh scissoring, as illustrated in Fig. 2(b). We use the edge information extracted from 3D digitized data as a supporting tool for 3D beautification, and this allows more meaningful 3D sketch modeling. Furthermore, we perform scissoring of the mesh data with beautified 3D curves so that alterations to the design, such as an airbag cover or a ventilation grill, can be sketched more precisely. Further details of the

constrained curve beautification and polygonal mesh scissoring are presented in Sections 3 and 4 respectively, followed by test cases in Section 5.

3. CONSTRAINED BEAUTIFICATION OF HAND-DRAWN CURVES

The key question for our sketch-based CAD system is how to provide a modeling environment that is as easy to use as pencil and paper but also offers more convenient modeling functionality for designers and engineers. Our answer to this question is the constrained beautification of hand-drawn curves.

In the proposed system the user can freely draw candidate sub-panel boundaries on the laser-digitized data of a clay model or a rough CAD model from design sketches using a digital pen, or stylus, and with a single click on the stylus button the user can beautify the free-hand curves to more precise intended shapes. If there are multiple candidate shapes the system shows all the candidates one by one as the user clicks on the stylus button. We call this operation constrained beautification because the final shape is defined based on two types of pre-defined parametric template geometry, as described below.

The first type of template geometry comprises pre-defined common shapes such as circular/elliptic arcs and line segments. As shown in Fig. 3(a), the user can draw a stroke similar to one of these template shapes and beautify it by simply clicking on the stylus button.

The second type of template geometry creates a family of parametric shapes based on geometric features on the input model. For instance, a user can draw a curve that looks like an offset curve of a fillet boundary, as shown in Fig. 3(b), and he/she can beautify it and make it an exact offset with a specified distance by a single button click. Another example is the connecting of curves that are constrained to match tangent directions at both ends, as illustrated in Fig. 3(c). For both types of template geometry, a hand-drawn curve is beautified with the geometric constraints represented by a family of pre-defined parametric shapes. This constrained beautification makes the proposed CAD system easy to use but also capable of more precise modeling.

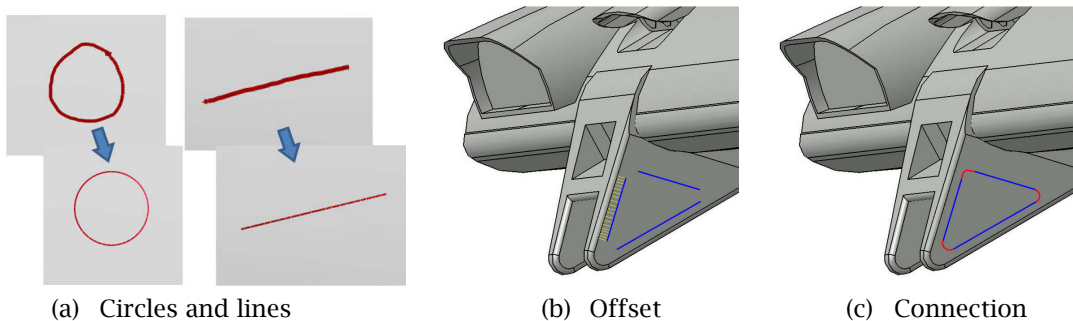


Fig. 3: Examples of constrained curve beautification.

3.1 Preparation for Constrained Beautification

To apply constrained beautification to a hand-drawn curve more reliably, a raw hand-drawn stroke needs to be re-sampled and smoothed. The point spacing in a raw input stroke varies depending on the input device as well as the drawing speed. The system thus needs to re-sample a raw stroke and convert it to a more evenly spaced set of points with a specified density. The point density is determined by the typical minimal feature size used in the automobile instrument panel design, 0.1mm. The system then applies a standard smoothing method, the Savitzky-Golay smoothing filter [14], to remove noise from the hand drawing. The filter performs a local polynomial regression of degree k on a distribution of at least $k+1$ equally spaced points to determine the smoothed value for each point. The method is advantageous in that it tends to preserve geometric features that are usually smoothed out by other adjacent averaging techniques. Finally, re-sampled and smoothed input strokes can be replaced by a set of B-spline curves using the minimum least-squares criterion described in [5].

Another preparation performed by constrained beautification of a hand-drawn curve is the identification of feature curves, such as the boundaries of the instrument panel, curves that represent sharp corners, and the boundaries of fillet regions. There are many methods published on the automated detection of such feature curves from a polygonal mesh. We used one of such methods, Polygon Crawling, to detect feature curves [15]. If the input panel geometry is defined as a preliminary CAD model created from design sketches, such feature curves can be exported directly from the CAD model and imported into our sketch-based CAD system.

3.2 Constrained Curve Beautification

Once the raw hand-drawn strokes are re-sampled, smoothed, and interpolated by using B-Spline, the curve is further beautified by using two-types of template geometry mentioned at the beginning of this section. Since the first type of constrained curve beautification is similar to commonly used methods in symbol and drawing recognition literatures (for example, [16]), the rest of this section focuses on the second type of the constrained curve beautification method.

When beautifying a hand-drawn curve by snapping it to an offset curve of a pre-defined feature curve, the offset distance can be measured on the surface as the geodesic distance or on the imaging plane as the distance on the plane. Our current implementation uses the latter because most of the boundaries of sub-panels cut out of the main instrument panel are defined by offsetting feature curves on a plane facing the driving direction. This is because the sub-panels are viewed by the driver and passenger from their seats, and the sub-panels need to look beautiful from this particular direction.

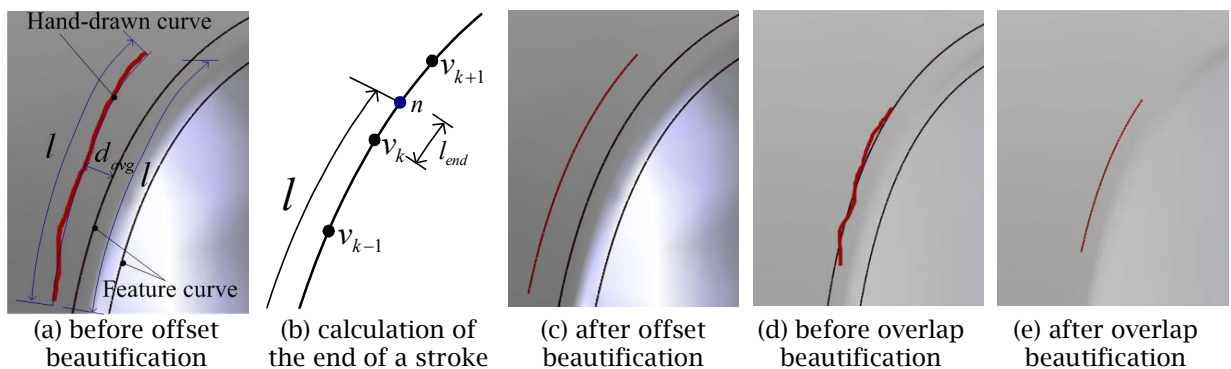


Fig. 4: Constrained curve beautification with offset and overlap template geometry.

Once a curve is hand-drawn on the imaging plane, the system performs a proximity search to see if the new curve is positioned closely to one of the pre-defined feature curves and if the direction and the shape of the curve are similar to one of the offset curves. Based on this geometric calculation and search, the system determines the most likely candidate curve for offset beautification. There often exist multiple candidate curves, in which case the system shows all the candidates one by one when the user prompts it by clicking the stylus button. The red curve shown in Fig 4(a) shows an example of a hand-drawn curve. The curve could be beautified by using the left-hand-side black curve shown in Fig 4(c), but it could be also beautified by using the right-hand-side black curve if the user so desires. Either way, after selecting the intended offset curve, the user can specify a desired offset distance by typing the value on the keyboard or by using a stylus. Note that this proximity and similarity search requires several pre-specified threshold values to decide if the curve should be beautified as an offset curve or based on another type of geometry, such as a circular/elliptic arc or a line segment.

The overlap beautification is a special case of the offset beautification described above. If the detected offset distance is less than a pre-defined small value -- for example 1mm for instrumental panel design -- the system suggests to set it to zero, yielding a beautified curve that is overlapping one of the pre-defined feature curves. Fig. 4(d) illustrates such a hand-drawn curve in red. As can be seen in Fig. 4(e) the beautified curve overlaps exactly one of the feature curves.

Once a beautified curve is determined on the imaging plane, the curve is projected onto the panel surface to define a three-dimensional curve. As also outlined in the flowchart shown in Fig. 5 below, if the average distance defined by Eqn. (3.1), d_{avg} , is within the preset tolerance range, potential feature curves are searched.

$$d_{avg} = \left\{ \sum_{i=0}^n \left(\sum_{j=0}^m \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} / m \right) \right\} / n \tag{3.1}$$

If the average distance is greater than parallel tolerance, T_p , then the offset/overlap beautification procedure is aborted. If the average distance is lower than overlapping tolerance, T_o , then the stroke is processed as an overlapping stroke. The identified feature line is then cut to the length calculated by Eqn. (3.2) and Eqn (3.3). Fig. 4(b) illustrate how l and l_{end} are defined.

$$l = \sum_{i=0}^{n-1} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \tag{3.2}$$

$$l_{end} = l - \sum_{j=0}^k \sqrt{(x_j - x_{j+1})^2 + (y_j - y_{j+1})^2}, \quad n(x, y) = (x_k + l_{end}, y_k + l_{end}) \tag{3.3}$$

Once the hand-drawn stroke is beautified to form an offset curve, the curve is mapped to the 3D panel surface.

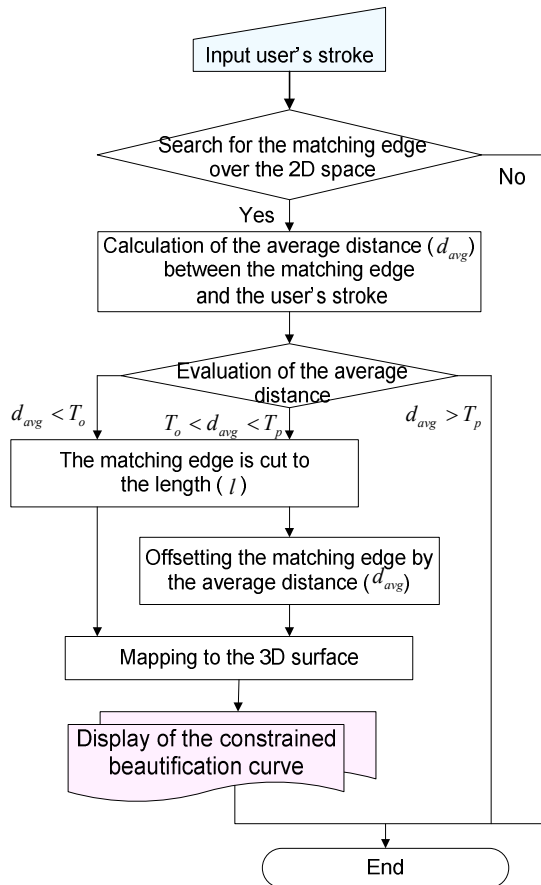


Fig. 5: Algorithm for constrained curve beautification.

The beautification of a set of hand-drawn strokes is followed by two post processes: the projection of the beautified strokes onto the panel surface; and the connection of the beautified curves into a closed loop. Fig. 6 illustrates how three hand-drawn strokes can be connected to form a single closed loop. The system checks the proximity of all the end points of nearby strokes and identifies which strokes need to be joined to form a closed loop. The stroke is first rotated by angle α and then scaled by Eqn. (3.4) as also shown in Fig. 6(b). The loop information is made available for the next step, polygon mesh scissoring, described in Section 4.

$$S = |p_1 - q_2| / |q'_1 - q_2| \tag{3.4}$$

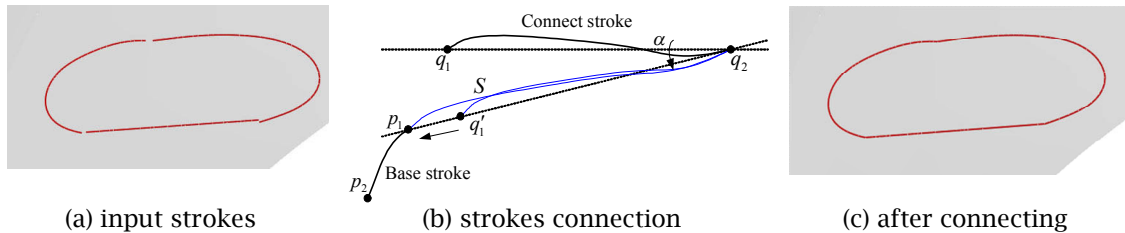


Fig. 6: Connecting multiple hand-drawn strokes to form a single closed loop.

4. POLYGONAL MESH SCISSORING

The proposed mesh scissoring method mimics the operations used by industrial designers and modelers' work on a clay model. These operations include drilling and chiseling on a clay model. If the user of the proposed sketch-based CAD draws a stroke similar to a circle, the system recognizes it and beautifies it to a perfect circle on the imaging plane. That circle is then projected on the panel surface and cut out by the mesh scissoring tool, just like a circular hole is created by a drilling operation on a clay model as shown in Fig. 2(a). Other types of sub-panel shapes can be drawn on the imaging plane, projected on the instrument panel surface and cut out, just like a rounded square hole is chiseled out from a clay model as shown in Fig. 2(a).

4.1 Algorithm

Since the input instrumental panel surface is represented by a triangular mesh, a robust mesh scissoring algorithm can be devised by implementing a limited number of scissoring operations for each triangle in the mesh. When a closed loop is defined on a triangular mesh surface, the curve can cut a triangle in a variety of ways. For example, a curve can go in the triangle through one edge and go out through another edge as shown in Fig. 7(a), or it can go out through the same edge as shown in Fig. 7(b). In another instance, a close loop can go in and out twice as shown in Fig. 7(c). Although there are a number of other possibilities, we recognized the three cases illustrated in Fig. 7 as the most common cases and implemented them in our system. For other cases the system splits the triangle into two by bisecting one of the edges and repeats this operation until the curve intersects all the sub-divided triangles with one of the three patterns shown in Fig. 7.

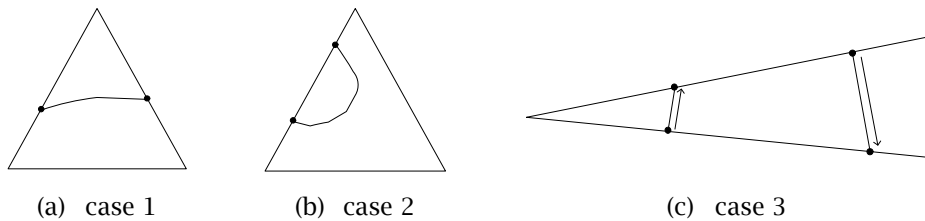


Fig. 7: Three cases of mesh scissoring operations for a triangle.

Once curve segments that form a closed loop are embedded on a triangular mesh by using the three split patterns, then the adjacent triangles need to be subdivided to make sure that the triangular mesh

is conformal, which means that none of the triangles has more than three nodes on its perimeter. Fig. 9(a) shows such a conformal subdivision of a triangular mesh that embeds a closed loop.

After the original triangular mesh is topologically separated by grouping all the triangles inside the closed loop, the sub-panel geometry can be cut out and moved out. The cut-out sub-panel is moved to the average direction of all the normal vectors of the triangles that form the sub-panel. Fig. 8(b) illustrates the cutting-out and moving-out operation.

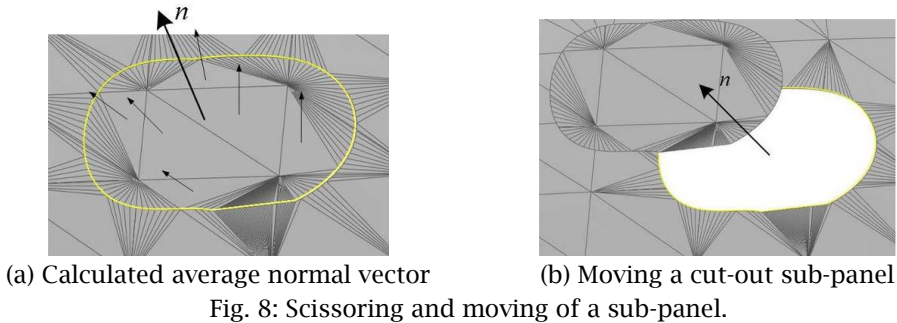


Fig. 8: Scissoring and moving of a sub-panel.

4.2 Performance Evaluation of Mesh Scissoring

It is critical to the success of the proposed sketch-based CAD to have a quick response time when a sub-panel is defined and cut out. We thus measured the computational cost of scissoring operations to verify that our algorithm is sufficiently fast for the purpose of our CAD system. All the computational time is measured on a Windows machine with the specifications described in Tab. 1.

Tab. 2 summarizes the computational cost of two mesh scissoring cases: one represents the largest sub-panel, and the other an average-sized sub-panel. The former took 1.297 seconds to cut a surface with 31,481 vertices and 59,579 triangular faces. The latter took 0.562 seconds.

<i>Item</i>	<i>Specification</i>
CPU	AMD Athlon 64 X2 Dual Core Processor 4600+ 2.41GHz
RAM	2 GB
Graphic	NVIDIA GeForce 7600GT
Graphic RAM	256 MB

Tab. 1: Specification of the test computer.

<i>Number of vertices</i>	<i>Number of triangular faces</i>	<i>Time of mesh scissoring</i>
31,481	59,579	1.297 sec
15,770	28,506	0.562 sec

Tab. 2: Test result for the mesh scissoring.

5. CASE STUDIES AND DISCUSSIONS

Fig. 9 through Fig. 11 show examples of the configuration design of an automotive instrument panel performed by the proposed sketch-based CAD system. Fig. 9 shows the entire process of defining the boundary of a sub-panel by sketching it with a digital stylus (Fig. 9(a)), beautifying the boundary curves (Fig. 9(b)-(d)), and finally cutting out the sub-panel (Fig. 9(e)-(f)). The efficiency of the proposed system for the styling process was investigated by defining typical sub-panel shapes as shown in Fig. 10 and Fig. 11. The sub-panels shown in Fig. 9 and Fig. 10 were created using the offset and connection beautification method, while the operation shown in Fig. 11 shows an example of curve beautification using a circle template. The system has been tested by designers and engineers at an automotive company.

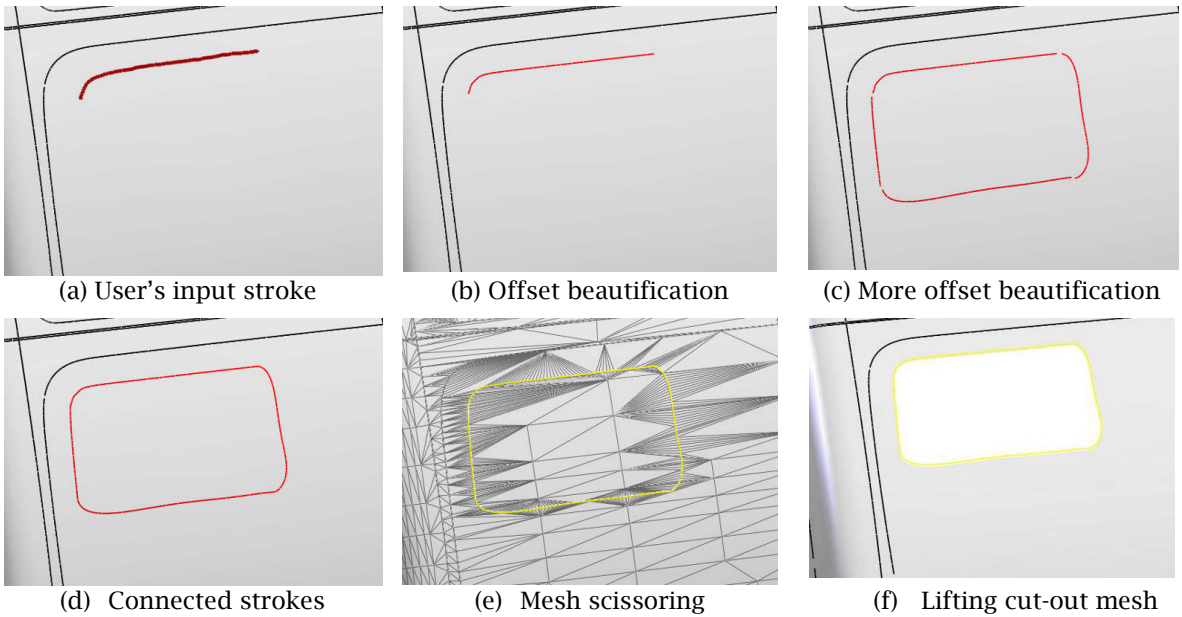


Fig. 9: Drawing, beautification, and scissoring of ventilation grill sub-panel.

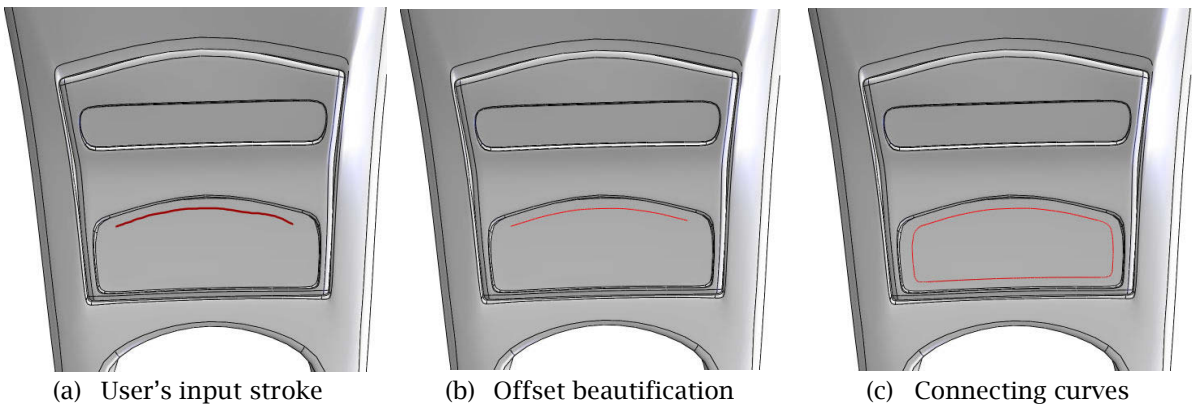


Fig. 10: The constrained beautification operation for the center panel.

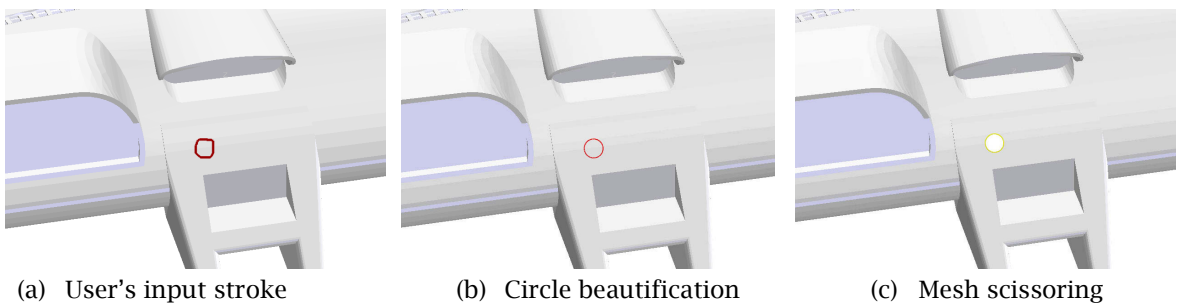


Fig. 11: Circle beautification with mesh scissoring for the instrument panel.

6. CONCLUSIONS

With the proposed sketch-based CAD, industrial designers and mechanical engineers can work more closely and effectively together in the configuration design of instrument panels. The system offers a superior alternative to drawing configuration ideas on a sheet of paper or on a whiteboard. Designers and engineers can evaluate and verify a design idea more precisely and quickly by using an intuitive sketch-based interface. Two critical geometric operations, constrained curve beautification and mesh scissoring, are developed for the sketch-based CAD system. As described in detail in this paper these two geometric operations not only mimic the current physical operations on a clay model but also enable rapid and precise generation and evaluation of sub-panel designs. The proposed constrained beautification methods turn free-hand drawings into more accurate drawings that can be used for defining sub-panel boundaries. A sub-panel can be cut from the instrument panel immediately so that the resultant design can be visually confirmed. The system has been evaluated by designers and engineers of an automobile manufacturer for identifying areas for future improvement. We also plan to expand the application of the proposed sketch-based CAD system to the configuration/layout design of non-automotive products such as toys and consumer electronics.

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