EUROGRAPHICS Workshop on Sketch-Based Interfaces and Modeling (2006)
Thomas Stahovich and Mario Costa Sousa (Editors)

A Sketching Interface for 3D Modeling of Polyhedrons

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Abstract

We present an intuitive and interactive freehand sketching interface for 3D polyhedrons reconstruction. The interface mimics sketching with pencil on paper and takes freehand sketches as input directly. The sketching environment is natural by allowing sketching with discontinuous, overlapping and multiple strokes. The input sketch is a natural line drawing with hidden lines removed that depicts a 3D object in an isometric view. The line drawing is interpreted by a series of 2D tidy-up processes to produce a vertex-edge graph for 3D reconstruction. A novel reconstruction approach based on three-line-junction analysis and planarity constraint is then used to approximate the 3D geometry and topology of the graph. The reconstructed object can be transformed so that it can be viewed from different viewpoints for interactive design or as immediate feedback to the designers. A new sketch can then be added to the existing 3D object, and reconstructed into 3D by referring to the existing 3D object from the current viewpoint. The incremental modeling enables a 3D object to be reconstructed from multiple sketching sessions from different viewpoints. However, the interface is limited to reconstructing trihedrons from sketches without T-junctions to avoid ambiguity in the hidden topology determination.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Methodology and Techniques]: Interaction techniques I.3.5 [Computational Geometry and Object Modeling]: Geometric algorithms, languages, and systems

1. Introduction

Freehand sketching is a fast and efficient way to visualise an idea in conceptual design. A sketch assists designers by allowing their mental images to be expressed externally for further mental synthesis. With the introduction of faster computers, there is a stronger interest in using a CAD system for conceptual design that allows designers to sketch a series of drawings and transfer them to 3D models automatically. There are many advantages to such a computerized system. Some of these relate to how the sketch data is stored (i.e., digital). For example, recent advancements in data storage make it relatively inexpensive to store many sketches in a single data drive (e.g., hard disk). Furthermore, with digital data, sharing and communication of ideas through sketches can be performed easily without loss of information (e.g., strokes sketching sequence, sketching speed and pressure).

However, currently available commercial CAD systems, such as SolidEdge and Pro/ENGINEER, cannot create 3D objects directly from freehand sketches. In particular, extensive menu selections are needed to create a 3D object. Such a process is not as intuitive as sketching with pencil on paper, and hence is not suitable for conceptual design.

In this paper, we present an interactive freehand sketching interface to assist the designers in the early design stage. The interface is intuitive, allowing the designers to sketch out their desired shapes without enforcing gesture sketching, while avoiding excessive menu selection that adds overhead to the design process. In addition, it provides a more natural sketching environment by enabling discontinuous strokes and overtracing, and interpreting natural line drawing (hidden line removed). A novel 3D reconstruction approach is developed to interpret inaccurate online freehand sketches and reconstruct into 3D objects. The 3D object can be transformed by designers to evaluate their design from different viewpoints. The interface is interactive so that designers can work on the sketches progressively. Finally, the reconstructed objects are rendered in sketchy style that have the appearance similar to the original sketches. Figure 1 shows an example of progressive 3D object reconstruction from incremental freehand sketching along the processing pipeline

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of the prototype system. Figure 1(a) shows an initial input freehand sketch. Figure 1(b) shows the line drawing drawing from the vertex-edge graph after 2D tidy-up. Figure 1(c) is the 3D object after the 3D geometry approximation and hidden topology determination. Figure 1(d) shows the transformed object from a different viewpoint rendered in sketchy style. Figure 1(e) shows the object from another viewpoint with new sketches added into the scene. Figure 1(f) shows the updated object with the new sketches reconstructed into 3D. Figure 1(g-h) show the object after several sketching and reconstruction sessions.

There are always ambiguities in hidden topology determination from a natural line drawing because there are infinite possible hidden topology interpretations. However, we have chosen the simplest interpretation, although it might not always be the most plausible. The prototype system is limited to line drawing with T-junction to minimise the ambiguities in hidden topology determination. To date, there is no general solution to determine hidden topology from such line drawing [VMS05]. However, the objects with T-junction can be modelled from incremental reconstruction with multiple sketching sessions.

2. Related Works

There is extensive research in 3D modelling systems based on freehand sketching. It can be grouped into three approaches, based on the sketch interface and 3D reconstruction algorithms utilised by the systems.

1. *Gesture-sketching*: Gestural sketching interprets freehand sketches in a specific way so that some sketching gestures actually mean the 3D reconstruction commands, besides being the objects profile lines. This approach has the advantage of being able to reconstruct 3D objects almost instantly without sophisticated 3D reconstruction algorithms. Zeleznik et al. [ZHH96] was the first to introduce sketching gestures for 3D object reconstruction. [EHBE97] uses a combination of gesture and graph-based geometric constraints to reconstruct 3D objects. In [QWJ00], a system based on fuzzy knowledge is developed to infer user's sketching intentions. SMARTPAPER [SC04] uses a combination of gesture and modified optimization proposed by [LS96] to reconstruct 3D objects. [IMT99] extended the method to model objects with free-form surfaces.
   Although the systems enable direct 3D object reconstruction in real-time from freehand sketches, they are limited in providing a natural sketching interface. Users cannot sketch freely in the gesture-based systems as some of the sketch gestures are interpreted as operation commands rather than sketch contents. Meanwhile, users need to learn and memorise the gestures in advance, and adopt to the associated sketching sequence. Furthermore, new gestures are needed for new objects and must be designed carefully to avoid repetition. Eventually, users will be loaded with too many gestures and get confused.
2. *Geometric correlations approach (analytic heuristic)*: Lipson and Shiptalni [LS02] introduced an optimisation-based 3D reconstruction approach based on geometric correlations between a 3D object and its projection on a 2D plane. Company et al. [CCCP04] improved the approach by introducing tentative model and regularities categorization in the optimisation algorithm. Oh and Kim [OK03] modified the approach by acquiring correct sequence of line sketching.
   Although the systems avoid setting threshold values in decision-making (e.g., parallel and perpendicular lines), the optimisation process is computationally expensive. Furthermore, finding the global minima during the optimisation process still remains a challenge in the implementation of the approach. It fails to generate the most plausible 3D objects when the process fails to reach its global minima. The overall response speed is slowed down by the optimisation process, which makes it inappropriate for interactive sketch-based applications. In [MKL05], an angular distribution graph (ADG) of strokes is used to obtain a preliminary estimation of the shape of the objects. This reduces the complexity of the optimisation method and improves the reconstruction speed. However, it only works well with drawings of objects whose edges predominantly conform to some overall orthogonal axis system.
3. *Perceptual approach*: Lamb and Bandopadhay [LB90] proposed an approach that reconstructs 3D objects from line drawings along the identified principal axis in the axonometric view. A junction is chosen as the 3D reference. The 3D vertices for other junctions are then propagated along the associated axis, referring to the reference junction. Digital Clay [SG00] implemented the algorithm to reconstruct 3D objects from freehand sketches. [CNJC03, NJC*02] extended the approach by using an axonometric inflation method to reconstruct quasi-normalon objects.
   The systems are insusceptible to inaccuracies in the freehand sketches and always return meaningful 3D objects. However, ambiguities can exist in some cases when applying the heuristic perceptive rules. Another limitation is that the approach is only applicable to objects with edges parallel to the principal 3D axes, with vertices lying on an oblique plane that can be identified, or where a symmetry rule can be used to obtain the unknown vertex.

In general, the development of an intuitive sketching interface for conceptual design remains a challenge that has yet to be fully addressed.

3. 3D Modelling Approach

The proposed sketch-based 3D modelling method interprets sketches in an isometric view, which is the preferred viewpoint of most designers. The input is a freehand sketch that is

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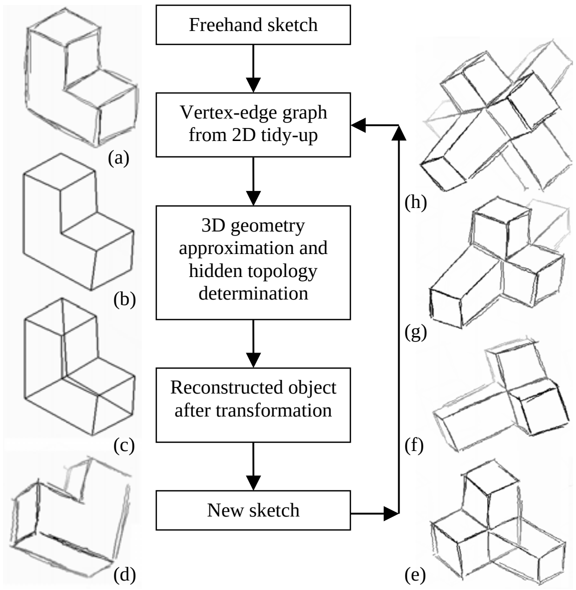

Figure 1: *The processing pipeline of the prototype sketching system.*

captured through a calligraphic interface (Figure 2(a)). The sketch with overtracing is interpreted by a series of tidy-up processes to produce a vertex-edge graph. The graph consists of 2D coordinates and their connectivity of tidied-up line segments from the sketched strokes. The tidy-up process consists of four stages: stroke classification, strokes grouping and fitting, 2D tidy-up with endpoint clustering, and in-context interpretation. Figure 2(d) shows the output after the 2D tidy-up process. The overtracing strokes are grouped into the appropriate segments by grouping process (Figure 2(b)). The grouped strokes are least-square fitted to obtain parametric equations (Figure 2(c)). The endpoint clustering ensures the corresponding edge endpoints meet together and loops are closed formed in the vertex-edge graph (Figure 2(d)). The in-context interpretation ensures that the graph has no 'open' endpoints, i.e., a line drawing depicting a 3D geometry has no unconnected endpoints (more details are discussed in [KQW06]).

After that, a 3D object is reconstructed from the graph. The reconstruction process involves reference junction determination, three-line-junction analysis, vertices approximation, hidden topology determination and planarity enforcement. The approach is not computationally expensive, thus it is simple, easy to implement and able to generate output almost instantaneously. Similar to the perceptual approach that uses the chain propagation process, the proposed approach always returns meaningful 3D objects as output. It is able to reconstruct non-symmetrical, non-perpendicular and non-axis-aligned objects. The characteristics of the reconstruction approach allow 3D objects to be modelled incrementally from multiple sketching sessions. The 3D objects can then be transformed so that it can be viewed from different viewpoints with an appearance similar to the original sketches.

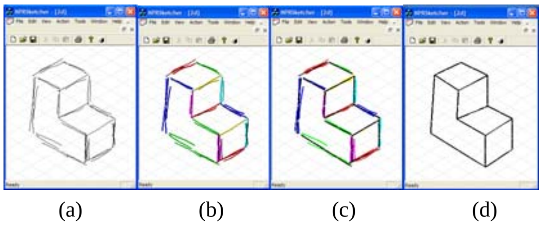

Figure 2: *An example of the 2D tidy-up: (a)Initial sketch; (b)strokes are grouped into segments, which are indicated by different colour; (c)strokes are fitted into parametric lines; (d)the line drawing generated from the vertex-edge graph after 2D tidy-up processing.*

3.1. Reference Junction Determination

The proposed 3D reconstruction approach begins with the identification of edge circuits from the vertex-edge graph that corresponds to actual faces in 3D object. For a natural line drawing with the hidden lines removed, a 3D face corresponds to a non-self-intersecting closed contour without internal circuit [LF92]. It is followed by selection of a reference junction in the sketch plane to be set as the 3D reference. The junction is selected based on the following criteria:

1. The junction consists of only three lines. The reference junction needs to be a junction with three lines so that the three-line-junction analysis can be applied to the line drawing.
2. The junction consists of only three lines. The reference junction needs to be a junction with three lines so that the three-line-junction analysis can be applied.
3. The junction with the longest lines. Longer lines are taken to be more important than shorter lines in the sketch. Effects due to the dimensions represented by the longer lines are more prominent compared to that of the shorter lines. As such, we start the reconstruction process from the longer lines to minimise the deviation while approximating the vertices for the line drawing. Let the lines in a junction be represented by vectors, $\vec{L_i} \mid i = 1, 2, 3$. The line with the shortest length is $L_{short} = min(|\vec{L_i}|)$. The junction that satisfies this criterion is the junction with the longest L_{short}. The longer shortest-line in the junction minimises the deviation. Such selection ensures the junction with the three individual longer lines to be selected as the reference.
4. The junction with lines most aligned to the projection

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axes (x, y and z in Figure 3). That is, the junction with

$$max\left(\sum_{i=1}^{3} max\left|\left(\vec{L}_i \left| \begin{array}{c} \vec{L}_i.\vec{x} \\ \vec{L}_i.\vec{y} \\ \vec{L}_i.\vec{z} \end{array}\right.\right)\right|\right)$$

The selected reference junction is set as (0, 0, 0). The three-line-junction analysis will be applied to the junction to approximate the vertices at the opposite end of the lines.

3.2. Relationship between 2D sketch plane and 3D space

In this section, we identify the relationship of a vertex in 3D world coordinate system and its isometric projection. The relationship allows a line segment in the 2D plane to be interpreted as a corresponding 3D components that give a 3D vertex. Let the 2D sketch plane defined in (u, v) unit. In the isometric projection, the principal axes of the 3D world coordinate system X, Y, Z are projected as x, y, z (Figure 3). The y-axis is parallel with the v-axis, the x and the z-axis are 30° below the u-axis from the origin.

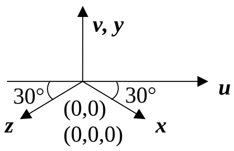

Figure 3: *The axes of the 2D sketching plane and the 3D world coordinate system in the isometric projection.*

A three-line-junction in the sketch represents a three-edge-corner on a 3D object. A three-line-junction with the isometric lines, i.e. lines that are parallel to the projection axes, represents a perpendicular corner. An edge in 3D can be represented by a vector, $\vec{E} = w\vec{X} + h\vec{Y} + d\vec{Z}$, with w, h and d representing width, height and depth in the world coordinate system, respectively. The length of the edges shown in the isometric projection is approximately 0.8165 times shorter than the actual length of the edges on the object itself. In the isometric projection, the vector $\vec{E}$ becomes

$$\vec{L} = a\vec{x} + b\vec{y} + c\vec{z}, \tag{1}$$

with $a = 0.8165w$, $b = 0.8165h$ and $c = 0.8165d$ (Figure 4).

In the 2D sketch plane, a line represented by a vector $\vec{L}$ (Figure 4) can be derived as follows:

$$\vec{L} = i\vec{u} + j\vec{v}, \tag{2}$$

where i and j are the values of the associated 2D vectors, $\vec{u}$

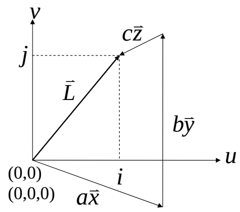

Figure 4: *A vector $\vec{L}$ in 2D and 3D vectors.*

and $\vec{v}$. From equation (1) and (2), decomposition of the vector $\vec{L}$ to its vertical and horizontal components results with the following:

$$i = a\cos 30^\circ - c\cos 30^\circ, \tag{3}$$

$$j = -a\sin 30^\circ + b - c\sin 30^\circ. \tag{4}$$

For the isometric lines, two of the unknown a, b or c are zeros and the 3D vertices of the lines can be calculated from the equation (3) and (4). However, for non-isometric lines, all unknowns are non-zeros. With only two equations available, there is no direct solution to the values. We introduce a novel approach to approximate the values in the following section.

3.3. Three-line-junction Analysis and Assumptions

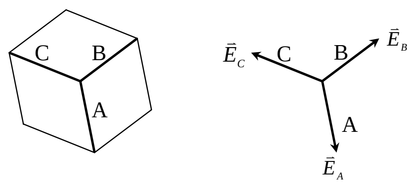

Figure 5: *A three-lines-junctions in a 2D sketch.*

Vertical edges in 3D are more likely to be drawn as vertical lines in 2D sketches based on observation by [LS96]. In a three-line-junction (Figure 5), the line with the greatest slope, line A, is assumed to have $|b_A| \gg |a_A|$ and $|b_A| \gg |c_A|$. Therefore, eliminating either c_A or a_A has little effect on the vertex approximation. That is, the line A is simplified as lying on the XY-plane or the YZ-plane:

$$\vec{L}_{A1} = a_A\vec{x} + b_{A1}\vec{y}$$

or

$$\vec{L}_{A2} = b_{A2}\vec{y} + c_A\vec{z}.$$

With the above assumption, the solution that generates the

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greater b_A value is selected. Line B and C in the junction (Figure 5) are assumed to have least change in the height compare to the line A, which means $|b_A| \gg |b_{B,C}|$. We simplify the solution for the line B and C as lying on the XZ-plane,

$$\vec{L}_{B,C} = a_{B,C}\vec{x} + c_{B,C}\vec{z}.$$

Substituting the equation (3) and (4) into the above equations, the value a, b and c can be calculated. The vetices for the lines in the junction can be determined by using the appropriate equations from the above, based on their orientation in the junction.

Note that there is no assumption of the junction being perpendicular, i.e., the line A is not set perpendicular to the line B and C, and the line B is not set perpendicular to the line C.

3.4. Vertices Approximation

Having selected the reference junction and approximated the vertices for the associated lines, the 3D face equations for the faces touching the junction can be calculated. From the face equations, we can approximate the vertices for the rest of the junctions in the faces. Let a 3D face equation be $px+qy+rz=s$. The 3D vertex for a point in the face with coordinates (i, j) is

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} p & q & r \\ 0.7071 & 0 & 0.7071 \\ 0.4082 & 0.8165 & -0.4082 \end{bmatrix}^{-1} \begin{bmatrix} s \\ i \\ j \end{bmatrix}.$$

After the vertices in the faces touching the reference junction are obtained, the 3D geometric approximation can be propagated to adjacent faces. The vertices for the adjacent faces can be obtained by repeating the above process as long as there are at least three vertices known for the faces. The process is repeated until the vertices for all junctions in the line drawing are obtained. There could be more than one vertex for a junction calculated from the touching faces, the junction will be assigned to the average of the vertices.

3.5. Hidden Topology Determination

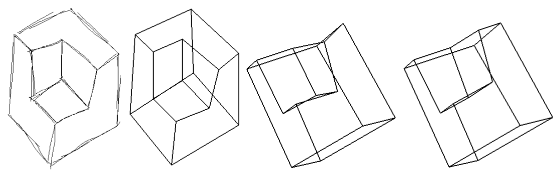
Mathematically, there are infinite hidden topology interpretations for a natural line drawing. We assume the simplest possible objects from the sketches by assuming that every front face and hidden face in the objects meets at an occluding edge.

Determination of the hidden topology generally involves interpretation of junctions. The junctions give information about the existence of hidden edges. To simplify the analysis, the system is limited to interpret trihedrons. There are exactly three lines (front and hidden edges included) connecting to a complete junction in the line drawings.

The analysis starts by searching through junctions in the line drawing. The junctions formed with only two lines are identified. The two-line-junction is the junction with a hidden edge blocked by other parts of the object in the current viewpoint. Two two-line-junction indicating a hidden edge, three two-line-junction indicating a hidden vertex of the object. The hidden edge is the edge connecting the two two-line-junction. For the object with a hidden vertex, the hidden face equations can be calculated from the visible vertices of the faces in the sketch. The hidden vertex is the intersection point of the three hidden faces. Geometry symmetry and mirror are used for the hidden topology determination when there are more than one hidden vertex (also see [VMS04]).

3.6. Planarity Enforcement

A closed contour without internal circuit in a line drawing represents a face in a 3D object, and the contour formed by straight-lines represents a 3D planar face. The vertices approximated in the sections 3.4 might not lie on the associated planar faces. The errors can be caused by the imperfections in the freehand sketches, e.g., the parallel edges are not sketched parallel, the edges that are supposed to be the same length are not sketched to have the equivalent length, and others. We apply the unambiguous planarity constraint to correct the errors on the reconstructed objects. The best-fit face equations are computed from the data points as in [LS96]. The inaccurate vertices are adjusted to form planar faces. Figure 6 shows an example of the reconstructed object before and after the planarity enforcement.



(a) (b) (c) (d)

Figure 6: *An example of a reconstructed object before and after planarity enforcement; (a) initial sketch; (b) reconstructed 3D object; (c) the object before the planarity enforcement; (d) the object after the planarity enforcement.*

The new vertex is obtained by solving the three face equations of the faces connecting to the associated junction. Let the faces connecting to the junction represented by $F_i|i = 1,2,3$ with face equation $p_ix+q_iy+r_iz = s_i$. The intersection vertex of the faces is

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} p_1 & q_1 & r_1 \\ p_2 & q_2 & r_2 \\ p_3 & q_3 & r_3 \end{bmatrix}^{-1} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix}.$$

Although the best geometry might not be approximated through the process, the approach ensures a consistent

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(though not always accurate) approximation. We repeat the reconstruction process from different reference junction to obtain different sets of the 3D vertices, and then have the plane equation calculated from the sets of vertices to minimize the inaccuracies.

3.7. Progressive 3D Reconstruction from Incremental Sketching

Referring to Figure 1, the new input sketch received after the first 3D object reconstruction will be tidied-up to generate a new vertex-edge graph. A new 3D object will be generated from the graph with the same reconstruction procedures as discussed in the previous sections. However, the new 3D object is reconstructed with a new 3D reference, which is on a local reference system (the 3D reference for the first object is taken to be the global reference). The new object needs to be incorporated with the first object in the global reference system to be interpreted in a scene. With the objects in the same viewpoint, changing from the local to the global reference system is simply by translating the new object by the difference between the reference systems. The new object needs to be attached to the first object at the appropriate face. We assume the new object is always added to the visible part of the first object, thus limiting the possible attaching face to visible faces for the first object and hidden faces for the new object. We further apply the condition that only a face from the new object is attaching to a face on the first object. The two faces will be touching each other only when they are overlapping in the sketch and parallel in 3D. However, the perfectly parallel faces seldom present in practical, especially the objects are reconstructed from inaccurate freehand sketches. Let the normal vectors for the visible faces on the first object, $N_i = (l_i, m_i, n_i) \mid i = 1, 2, 3 \ldots$; and the normal vector for hidden faces on the new object, $N_j = (l_j, m_j, n_j) \mid j = 1, 2, 3 \ldots$. The attaching faces are the faces with

$$max\left(\frac{l_i l_j + m_i m_j + n_i n_j}{\sqrt{l_i^2 + m_i^2 + n_i^2}\sqrt{l_j^2 + m_j^2 + n_j^2}}\right).$$

After the parallel faces pair is identified, the overlapping point of the faces in the sketch is identified. The point might be a junction for the new object in the first object face's boundary and vice versa, or an intersection point of the new and first object edges. The global vertex for the overlapping point can be calculated by referring to the first object; meanwhile the local vertex for the point is obtained by referring to the new object. The difference between the global and the local vertex is the translation needed to incoporate the new object with the old object.

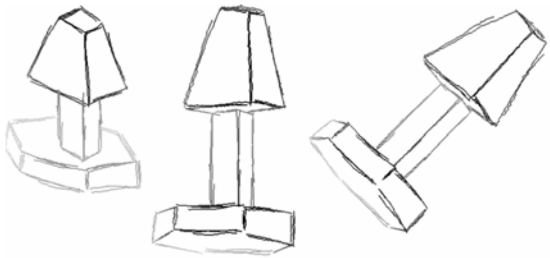
Finally, the attaching face on the new object is adjusted so that it is lying on the attaching face of the first object. After this, the two objects are using the global reference system and can be treated as a uniform scene during transformation. The sketching and reconstruction process is repetitive.

3.8. Personalised Non-photorealistic Rendering (PNPR)

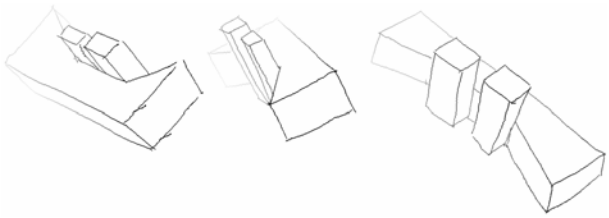
The reconstructed objects are rendered in non-photorealistic rendering (NPR). The silhouettes of the objects are rendered with the sketched strokes, which give the objects an appearance similar to the input sketches (PNPR). The strokes are also rendered in various grey tones to provide depth cues for the 3D objects, with darker tones indicating the closer end and lighter tones indicating the further end.

4. Results

Figure 7 shows examples of the objects reconstructed with the prototype system. The results show that the system is able to reconstruct non-symmetrical, non-perpendicular and non-axis-aligned objects from freehand sketches. It is also able to reconstruct 3D objects incrementally from multiple sketching sessions, as shown in Figure 1(a-h). Figure 8 shows more objects reconstructed by incremental modelling.



(a)



(b)

Figure 8: *Examples of 3D objects reconstructed from incremental sketching with our prototype sketching system.*

5. Discussion

The sketching interface presented in this paper aids designers in the early design stage by reconstructing 3D objects from freehand sketches. It helps designers to compare the spatial relations and relative sizes of objects. The interface provides a natural sketching input environment by handling the freehand sketches with overtracing. Designers can sketch over existing sketches to enhance, complete or correct a line.

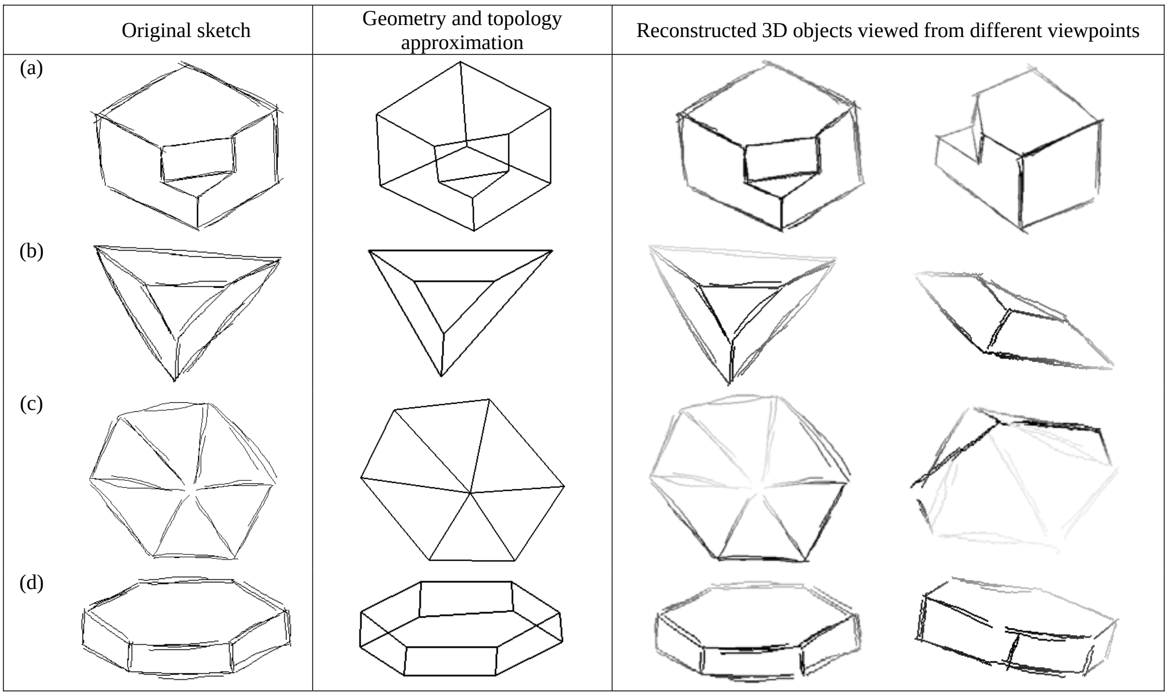


Figure 7: *Examples of 3D objects reconstructed from freehand sketches with our prototype sketching system: (a) non-symmetrical object; (b) non-perpendicular object; (c-d) non-axis-aligned objects.*

Sketches are tidied-up to extract the vertex-edge graph that represents the connectivity of the sketched strokes.

The sketch is then reconstructed into a 3D object by a novel 3D reconstruction algorithm. The reconstruction algorithm utilised by the system is computationally inexpensive, simple and robust compared to algorithms involving many computational parameters and extensive searches, e.g. compliance function and optimization processing [LS96, CCCP04, OK03, MKL05]. In addition, it can be applied to more objects compared to the perceptual-based systems [LB90, SG00, CNJC03, NJC*02], i.e. it interprets not only normalons and quasi-normalons, but also the non-axis-aligned, non-symmetrical and non-perpendicular objects. Extended trihedrons can be reconstructed incrementally from multiple sketching sessions (Figure 1(a-h)). It also avoids the ambiguous heuristic rules. Furthermore, it does not use gestural sketching input that enforces constraints about how objects can be sketched out as in [ZHH96, EHBE97, QWJ00, SC04].

The proposed 3D reconstruction approach is novel and suitable for online sketching applications. The approach approximates the 3D geometry from inaccurate sketches with three-line-junction analysis and unambiguous planarity constraint. In the three-line-junction analysis, the 3D vertices for the lines in the junction are approximated by limiting the changes of up to two 3D components (x, y and z). The approach automatically corrects the inaccuracies in the sketches by enforcing the planarity constraint to the associated faces.

The process of sketching and 3D object reconstruction is repetitive. Designers can sketch directly on any part of the reconstructed object from different viewpoints. The new sketches are reconstructed into 3D and incorporated with the existing 3D objects. The incremental sketching allows the progress of the design to be recorded. The design process can be reused completely or partly to modify or explore other possibilities of the design. The record can be interpreted in a specific manner for evaluation, e.g., a video generated from sketches across a fixed time interval to show the flow of the design process. The output is rendered in a sketchy style with a similar appearance to the original sketched strokes. This helps designers to focus on the design instead of being distracted by the output appearance.

In addition, the 3D reconstruction approach can be extended to reconstruct 3D non-solid objects. Figure 9 shows an example of the non-solid object reconstructed from a freehand sketch with a modified version of the prototype system.

6. Conclusion and Future Work

Several contributions have been made with this prototype sketching system. First, it supports a natural freehand sketching environment with overtracing, which allows designers to

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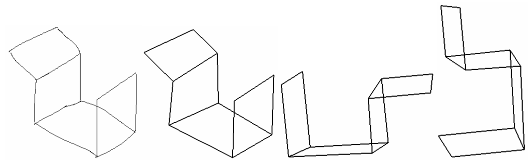

Figure 9: *An example of the non-solid object reconstruction.*

sketch more freely as with pencil and paper. Second, it uses a novel 3D reconstruction algorithm to reconstruct sketches into 3D objects. The nature of the approach, e.g., computationally inexpensive, heuristic-free, insusceptible to input inaccuracies and fully automatic, allows it to support an intuitive and interactive calligraphic interface for conceptual design sketching. In addition to removing the need for gestural sketching, the approach is able to reconstruct the non-axis-aligned, non-symmetrical and non-perpendicular objects. Third, it allows incremental modeling by sketching directly on any part of the reconstructed 3D objects from various viewpoints. Fourth, the objects are rendered in an appearance similar to the original sketches to discourage distraction from the designers to the presentation on the computer.

The system presented here is part of our personalised-sketched-based 3D modelling and rendering system for conceptual design. Further study is required for more polyhedrons and simple curve object reconstruction. The rendering effect of the reconstructed scenes could be improved with more detailed sketches e.g. shadows and textures.

References

[CCCP04] COMPANY P., CONTERO M., CONESA J., PIQUER A.: An optimisation-based reconstruction engine for 3d modelling by sketching. *Computers & Graphics (Pergamon) 28*, 6 (2004), 955–979.

[CNJC03] CONTERO M., NAYA F., JORGE J. A., CONESA J.: Cigro: A minimal instruction set calligraphic interface for sketch-based modeling. In *ICCSA (3)* (2003), Springer-Verlag GmbH, pp. 549–558.

[EHBE97] EGGLI L., HSU C., BRUDERLIN B. D., ELBER G.: Inferring 3d models from freehand sketches and constraints. *CAD Computer Aided Design 29*, 2 (1997), 101–112.

[IMT99] IGARASHI T., MATSUOKA S., TANAKA H.: Teddy: A sketching interface for 3d freeform design. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques* (1999), ACM Press/Addison-Wesley Publishing Co, pp. 409–416.

[KQW06] KU D. C., QIN S. F., WRIGHT D.: Interpretation of overtracing freehand sketching for geometric shapes. In *Proceedings of the 14th International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision'2006* (2006), UNION Agency - Science Press, pp. 263–270.

[LB90] LAMB D., BANDOPADHAY A.: Interpreting a 3d object from a rough 2d line drawing. In *VIS '90: Proceedings of the 1st conference on Visualization '90* (1990), IEEE Computer Society Press, pp. 59–66.

[LF92] LECLERC Y. G., FISCHLER M. A.: An optimization-based approach to the interpretation of single line drawings as 3d wire frames. *Int. J. Comput. Vision 9*, 2 (1992), 113–136.

[LS96] LIPSON H., SHPITALNI M.: Optimization-based reconstruction of a 3d object from a single freehand line drawing. *CAD Computer Aided Design 28*, 8 (1996), 651–663.

[LS02] LIPSON H., SHPITALNI M.: Correlation-based reconstruction of a 3d object from a single freehand sketch. In *AAAI Spring Symposium on Sketch Understanding* (2002), AAAI Press, pp. 99–104.

[MKL05] MASRY M., KANG D., LIPSON H.: A freehand sketching interface for progressive construction of 3d objects. *Computers & Graphics 29*, 4 (2005), 563–575.

[NJC*02] NAYA F., JORGE J. A., CONESA J., CONTERO M., GOMIS J. M.: Direct modeling: from sketches to 3d models. In *1st Ibero-American Symposium on Computer Graphics - SIACG02* (2002).

[OK03] OH B., KIM C.: Progressive reconstruction of 3d objects from a single free-hand line drawing. *Computers & Graphics 27*, 4 (2003), 581–592.

[QWJ00] QIN S. F., WRIGHT D. K., JORDANOV I. N.: From on-line sketching to 2d and 3d geometry: A system based on fuzzy knowledge. *CAD Computer Aided Design 32*, 14 (2000), 851–866.

[SC04] SHESH A., CHEN B.: Smartpaper: An interactive and user friendly sketching system. *Computer Graphics Forum 23*, 3 (2004), 301–301.

[SG00] SCHWEIKARDT E., GROSS M.: Digital clay: Deriving digital models from freehand sketches. *Automation in Construction 9* (2000), 107–115.

[VMS04] VARLEY P. A. C., MARTIN R. R., SUZUKI H.: Can machines interpret line drawings? In *Sketch-Based Interfaces and Modelling, EUROGRAPHICS* (2004), pp. 107–116.

[VMS05] VARLEY P. A. C., MARTIN R. R., SUZUKI H.: Frontal geometry from sketches of engineering objects: Is line labelling necessary? *Computer-Aided Design 37*, 12 (2005), 1285–1307.

[ZHH96] ZELEZNIK R. C., HERNDON K. P., HUGHES J. F.: Sketch: An interface for sketching 3d scenes. In *SIGGRAPH '96: Proceedings of the 23rd annual conference on Computer graphics and interactive techniques* (1996), ACM Press, pp. 163–170.

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