A New Interface for Conceptual Design Based on Object Reconstruction from a Single Freehand Sketch

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Received on January 6, 1995

Abstract

A new system has been developed for improving user interaction with CAD systems, particularly in the conceptual design stage. The system is based on interactive, part-by-part formation of a geometrical model using freehand sketching. A single 2D inaccurate projection is entered in the form of a line drawing. The system analyzes and interprets the input and then reconstructs a 3D model of the object most likely to be represented by the sketch. This 3D model can be further manipulated or modified, and more parts can be sketched. This approach provides a fluent and intuitive tool for conceptual design. In the paper, the proposed system is presented and the basic ideas are discussed and exemplified.

Keywords: CAD, Conceptual Design, Interface

1. Introduction

Recent developments in CAD systems have not brought CAD close enough to product conceptualization in the preliminary design stages. Most users of conceptual design software claim that the CAD interface is not appropriate for sketching even the most basic ideas. Too often, engineers and industrial designers state, "I can do 30 sketches on paper in the time it takes to do two on the computer" [1]. Even though current graphical systems are user-friendly and can be operated by icons, tool-bars, and menus, they are not sufficiently fluent. Moreover, while dimensions and geometrical information are not essential at the conceptual design stage, current CAD systems still require the user to supply this information, thus interrupting the natural flow of ideas.

This research is aimed at developing a natural and fluent graphic interface for producing a conceptual geometrical model in a CAD system. The proposed interface is based on the interpretation of a single hand-drawn projection sketch as a three dimensional object. That is, designers will be able to convey their ideas to the CAD system in the same natural way that they do to other designers. Furthermore, the proposed method represents an improvement over a hand drawn sketch because the model can be entered at several stages and rotated spatially between subsequent sketches, thus always allowing for drawing from convenient viewpoints.

A single two dimensional sketch can be considered as a projection of an infinite number of possible three-dimensional objects (Fig. 1). While unique identification of the source object is impossible, human observers seem to have a definite idea about the original three dimensional object.

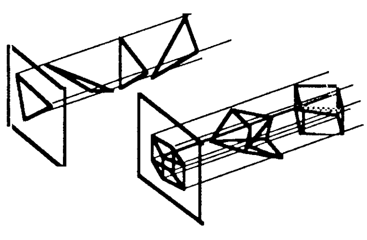

Fig 1. A single 2D sketch can be a projection of an infinite number of 3D bodies

This human capability is not seriously impaired even when the projected drawing is only a rough sketch or if some arbitrary lines are omitted by mistake. It is this capability that must be emulated as the basic model-construction tool for designers in the preliminary stages of product conceptualization.

To meet the needs of the designer, the system must be able to perform on-line reconstruction of the 3D model as the user sketches his 2D representation onto the screen. Since the interpretation is performed on-line, the user can pause at any stage, manipulate the 3D reconstructed model in space, and then proceed to sketch further details, perhaps from a more convenient point of view. This interactive capability also allows the user to verify the system's interpretation of the sketch, delete unwanted elements, and sketch incorrect entities again. The final output of the system is a three-dimensional abstract model, where topology and geometrical relationships represent the intended geometrical concept of the design. Hence, the model has been created without the need for operating commands or providing keyboard input. While the dimensions are not exact, the model is sufficient to communicate the design idea among designers or to transfer it to a conventional CAD system for more detailed design.

The purpose of this paper is to present this new approach, discuss its importance and demonstrate its functionality. In this paper, related work is reviewed first. The basic principles of the proposed system are discussed, an implementation is described, and some examples are provided.

2. Related work

Identification and classification of pen strokes as basic geometrical entities has typically been achieved using curvature analysis [2], where curve-fitting is used primarily for smoothing [3]. Work on reconstruction from single sketches so far has dealt only with linear segments of polyhedral scenes and therefore has not confronted the classification problem. Considerable work has been done on reconstruction of 3D objects from three or two orthogonal projections, e.g. [4-5]. These methods rely mainly on correlating different views while making use of mutual orthogonality for deriving spatial information; thus, they are not applicable here. Single view scene analysis has been studied qualitatively by Huffman [6] and Clowes [7]. Their approach was further developed by Kandae [8] and Sugihara [9]. Refer to the bibliography of [9] for more extensive discussion of this subject. These works resulted in line-labeling schemes based on junction libraries. According to these techniques, all line segments in a drawing are labeled either as concave or convex junctions of faces or as edges of an occluding face. Using a library of possible junction configurations, a set of consistent line-labels is determined and then reconstructed into 3D using additional information. Because these methods are based on analytic analysis, they are not able to adequately handle sketch inaccuracies or missing entities. An alternative reconstruction approach based on optimization of accurate views was demonstrated by Marill [10] and Leclerc [11]. With this approach, the third dimension of a body is optimized until the minimum standard deviation of angles (MSDA) between line pairs at junctions is reached and facial planarity is retained. Reconstruction from sketch-level input has also been treated by [12] and [13]. In [12], a scanned paper sketch is pre-processed, and line labeling procedures are used, and in [13], user intervention is required in cases of ambiguity. The object domains considered in these works are confined to polyhedral bodies or objects from Origami-world defined by linear segments. Work on general applications for machine interpretation of line drawings, including non-geometrical data, is reviewed by Spur [14] and Dori [15].

3. Basic Principles of the Proposed System

The proposed system is based on the following principles:

- Seeking the most probable reconstruction
- Including obscured edges
- Using a general (non-accidental) viewpoint
- Retaining consistency of interpretation
- Supporting a wide domain of objects

Seeking the most probable reconstruction

While a single sketch cannot uniquely define a 3D object, human observers all seem to agree on the source body depicted by a sketch. The reconstruction process seems to be built upon implicit assumptions based on previous experience in seeing pictures and general knowledge about objects. Therefore, a *correct* model reconstructed by the algorithm must be the one that human observers are most likely to select, i.e., the *most probable* 3D object described by a given projection sketch.

Including obscured edges

The input sketch should include all the edges which make up the object, whether seen or obscured. The reasons for this requirement are as follows: (a) Obscured lines are not strictly defined since those obscured from one viewpoint may be visible from others, and (b) The system must be able to build a model which includes the obscured part of the object and thus needs information on that part of the object.

In spite of this requirement, if one or two lines are missing, the system should still be able to reconstruct the 3D model. Also note that nothing but edges should be entered, that is, no shadings, surface marks or shadows.

Using a general (non-accidental) viewpoint

It is assumed that the user selects a viewpoint which reveals as much information as possible and is not an accidental viewpoint. This also supports the hypothesis of a sketch as an extension of the designer's short-term memory capacity. More specifically: (a) the viewpoint should not be collinear with any two object vertices; (b) the viewpoint should not be coplanar with any two (non-collinear) edges or edge and vertex; and (c) the viewpoint should not be coplanar with any (nonlinear) curve. However, since it is assumed that *all* entities will be entered, it is possible to relax requirement (b) because even if two edges coincide, each will be drawn separately.

Retaining consistency of interpretation

An important principle in the reconstruction process is that interpretation should not vary with small changes in the input sketch. When a human observer interprets a sketch, no minor change in the sketch would make him interpret the sketch differently. This principle dictates that no sharp thresholds should be used but rather smooth transition coefficients. Inclusion of this principle represents a significant contribution to the robustness of the interpretation.

Supporting a wide domain of objects

The domain of objects handled by the system includes wire-frame, surface, or solid models containing planar or cylindrical faces. Note that no restrictions are imposed on the number of surfaces meeting at an edge or the number of edges meeting at a vertex.

4. Structure and Implementation

The system consists of two modules, the modeling system and the sketch interpreter, as illustrated in Fig. 2. The modeling system is responsible for collecting sketch strokes and displaying the reconstructed model. The sketch interpreter receives the strokes and reconstructs the 3D model.

4.1 Modeling system

The modeling system is the interactive shell in which the interpreter operates. It is responsible for gathering the two-dimensional sketch strokes, passing them on to the sketch interpreter and receiving a three-dimensional model. Once a model is available, the modeling system displays it so that the user can manipulate it spatially, verify its correctness, and add details. It passes on any newly entered sketch strokes to the sketch interpreter which merges them with the existing model. Since the model may have changed its position or orientation between subsequent sketch strokes, every sketched entity is assigned a direction vector perpendicular to the sketch plane. The vector associated with the entity defines the degree of freedom resulting from the missing depth information. Consequently, in a model built in several stages, different entities have different direction vectors.

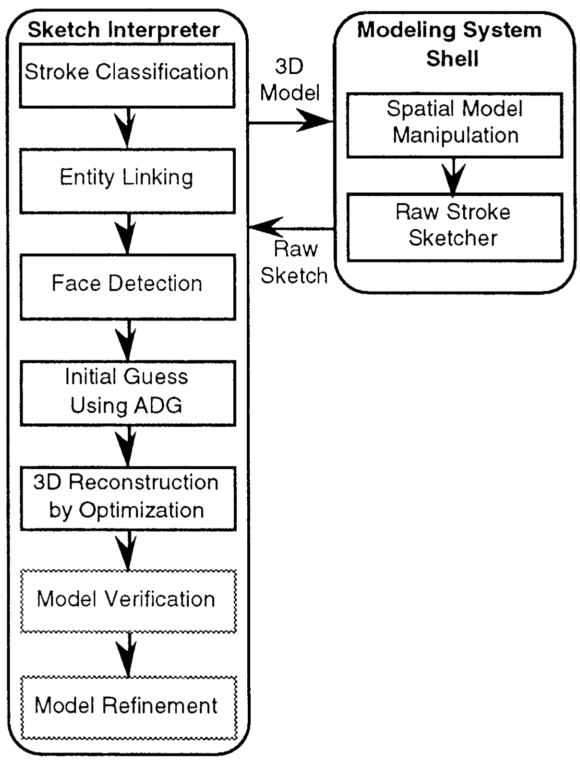

Fig 2. System structure and flow of information.

4.2 Sketch Interpreter

The sketch interpreter operates according to the following seven steps:

Step 1: Stroke Classification

The input to the sketch interpreter is a list of strokes, each represented by its x-y coordinates. A conic equation is used for best-match fitting of the strokes. The result of this matching is a group of conical sections representing lines, arcs, elliptic arcs and corners (hyperbolas). Fig. 3 shows some examples of stroke classification, where lines and elliptic arcs are fitted to various sketch strokes. Note how the corners in shape 3(c) have been associated with a hyperbola.

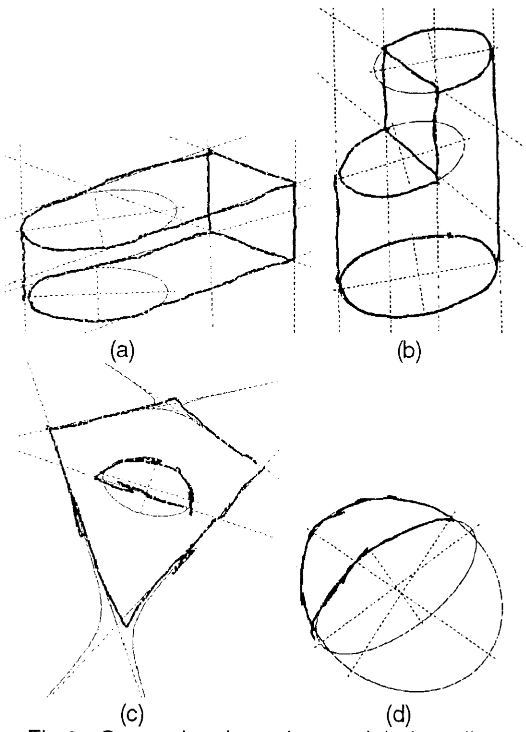

Fig 3. Some sketch-strokes and their on-line classification

Step 2: Entities Linking

In this step, an adaptive method is used to link together the geometrical entities, identified in Step 1. The result is an entity connectivity graph which uniquely defines the edge-vertex topology. Fig. 4 shows sketched entities as they are linked to form a graph. Note that the sketch in Fig. 4(a) contains a variety of gap sizes which are adaptively merged, while the fine details are preserved.

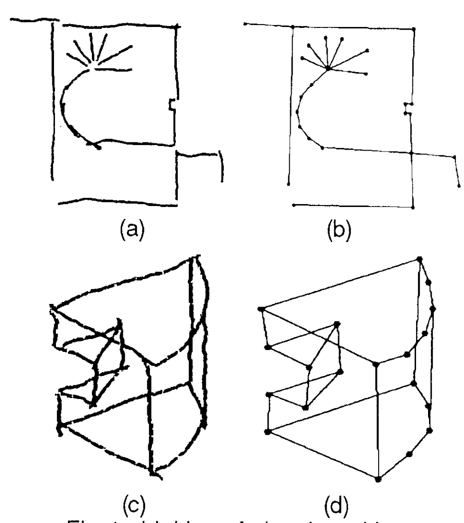

Fig 4. Linking of sketch-entities

Step 3: Face Detection

In order to reduce the number of degrees of freedom in the reconstruction step, faces are identified in the 2D domain. This is achieved by identifying minimal, closed and non-intersecting loops of entities in the connectivity graph. Some special ambiguous situations are handled with further decision-making techniques. Fig. 5 illustrates two conflicting potential faces in a body. Each one of the two highlighted faces could be a valid object face, but the two faces cannot co-exist on the same model. In such cases, special heuristics algorithms are used to select a subset of self-consistent potential faces.

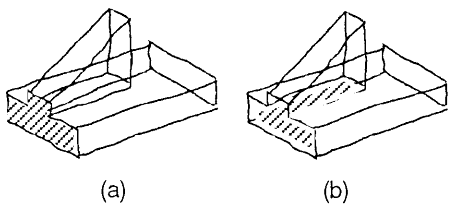

Fig 5. Example of two conflicting potential faces in a body.

Step 4: Preliminary Reconstruction

In Step 4, a preliminary reconstruction is obtained by analyzing the angular distribution graph (ADG) of lines in the sketch. The three prevailing angles are assumed to correspond to the principal coordinate system of the body, from which the general shape of the body can be determined. For objects which are generally orthogonal, this step provides an improved starting point for optimization, as can be seen in Fig. 6.

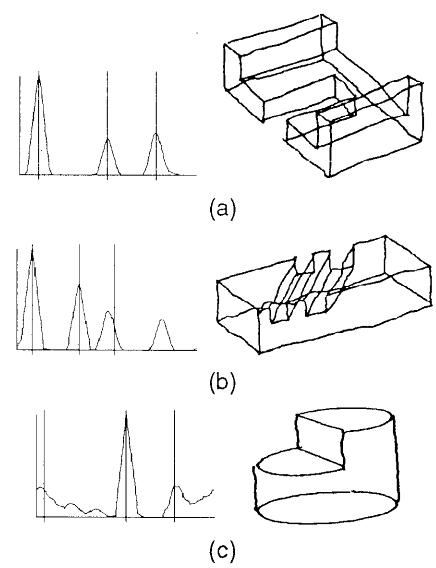

Fig 6. ADG of various models.

Step 5: Optimization-based Reconstruction

In this step, the reconstruction process optimizes the depth of model vertices with respect to a target function that is minimal in a correctly reconstructed model. The target function is composed of several components derived from assumptions about image regularities. An image regularity is a special geometrical relationship between entities. Some such regularities may correspond to a particular 3D configuration. Fig. 7 shows a reconstruction at various optimization stages. Note how the flat sketch is "inflated" into three dimensions in stages 7(b) through 7(e). To illustrate correct model reconstruction, the resolved model in Fig. 7(e) is displayed with hidden lines removed.

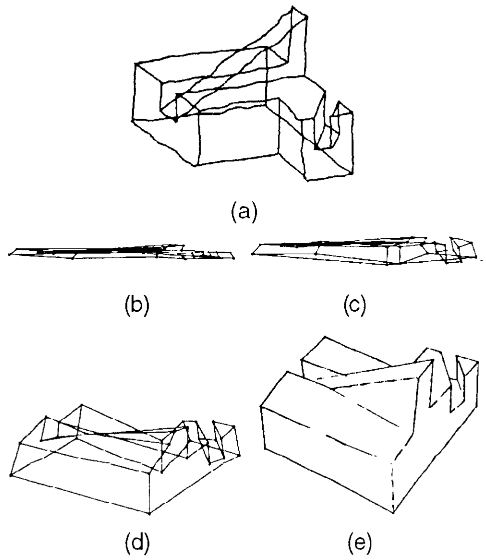

Fig 7. A 2D sketch "inflated" into 3D by optimization.

Step 6: Verification

Two criteria are used to evaluate the correctness of the reconstructed model. The first criterion is face intersection. A wrong reconstruction typically includes several intersecting faces. The second criterion is detection of severe non-planarity in supposedly planar faces. Fig. 8 shows an example of an incorrectly reconstructed model, seen from different viewpoints.

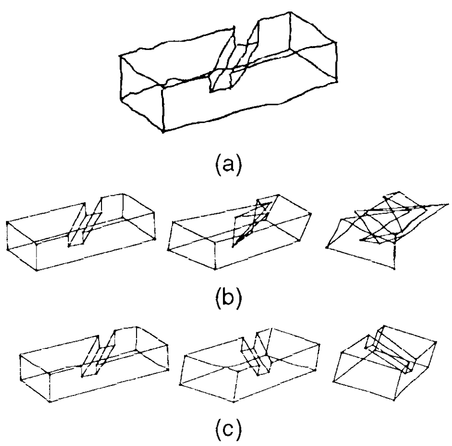

Fig 8. (a) Original sketch; (b) incorrect reconstruction; (c) correct reconstruction.

Step 7: Refinement

After a stable reconstruction has been obtained, the final reconstruction step is an attempt to refine the sketch itself. The X and Y coordinates of the vertices can also be adjusted to improve the target compliance function, as illustrated in Fig. 9.

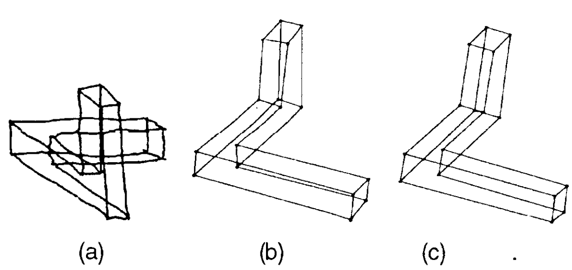

Fig 9. (a) Original sketch (b) reconstructed, and (c) refined.

5. Summary

In this research, a new type of 3D CAD interface for conceptual design has been proposed. Basic principles for implementing a working 3D sketch interpreter have been established, with emphasis on fluency, robustness and ability to support a wide variety of object types. The reconstruction approach is based on searching for a 3D object conforming to image regularities. At a time when handwriting and voice recognition are becoming feasible solutions, sketch and picture interpretation should be introduced as well for improving one of CAD's weakest frontiers, the user interface.

Acknowledgements

This research has been supported in part by the Fund for the Promotion of Research at the Technion, Research No. 033-028.

Sincere thanks are due to Mrs. D. Bossin for her contribution in preparing this paper.

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