



Title:

From Conceptual to Embodiment Design Using Sketch-Based Modeling and Feature Recognition Techniques

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Introduction:

Freehand sketching plays a central role in early-stage engineering design, enabling designers to rapidly externalize ideas, explore alternatives, and reason about form and function with minimal cognitive overhead. Despite decades of progress in Computer-Aided Design (CAD), contemporary CAD systems remain largely optimized for embodiment and detailed design, requiring users to commit early to precise geometry, constraints, and modeling strategies. As a result, designers frequently rely on fragmented workflows in which sketches are created separately (on paper or in digital sketching environments) and then manually recreated in CAD systems, leading to loss of intent, inefficiencies, and limited support for early conceptual exploration.

Sketch-Based Modeling (SBM) and Feature Recognition (FR) offer complementary capabilities that together could address this disconnect. SBM enables the reconstruction of three-dimensional geometry from informal sketches, while FR seeks to recover high-level parametric structure and procedural feature histories from explicit geometric models. This paper investigates whether coupling these two approaches can support a seamless transition from conceptual sketching to embodiment design. By analyzing a two-stage workflow that links sketch-based reconstruction with automatic feature recognition in commercial CAD systems, this work evaluates both the feasibility of the approach and the technical limitations that currently prevent reliable automation.

Background

Sketch-Based Modeling refers to a broad class of techniques that interpret two-dimensional sketches as representations of three-dimensional objects. Early work in this area focused on reconstructing polyhedral shapes from line drawings, relying on assumptions about orthogonality, symmetry, and human perception of depth [1]. More recent approaches incorporate interactive sketching, multiple views, and machine learning to improve reconstruction accuracy and usability.

Despite these advances, most SBM systems remain fundamentally geometric. They excel at producing visually plausible shapes but typically generate B-Rep or mesh-based models that lack explicit parametric structure. From an engineering perspective, these models are difficult to modify, constrain, or integrate into downstream workflows. The absence of a procedural model tree limits the designer's ability to encode design intent, manage dependencies, and perform systematic changes. [2]

Furthermore, SBM must contend with the inherent imperfections of hand-drawn sketches. Stroke noise, inconsistent proportions, and ambiguous depth cues all contribute to geometric inaccuracies in

the reconstructed models. While humans readily interpret such sketches as idealized shapes, computational systems must operate on imprecise numerical data, which complicates subsequent processing.

Conversely, Feature Recognition (FR) aims to identify high-level geometric features such as extrusions, cuts, pockets, and holes from explicit geometric representations. The ultimate goal is to reconstruct a procedural, feature-based model that captures design intent and supports parametric modification. FR has been studied extensively in the context of reverse engineering, manufacturing planning, and model interoperability [3,4].

Most FR approaches operate on geometrically precise input, such as B-Rep models generated directly within CAD systems. They rely on identifying characteristic configurations of faces, edges, and surfaces and mapping these configurations to predefined feature classes. However, topological variations, numerical tolerances, and incomplete semantic information make fully automatic feature recognition a persistent open problem.

Commercial CAD systems include limited FR capabilities, often optimized for relatively simple, clean geometry. These tools typically struggle with noisy input, slanted faces, or models derived from mesh-based representations. As a result, their applicability to SBM-generated geometry remains uncertain.

Main Idea:

The main contributions of this paper are threefold: (1) the development of a two-stage SBM-FR workflow, (2) an empirical evaluation conducted using two commercial systems and two datasets, and (3) an analysis of how model imperfections and data formats influence feature recognition (FR) outcomes. The central hypothesis is that Sketch-Based Modeling can convey sufficient information to Feature Recognition systems to enable the automatic reconstruction of procedural CAD models from freehand sketches. To test this hypothesis, a two-stage workflow is proposed that deliberately separates sketch interpretation from parametric feature reconstruction. This separation allows each stage to be examined independently while also exposing how geometric inaccuracies and semantic ambiguities propagate through the pipeline.

In the first stage, freehand sketches are processed using an SBM system to reconstruct a three-dimensional B-Rep model. This stage prioritizes preserving the overall structure and intent of the sketch while generating explicit geometry. The reconstructed B-Rep model serves as an explicit geometric intermediary between conceptual and embodiment design. While this representation lacks parametric structure, it provides a concrete basis for subsequent interpretation by downstream CAD tools.

In the second stage, the B-Rep model is imported into a commercial CAD system and processed using automatic feature recognition tools. These tools attempt to identify high-level features such as extrusions, cuts, pockets, and holes by analyzing face adjacency, surface orientation, and topological relationships. If successful, this process produces a procedural feature tree that encodes modeling operations and dependencies, enabling parametric modification and reuse. The process is illustrated in Fig. 1.

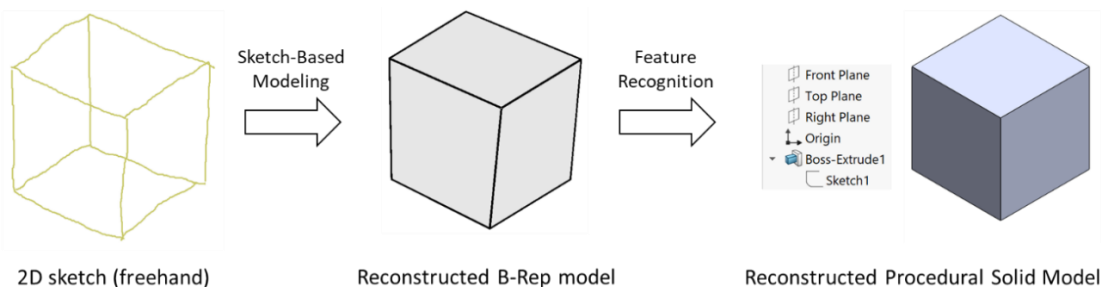
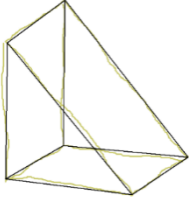
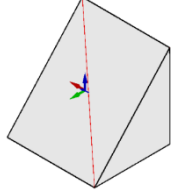
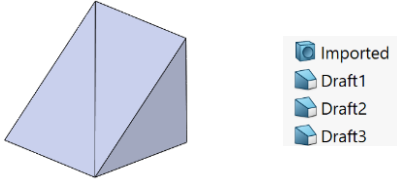
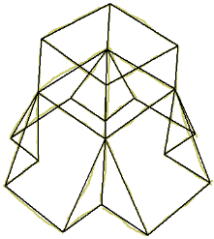
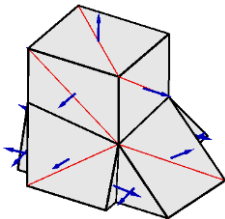
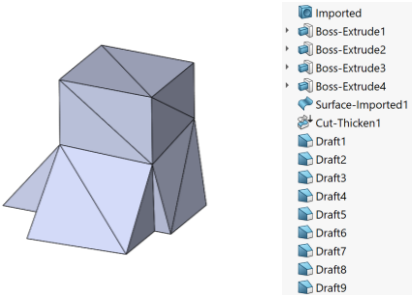
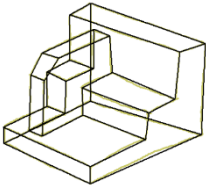
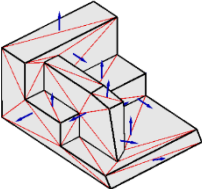
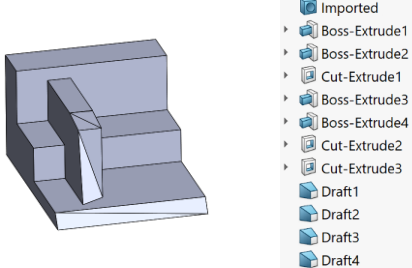


Fig. 1: Proposed strategy. Two-stage strategy for converting sketches to procedural CAD models.

The proposed strategy deliberately separates sketch interpretation from feature reconstruction. Rather than attempting to generate a procedural model directly from the sketch, it leverages existing FR technology to infer parametric structure from the reconstructed geometry. This separation allows each stage to be analyzed independently while also revealing how errors and ambiguities propagate through the pipeline.

A proof-of-concept implementation was developed using a custom SBM system capable of reconstructing B-Rep models from freehand sketches [5]. The system allows users to sketch polyhedral shapes from pictorial views and automatically generates three-dimensional geometry. The reconstructed models were exported using multiple file formats and processed using fully automatic feature recognition tools in two commercial CAD systems (SolidWorks and Autodesk Inventor).

Two sets of test cases were used. The first set (shown in Tab. 1) consisted of purely freehand sketches, designed to assess how sketch-induced imperfections affect feature recognition. The second set (shown in Fig. 2) used geometrically precise line drawings as input, allowing the impact of reconstruction and data exchange to be isolated from sketch noise. The validation focused on simple polyhedral parts that could, in principle, be represented as sequences of orthogonal extrusions. This restriction allowed failures to be attributed to geometric and semantic issues rather than to inherent feature complexity.

Input sketch + line-drawing	Reconstructed B-Rep in custom SBM system	Reconstructed procedural model and corresponding model tree
		
		
		

Tab. 1: Examples of hand-drawn sketches in dataset 1 overlaid with corresponding line-drawings, reconstructed B-Rep models with face triangulation and normal vectors visible, and procedural models with corresponding model trees generated automatically through FR in SolidWorks.

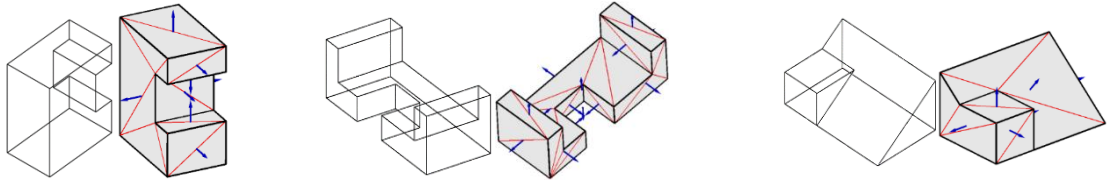


Fig. 2: Examples of input line-drawings in dataset 2 and their corresponding reconstructed refined B-Rep models.

The experimental results demonstrate that, under extremely favorable conditions, sketch-based modeling outputs can be successfully processed by commercial feature recognition tools to produce procedural CAD models. In these cases, however, the reconstructed feature trees may not accurately reflect the most effective modeling sequences and operations.

The experiments also revealed additional important limitations. Geometric inaccuracies introduced during freehand sketching and 3D reconstruction frequently exceeded the tolerance thresholds of existing feature recognition algorithms. Minor deviations from ideal planarity, parallelism, or orthogonality (often imperceptible to human designers) were sufficient to prevent feature detection or to produce fragmented and unstable feature trees. An example is shown in Fig. 3.

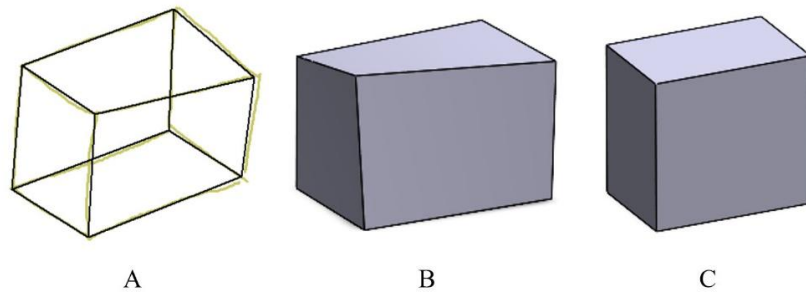


Fig. 3: Propagation of imperfections. Imperfect sketch (A), slanted solid (B), and refined solid (C).

Data exchange formats were found to significantly influence recognition outcomes. Formats that triangulate faces or approximate planar surfaces resulted in substantial loss of higher-level geometric structure, severely degrading feature recognition performance. Even when polygonal faces were preserved, many CAD systems internally tessellated imported geometry, further eroding semantic richness.

Differences between commercial CAD systems also led to divergent results. Identical input geometry often produced different feature trees in different systems, reflecting variations in recognition heuristics and modeling assumptions. While multiple procedural representations may be formally valid, some were considerably more robust, editable, and expressive of design intent than others. This variability raises important questions about model quality, consistency, and downstream usability.

Conclusions:

Overall, the results suggest that successful integration of SBM and FR requires improvements at multiple levels. The current two-stage pipeline works only for very simple, nearly ideal polyhedral parts, and breaks down with modest sketch noise or tessellated formats. Enhanced geometric refinement during sketch-based reconstruction, more tolerant feature recognition algorithms, and

earlier recognition of design intent (potentially at the sketch level) are all critical. These findings point toward hybrid approaches that combine geometric reasoning with symbolic and learning-based methods.

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References:

- [1] Babic, B.; Nestic, N.; Miljkovic, Z.: A review of automated feature recognition with rule-based pattern recognition, *Computers in Industry*, 59(4), 2008, 321-337. <https://doi.org/10.1016/j.compind.2007.09.001>
- [2] Camba, J.D.; Company, P.; Naya, F.: Sketch-Based Modeling in Mechanical Engineering Design: Current Status and Opportunities, *Computer-Aided Design*, 150, 2022, 103283. <https://doi.org/10.1016/j.cad.2022.103283>
- [3] Lipson, H.; Shpitalni, M.: Optimization-based reconstruction of a 3D object from a single freehand line drawing, *Computer-Aided Design*, 28(8), 1996, 651-663. [https://doi.org/10.1016/0010-4485\(95\)00081-X](https://doi.org/10.1016/0010-4485(95)00081-X)
- [4] Shi, Y.; Zhang, Y.; Xia, K.; Harik, R.: A critical review of feature recognition techniques, *Computer-Aided Design and Applications*, 17(5), 2020, 861-899. <https://doi.org/10.14733/cadaps.2020.861-899>
- [5] Company, P.; Camba J.D.: *Handbook of Sketch-Based Modeling for Engineering Design: A Practical Approach with REFER*. World Scientific Publishing. Singapore, 2026. <https://doi.org/10.1142/14656>