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Computational Support for Sketching in Design: A Review

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Abstract

Computational support for sketching is an exciting research area at the intersection of design research, human–computer interaction, and artificial intelligence. Despite the prevalence of software tools, most designers begin their work with physical sketches. Modern computational tools largely treat design as a linear process beginning with a specific problem and ending with a specific solution. Sketch-based design tools offer another approach that may fit design practice better. This review surveys literature related to such tools. First, we describe the practical basis of sketching — why people sketch, what significance it has in design and problem solving, and the cognitive activities it supports. Second, we survey computational support for sketching, including methods for performing sketch recognition and managing ambiguity, techniques for modeling recognizable elements, and human–computer interaction techniques for working with sketches. Last, we propose challenges and opportunities for future advances in this field.

Contents

1

Introduction

People often sketch when solving problems. Some sketches are personal; others are collaborative. Some sketches help people make quick calculations and are quickly forgotten; others serve longer-term purposes. For professional designers, sketching serves as a means for thinking about problems as much as it does for communicating proposed solutions. For people who are not designers, sketching is a natural means for quickly recording spatial information such as directions to a point of interest.

Design can be seen as an iterative process of problem-framing and exploring possible solutions within the current conception of the problem. Sketching allows people to visually represent ideas quickly, without prematurely committing to decisions. A sketch is not a contract: it is a proposal that can be modified, erased, built upon. The rough look of hand-made sketches suggests their provisional nature.

Some theories of cognition give the human mind two distinct tasks: to perceive the world via our senses, and to reason about what our senses provide. In contrast, the late psychologist Rudolf Arnheim argues that perception and thinking are inseparable: "Unless the stuff of the senses remains present the mind has nothing to think with" [11]. Visual thinking is valuable in evaluating what is and designing what might be.

Sketching allows people to give form to notions that are otherwise imaginary; the act of seeing fuels the process of reasoning.

The term “sketch” is used in many ways in vernacular and academic work. Some speak of sketching as a process — we sketch out an idea by talking about it, drawing pictures, or play-acting while considering possible solutions or problem formulations. Alternately we may use the term “sketch” to mean the product of an exploration, as when we make a prototype out of modeling clay, cardboard, or code.

In this survey, we define a *sketch* based on the utility hand-made drawings afford: sketches are quickly made depictions that facilitate visual thinking. In this way, sketches may include everything from doodles to roughly drawn circuit diagrams to an architect’s quick isometric projection. We restrict neither the drawing medium nor the subject matter. Sketches are most often two-dimensional graphic depictions, but often incorporate textual annotations.

Sketching has been a topic of interest to computer scientists and HCI practitioners for quite some time. Early efforts such as Sketchpad [161] and GRAIL [39] hinted at the potential of pen-based interfaces. In fact, many of today’s sketch-related research challenges were suggested by these systems 45 years ago.

Recently there has been a recurrence of interest in supporting sketching with computation. Computers can recognize user input and let people interact with drawings in ways that are impossible with paper alone, augmenting the sketching process in various ways. A rough sketch may contain enough information to infer the user’s intentions. The drawing could then come alive, for example providing a simulation. Alternately the user’s sketch may serve as a search query. Beyond recognition, a computer can render, rectify, or beautify a user’s sketchy input into some other representation. Computation also supports editing operations that are impossible with physical sketches, for example, enabling collaborators in different locations to share an electronic drawing surface.

Researchers from many disciplines have contributed to knowledge about sketching and computational techniques for supporting it. Their diversity makes it difficult to get a complete sense of what has been done on this topic. This review draws from journals, conference proceedings, symposia and workshops in human–computer interaction, cognitive science, design research, computer science, artificial intelligence, and engineering design. These fields certainly overlap; however research in sketching lacks a unifying publication venue.

Some who study sketching as an element of design practice published in the *Design Studies* journal. Sketching has become a recurring theme at HCI conferences like CHI, UIST, IUI, and AVI, and visual languages conferences such as IEEE's VL and VL/HCC. The Association for the Advancement of Artificial Intelligence (AAAI) held symposia on diagrammatic representation and reasoning [49] and sketch understanding. The community brought together by the AAAI sketch understanding symposia continues meeting at the annual Eurographics Sketch-Based Interaction and Modeling workshop (SBIM). Related work has been published in computer graphics venues such as *Computers and Graphics* and the NonPhotorealistic Animation and Rendering conference. There is also a substantial amount of work published in various journals for electrical, mechanical, or software engineering.

Surprisingly, few surveys on sketch recognition and interaction have been published. Readers interested in pen computing in general may find Meyers' earlier review helpful [109]. That survey covers pen-related hardware, handwriting recognition, and presents a brief history of the traditional and computational use of pens but only briefly mentions sketching. Ward has compiled an online annotated bibliography of pen computing references that spans most of the 20th century [176].

1.1 A Brief History of Pen and Sketching Systems

Sketchpad was the first to demonstrate many techniques in computer science, human–computer interaction, and computational design [161]. It was an interactive design system allowing an engineer to create models by drawing with a light pen on a graphical display. The user could apply constraints (such as "make this line parallel to that line and maintain that relation") that relieved the burden of manually maintaining such relations. Figure 1.1 shows the user defining the shape of a rivet through a combination of drawing and constraint specification.

RAND's GRAIL system (GRAphical Input Language) interpreted stylus input in a particular visual programming language for creating control sequence flowcharts [39]. GRAIL allowed users to quickly specify these programs graphically, rather than textually. To provide input, users drew or wrote freely on a digitizing tablet. GRAIL then attempted recognition using domain and contextual information to determine what the input meant (see Figures 1.2 and 1.3). The user could add semantically meaningful model data (boxes, arrows, writing) and issue commands (erase a line, move a box, change the data type of a node) without explicitly entering a mode.

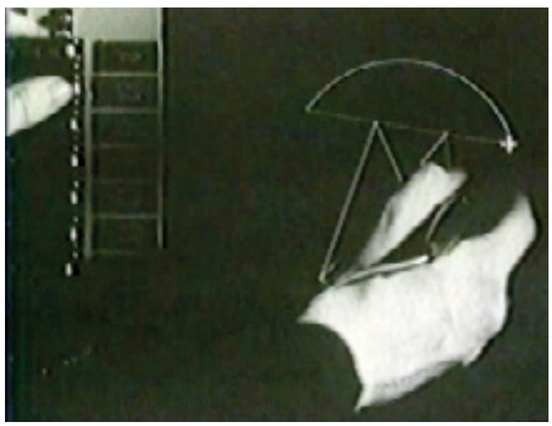

Fig. 1.1 Sketchpad supported users in creating design drawings using pen input (right hand) and constraints (specified by buttons aligned vertically at left).

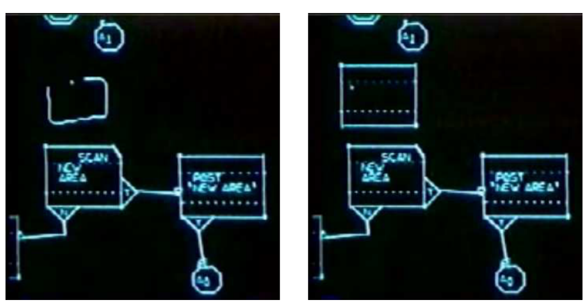

Fig. 1.2 On left, a GRAIL user draws a model element in place. At right, the rectified element is displayed as a box.

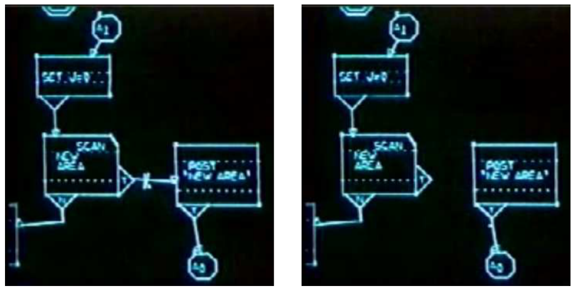

Fig. 1.3 GRAIL's sketch interpretation is context sensitive. At left the user crosses out the connector, which is interpreted as a delete command, shown at right.

Alan Kay discussed Sketchpad and GRAIL in a 1986 lecture. A portion of that talk is available on the Internet as part of the New Media Reader [83, 177]. Kay shows the video of these pioneering systems and provides insightful commentary, reminding viewers that much of the work in computer support for sketching has roots from several decades ago.

There was no widely used pointing device until the Macintosh brought about the mouse's widespread adoption in the mid 1980s. Owing to the success of the mouse, pen and sketch-based interaction was largely ignored for years. This began to change when commercial pen computing products came to market in the early 1990s, bolstered by the prospect of interaction based on handwriting recognition. Companies such as GO and GRiD developed and sold pen-based tablet devices. IBM's early ThinkPad computers (700T and 710T) were tablets. Yet these products fared poorly, and by 1995 many pen computing ventures had gone out of business. Pen computing did find a niche in the personal digital assistant (PDA) market with devices such as the Apple Newton and subsequently the more popular Palm Pilot. However, today's PDAs typically favor on-screen keyboards over stylus input. Tablet PCs are currently gaining popularity, primarily for making hand-written notes.

1.2 Sketching Challenges in HCI

The strength of sketching input lies in the speed and fluidity with which people can express, interpret, and modify shapes and relationships among drawn elements without necessarily attending to details such as alignment or precise measurement. These strengths can also be seen as the weaknesses of sketching. The equivocal, imprecise nature of free-hand drawing that so benefits humans is exactly why machines have difficulty recognizing sketches.

Those who aim to create useful and usable systems based on sketch recognition face a set of challenges including:

- Make hardware to support pen-based interaction.
- Build comprehensive, robus toolkits for building sketch-based systems.
- Create robust sketch recognition algorithms.
- Develop user friendly methods for training and modeling recognizable content.
- Design better interaction techniques for sketch-based systems.

This review elaborates on each of these challenges. Progress in one area will likely require simultaneous work in others. For example, in order to fully explore interaction design issues in recognition-based interfaces, we first need sufficiently robust and accurate sketch recognizers. In order to build recognizers capable of interpreting sketches made by any person in any domain we must have methods for modeling domain content. This in turn requires appropriate hardware and interaction methods.

1.3 Research Themes in Sketch-Based Interaction

This review details the primary themes of research shown in Figure 1.4: support for design, hardware, sketch recognition, and human–computer interaction techniques.

Traditional sketching: (Section 2) Sketching plays a crucial role in the practice of design. Sketching helps designers think about problems and offers an inexpensive but effective way to communicate ideas to others. The practice of sketching is nearly ubiquitous: One recent study of interaction designers and HCI practitioners found that 97% of those surveyed began projects by sketching [116]. We must understand the purpose and practice of sketching as it is done *without* computation if

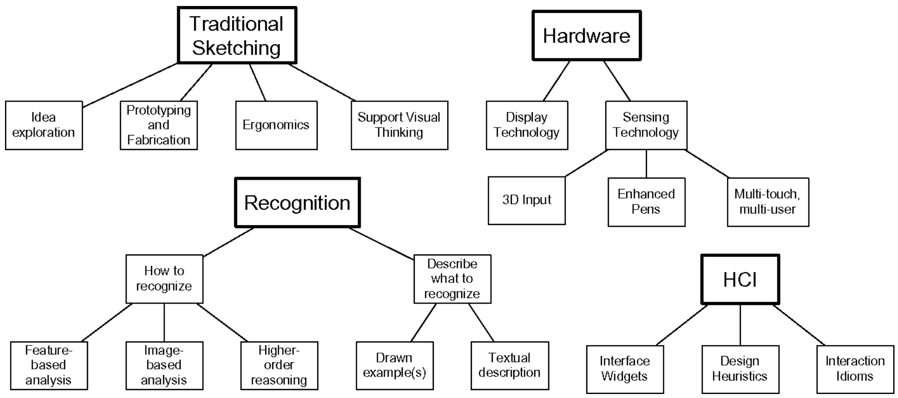

Fig. 1.4 Research themes for sketch-based interaction in design.

we hope to effectively support it *with* computation. Most research in computational support for design sketching has focused on the *early* phases when designers are exploring high-level ideas. Fewer sketch-based design systems support *later* stages of design when decisions must be formalized. This section provides a basis for thinking about how, why, and when (and when not) we may augment sketching with computation. This discussion covers the cognitive affordances of sketches and describes several empirical studies.

Hardware: (Section 3) Physical devices supporting pen-based input have existed since RAND's digitizing tablet was developed in the 1950s. Sensing technology (input) comes in many forms. Sutherland's Sketchpad system in the early 1960s accepted input from a light pen [161]. Some devices promote using fingers rather than pens, trading accuracy for convenience. Pen-based devices range in size from small (such as PDAs or "pentop computers") to medium (Tablet PCs) to large (electronic whiteboards). Other hardware considered by sketching researchers includes electronic paper and ink. The device's size and means for providing input dictate how and where it may be used, and how mobile it is. New kinds of devices will lead to new ways of interaction.

Sketch recognition: (Section 4) Recognition is central to many research systems in sketching. For this reason, a large portion of this review is allocated to discussing sketch recognition. Some drawn marks indicate domain elements, others should be taken as commands, while others are annotations. As with other recognition-based modes of interaction such as speech, sketch-based systems must have a model of what is to be recognized, as well as algorithms for performing that recognition. Some recognition techniques rely on input features such as corners, lines, and pen speed. Other techniques compare the image formed by user input with known elements. Still other techniques use artificial intelligence methods such as Bayesian Networks for reasoning about likely sketch interpretations. To recognize input the system must first have a model of what may be recognized. Models are frequently made by drawing examples. Other useful modeling strategies involve textual languages describing the shape and relationships among visual elements.

Human–computer interaction: (Section 5) User interfaces based on recognizing human speech, gestures, and sketching pose interesting challenges for researchers in human–computer interaction. New sketching input hardware, for example, may promote new interaction styles or allow people to interact with computers in new contexts, or collaborate in new ways. Because sketch input may be ambiguous, the interface should not necessarily treat it in the discrete, deterministic way that mouse and keyboard input is treated. Further, resolving ambiguity may be delegated to the user, which requires good interaction design.

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