Dissertation proposal

The Right Tool at the Right Time
-- investigation of freehand drawing conventions as an interface to knowledge based design aids

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1. INTRODUCTION

1.1. THE QUESTION

The goal of many intelligent computer aided design systems, and in particular knowledge based systems, is to provide advice in the form of critiques, relevant cases or examples, and the results of simulations. How can these systems decide when and what advice to provide the designer? Specifically, can intelligent design systems determine what advice to give designers by looking at their drawing? The drawing conventions that designers share in designing may be a good indication of what contexts and concerns they are interested at the time. If so, this raises the question: what drawing conventions should a computer understand?

1.2. GOALS OF THE THESIS

I propose to examine how design contexts and intentions are embedded in design drawings. The inference of context and intention from a design drawing will help understand the relationship of design communication to design thinking, and enable the development of a

digital sketching environment that invokes knowledge-based design tools at the appropriate time.

The first goal of the thesis is to determine whether, and to what extent, it is possible to infer, interpret, or guess what a designer was thinking about by looking at the drawing she has made. The indication of the design intent could be dynamic: the speed or pressure or the sequence of drawing might indicate the intended degree of commitment or precision; or, as I am exploring here: it could be static, the designer's intent could be indicated by the drawing symbols and their spatial relations. I do not propose to explore all the possible ways that a drawing, or the process of drawing can yield clues as to intention. I will only focus on some drawing features such as the symbols and the other drawing conventions designers use in different design contexts. Specifically, I will use office space design as an example domain to set up experiments for finding the symbols sets for the design tasks involving lighting, space arrangement and visual access.

The hypothesis is that the designers attention to, and interest in, these various tasks can be determined by examining the drawing symbols and spatial arrangement. If it is possible to associate symbols and spatial arrangements in the drawing with the designer's intention, or task context, then the second goal is to find out whether can we program a computer to recognize these drawing conventions. In other words: can these design drawings be computable? I will investigate how to program a computer to recognize these design symbols and arrangements and to infer from them the intended design contexts.

Finally, the third goal is to demonstrate how an intention recognizing computational environment can help make knowledge based systems more useful. I will implement an application manager (RT^2) that invokes right design tools at the right time for design by interpreting a freehand drawing to determine which tool to invoke. The "right tools" will be

decided based on the finding from the empirical studies of design intentions and drawing symbols. I will show a prototype of the "right-tool-right-time" manager that activates several tools that designers deem useful.

1.3. THE HYPOTHESIS

The hypothesis is that designers use consistent symbols and diagrams when they are thinking about certain aspects of their design problems. These drawing conventions, which are symbols and the arrangements of the symbols in a design drawing, serve as a means to explore alternatives and to communicate with each other, or perhaps even as tools to think about the design problems. (Conventions may come from a variety of sources such as common approaches to education, the media or the nature of drawing itself; however exploring the sources of conventions is beyond the scope of this project). Furthermore, these conventions may include a consistent mapping of symbols onto intentions. If these hypotheses are true, then perhaps a computer can be programmed to infer the designer's intentions from the drawing and, based on this inference, suggest appropriate computational tools for the task at hand. Also, the graphic symbols themselves may serve a purpose. For example, bubbles take up space and have size, shape; rays show (and test) the path of light; arrows indicate directions and strength of force.

1.4. THE PARTS OF THE THESIS

The dissertation will have three major parts. I propose to explore the questions outlined above through case studies, empirical experiments and software implementation.

The first, case studies part will include a literature survey of the use of drawing in design and my interpretations. I will briefly describe the role of drawing in design through the works from famous architects, and protocol analysis of design process. Then, I will comment and identify drawing conventions from these books. By looking at discussions of

design drawings in different design studies, we can identify the various the uses of diagrams and drawings in design thinking. My own study of architect's drawing will extend and augment the studies of others. The case studies will include the reading of what designers said or communicate about the drawing and my own attempts to interpret their drawing conventions. The studies of design protocols will show that previous research has not properly addressed the question about graphic symbols in design drawing. Therefore, further empirical studies is needed. The later empirical studies part will further verify my interpretation of drawing symbols and configuration conventions.

A second way to understand the question of making inferences from drawing is to conduct empirical, cognitive science style experiments. This second part of the thesis will include a series of original empirical studies on design drawing and intentions. Most analysis of design process protocols have mainly looked at the verbal descriptions of design problems and solutions— the "state shift "or chunking of the thinking— instead of the association of drawing marks with design thinking. Therefore, I will discuss my prior studies, including interviews with designers and experiments and I will propose a further investigation about the use of drawing in design, with particular focus on the relations between drawing conventions and design concerns.

The third, design computing part, will demonstrate the results of part I & II. I will complete the implementation of RT^2, Right Tool at the Right Time, an intelligent application manager that provides design tools targeting the task at hand by recognizing intentions from design drawing. For example, when the machine detects that the designer is working on lighting concerns, it can provide relevant cases, specification of lighting devices, or an interactive lighting simulation. The purpose of the software implementation is to demonstrate the practical consequences of the research. The implementation of RT^2 serves as a vehicle for

formulating and exploring research questions. Implementing a computer program can make more clear the ways by which one might compute the design intention.

It is difficult, but I believe possible, for the machine to infer that the designer is working on a general set of issues such as “spatial arrangement” and invoke the right aids to help with this. For example, many tools might be relevant to spatial arrangement such as building code advisors and space configuration generators. In my prototype implementation I will only use a narrow set of tools that I have worked with in the past, such as Archie and the Great Buildings Collection. For this thesis, I do not aim to exhaust all the possible tools that might be invoked when certain intentions are detected. However, I am proposing the "right-tool-right-time" manager as a drawing interface to various knowledge bases. My RT^2 scheme will show that if a designer can train the computer to recognize her drawing symbols, then the computer can automatically retrieve information based on her previously defined context of the symbols and the relevant databases. The designer can remain engage in drawing instead of stopping to activate the tools. In short, this scheme enables designers to use graphic gestures for index and retrieval instead of text.

The rest of the proposal is organized as follows: In Section 2 I describe the use of drawing in design activities based on literature survey, case studies of architects and design protocols with emphasis on the importance of drawing in design. Section 3 presents my own previous studies on drawing and design activities and a new experiment set up to explore the relations of drawing conventions to design intentions that other studies did not address. The experiment will be based on the findings from Section 2 and 3, and it aims to find out what different symbols are used in different design contexts. Section 4 discusses the approach to implement RT^2, an intelligent drawing environment that activates different design computation tools at the right time based on design drawing. Section 5 discusses

expected results, proposed evaluation and user testing on the symbols universe, and the RT^2 design environment.

2. PART I -- LITERATURE REVIEW AND CASE STUDIES

This design studies part of the thesis asks three questions : 1) What is the role of freehand sketching and diagramming in design? 2) What kind of drawing do designers make during design process? and 3) What are their intentions? I will present on a literature survey and case studies of architects' design drawing to attempt to provide the answers. This part of the thesis will establish the background information and the rationale for the system building that follows.

2.1. IMPORTANCE OF DRAWING IN DESIGN

In the early design process, designers usually draw diagrams and sketches to explore ideas and solutions. Designers, especially architects, are trained to use paper and pencil when developing conceptual designs. They draw to develop ideas graphically, and in the process of drawing, designers communicate their own thinking and others through the use and act of drawing. The iterative act of drawing on paper involves putting down ideas, recognizing functions and meaning from the drawings, finding and adapting new forms into design. The act of drawing is important not only as a vehicle for communication; it actually helps designers see and understand the forms they work with (Edwards 1979).

By "drawing" I mean freehand diagrams and sketches designers draw and use in their early design stages. I will discuss the roles of freehand drawing in design from three different backgrounds: 1) books on architectural pedagogy, 2) books on drawing importance based on interviews and survey of architect's drawing, 3) designers' own interpretation and

statement on use of drawing. At the end of each of these views I will add my own interpretation.

2.1.1. PEDAGOGICAL BOOKS

Several architectural books focus on specific drawing methods and techniques. In "Design Drawing Experiences", Lockard proposes that the ability to "diagram" a context depends on designers' knowledge of related issues in a setting, such as sun, wind, vegetation, traffic and surroundings. He proposes that the value of diagramming is to explore variations of design problems and allows our mind to "see, comprehend and respond" to more visual information than we can remember from verbal notes (Lockard 1973). Laseau's "Graphic Thinking" (Laseau 1980) is a guide to making drawings for working out problems, and communicating with others. He describes drawing as a means for design development.

These authors have based their books on their own experience practicing architecture and teaching design and drawing. They do not explicitly mention the use of graphic symbols. However, illustrations of the book show many examples of graphic symbols such as ovals for space, lines for view, squiggly winding lines for wind, and pictograms of people figures and sun. For example, Lockard demonstrated the use of putting figure, tree and furniture to identify the contents and contexts of the design drawing. He called the arrangement of drawings a "design process sentence" (p 110). Laseau uses the terms "graphic language" and illustrates the idea of graphic vocabulary and grammar with shapes, lines and arrows. Of course, there are research and discussion about notation system and visual language from different disciplines. However, for the scope of this work, I will limit myself on identifying graphic symbols and configurations for the specific task I design, and leave deeper investigation on visual language for future works.

In short, though these pedagogical books do not mention specifically the use of graphic conventions in drawing, there is ample use of symbols as communication clues in their illustrations and text. And perhaps more interestingly, they use a relatively small and consistent set of symbols – so that the implementation of a program will not be an endless effort.

2.1.2. BOOKS ON INTERVIEWS AND REVIEWS

Several recent design studies focus on the connection between design and drawing. They use case studies of famous architects through interviews, observations and works from portfolios. Lawson's "Design in Mind" (Lawson 1994) interviewed ten famous designers to analyze their design approaches in practice. His book provides abundant drawing, mostly freehand drawing, with occasionally some photographs of site and model for comparison. Lawson also reports on his interviews on designers talking about their design process. He concludes that the act of drawing plays an important role for the designers: "they find it hard to think without a pencil in their hand" (p 141). Several drawing symbols consistently appeared throughout the design drawings even though these designers came from different countries: tree, entrance, sun, column, view line, direction north, human figure, wall, door, and dimensioning.

Rowe's "Design Thinking" (Rowe 1987) describes the role of procedural and normative aspects in design thinking. He examines how architects and planners use drawings to inquire about shapes and ideas of buildings and public spaces. The freehand drawings in his book include diagrams with text annotations for entrance, lighting, and numeric calculations. Fraser and Henmi's "Envisioning Architecture" (Fraser and Henmi 1994) looks at how techniques used to make different drawing types influence the making of architecture. Their examples came from archives of architects' drawings, which vary widely in type and style among different architects. However, several shorthand notations can be

identified, such as figure, tree, movement direction, and dimensioning. In the "diagram" chapter, Fraser and Henmi note that architects "symbolize...intangible factors such as movement, access, sound, view, function, and time.." (p 110) in diagrammatic form to represent the abstraction and reduction of information.

Herbert's “Architectural Study Drawings” (Herbert 1993) examines the graphical media and design processes of six practicing architects. He argues that drawings are more than just a convenient strategy for solving design problems and that they are "the designer's principal means of thinking" (p 1). He argues that designer "must interact with the drawing" (p 121). Among the drawing and diagrams selected from interviews and archives demonstrated in his book, symbols of axial line, view, entrance, and number calculations can be identified. Robbins' “Why Architects Draw” (Robbins 1994), like Herbert's book, examines the work of well-known professional architects. However, Robbins' book focuses on the social role of drawings in architectural practice, including architects' own description of their personal design processes. Many architectural symbols such as door, stair, columns and human figure, sun, arrow for lighting can be identified from different architect's drawing.

None of these books focus or discuss the use of graphic symbols in design drawing. However, it is easy to look at the drawings and guess the context and intention by identifying their key symbols and configurations.

2.1.3. DESIGNER’S OWN VIEWS

Many architects express the importance and use of diagrams and drawing in their design process. For example, Graves explains that the “referential sketch” serves as “diary” or record of an architect's discovery (Graves 1977). It is a “shorthand” notation of an architectural theme recorded to be recalled, elaborated and combined with other sketches in a

later composition. Eisenman's "House of Cards" (Eisenman 1987) documents his use of diagrams and drawing for a series of house design projects. The drawings vary from extremely unstructured and informal sketches to rigorous and definitive hard-line technical drawing. Birkerts in his "Process and Expression in Architectural Form," like Eisenman, shows examples of his own many different design projects with drawings from various stages to illustrate the development of design (Birkerts 1994). Many drawings from these architects show shorthand for dimensioning, figure persons to indicate scale, letter "N" and arrow for the direction of North, number calculations for space requirement or material budgeting, and simple shapes for space

In sum, many books and architects' portfolios have examined and expressed the importance of the use of drawing in design. Their concerns are that drawing is an integral part in the design process and cannot be neglected. None of the researchers or designers mentioned specifically the use of graphic symbols in their drawing. One can identify several consistent ways of expressing design concerns through the symbols in their drawings. Many explain in the text what the drawing is about and in many include hand written annotations of the symbols. For example, a figure person in the sectional view is usually a circle above a triangle, a shape, and arrows often shoot out from the head, forming an angle to indicate view, and often accompanied by the word "view." A sun symbol appeared in many drawing when designers mentioned or explored lighting, and often lines start from the sun and penetrate the building envelope. Architectural details such as wall, window, door and furniture such as table, chair, bed, sink appear in plan view as simple lines and shapes.

2.2. DESIGN STUDIES ON PROCESS AND DRAWING

2.2.1 DESIGN PROCESS, STAGE MODELS

Many design studies researchers break design into different stages. For example, Asimow describes the primary design phases as three phases: 1) Feasibility study, 2) Preliminary

design and 3) Detailed design (Asimow 1962). Sanoff describes design as transforming information through stages of 1) Analysis, 2) Synthesis and 3) Evaluation (Sanoff 1977). Markus describes design as decision making sequence of 1) Identification, 2) Finding relationships, 3) Model buildings and 4) Optimization (Markus 1969). Christopherson described three stages for the tasks of designers as 1) Conception, 2) Realization and 3) Communication (Christopherson 1963). All these models suggest that the design development process has different stages with different kinds of activities.

2.2.2. RELEVANT RESEARCH ON EMPIRICAL STUDIES

Many researchers performed protocol analysis on design process to study problem solving in design. For example, Eastman showed that different types of representation such as words and drawings done by designers correlate with the problems they find and solve (Eastman 1968). Akin's "Psychology of Design" followed the theory of information processing (Newell and Simon 1972). He conducted design protocol studies of architects sketching in order to analyze their chunking of design actions and their attention shifts (Akin 1986). His experiment on recall looked at the time interval between the drawing of lines to identify the grouping of architectural elements in memory. His examples revealed several chunks: the wall and window segments, steps, furniture of similar size that have close spatial relations. However, he did not identify the symbols and their configurations these participants used when they performed the recalling tasks through drawing.

In a recent study (Akin and Lin 1995), Akin and Lin summarized that previous protocol research mostly emphasized recorded verbalizations. They note that little has been written about the role of drawings produced in the protocols although drawing is essential in the design process. They discussed symbolic encoding of different modes such as drawing, thinking, examining and speaking. They designed an experiment that has two parts: 1) to reproduce a drawing from a printed transcript, and 2) to predict the verbal data from a video

of the design drawing process that has no sound track. They point out that novel design decision usually occurred when the designer was in a "triple mode period": drawing, thinking, and examining. They also conclude that the transcripts and drawings are echoes of each other. Suwa and Tversky (Suwa and Tversky 1996) claim that seeing different types of information in sketches drives the refining of design ideas. They video taped architects sketching to design an art museum. While watching the tape, the participants then reported what they had been thinking about. Suwa and Tversky classified the information in the protocols into different categories such as spaces, things, shapes, views, lights and circulation, and thus proposed to develop a tool that will respond to sketches drawn to stimulate design thinking.

All the above protocols describe the association of thinking, verbal protocols with design drawing. However, none identified the graphic symbols designers use in design. They mainly looked at the verbal descriptions of design problems and solutions, the state shift or chunking of the thinking. The main focus of my project is to identify the association of the drawing marks with the design thinking. To begin to address this, I have conducted empirical studies on design problem description and diagramming in previous research (Do 1995a). I propose to conduct further experiments to extract the graphic symbols designers use when dealing with different design context and concerns. These new experiments are described in the following section, after a review of my previous empirical work.

3. MY RESEARCH

3.1. PREVIOUS STUDIES - PHASE MODEL

Based on prior experiments with designers and a study of Le Corbusier's design drawings for the Carpenter Center, I propose that early architectural design can be characterized as consisting of three distinct phases: Organization, Ideation and Fabrication. These phases

iterate with no particular sequence and each incorporates many different design contexts and intentions. The three-phase model serves as a framework to identify what different types of design support might be needed for different activities. For example, in the Organization phase, designers usually deal with abstract manipulation of entities in the functional aspects. They make bubble diagrams to explore adjacency concerns; they calculate to check space requirements. In the Ideation phase, designers are often concerned with finding relevant visual references to proposed configurations and with testing their design proposals. They make diagrams and sketches to analyze for example, visual access and lighting condition. In the Fabrication phase, designers trace over old sketchy lines and use tools for hard line drafting. These different design concerns can be facilitated by different kinds of computational support.

In summary, my design process model proposes that different activities and different kinds of drawings are employed in different design phases to intent to different concerns . The number of the phases is not critical for this research. The primary objectives of the research are to identify different features of design drawings, so in the future computational aids could have different modes to serve different concerns of designers. The tool (RT^2) I am proposing will deal with different modes of design activities and can be customized by designers.

3.2. EMPIRICAL STUDIES

A second way to understand the question of making inferences from drawing is to conduct empirical, cognitive science style, experiments.

This empirical studies part of the thesis asks two questions : 1) what different activities and drawings appear in conceptual design stages, 2) what kind of symbols and drawing

conventions are associated with different design activities. I propose to address the question with several experiments involving designers.

This part contains several original experiments on diagram making and design. On the basis of these investigations, I propose that different types of drawings and symbols express design intentions in the various design phases. Specifically, I will ask the question: (how) can we detect design contexts and intentions by looking at a designer's drawing?

I have conducted three empirical studies to explore the convention of drawings. They are 1) drawing from narration of concept and drawing on impression of a famous building, 2) drawing to design a poster, 3) diagramming from a text story and writing from given diagrams.

The first study was conducted at an undergraduate design seminar. Thirteen design students were asked to draw their impression of famous buildings such as Guggenheim, Falling Water, the Eiffel Tower and the Parthenon as well as design concepts such as two spaces connected by a path, a buffer zone between courtroom and lobby, a client with a clerk behind a booth at the same eye level. They were also asked to draw a map from a narrated story of campus map, and their own family tree. The experiment was designed to find out about 1) abstract memory representation of building, 2) diagrammatic representation of design concept and environment. I found the students used consistent drawing conventions though their design training varied from zero to six years.

The second study was conducted with a research group of six people, graduate students and faculty members in an architecture or computer science department. One computer science participant had a architecture undergraduate degree. They were asked to design a poster that included words, the Eiffel tower, a happy person and a phone number. They were then

asked to draw "a pizza pie" and "image of Guggenheim Museum" and a campus map from a verbal description. The experiment was designed to find out whether there is consistent convention for general concepts across disciplines. In this experiment, all participants drew long angular shapes for the Eiffel tower, and five out of six drew "x-shaped" crossings for its tower structure, and they all drew smile face for the happy person. The pizza pie drawing had an interesting result. Three participants who had architectural training drew the pizza as a cut open circle pie with a triangle piece separated from the whole while the other two participants who lacked architectural training drew a circular pie with eight pieces cut lines, and the designer turned computer scientist simply drew a triangular slice of pie. The Guggenheim drawings had similar results, the two computer scientists drew spiral lines while one designer drew a plan view of concentric circles and three designers drew a flower pot shape.

The third experiment focused on using diagrams to access the case based design aid Archie (Domeshek and Kolodner 1992; Kolodner 1991; Zimring and others 1995). Archie is a database library consists of post occupancy evaluation cases. (More detail descriptions appear in the Section 4.) To explore the feasibility of diagram based interfaces for design, I performed a pilot experiment to see whether designers would employ conventional drawing techniques in diagramming architectural design problems (Do 1995a). This experiment (qualifying paper (Do 1995a), titled The Feasibility Study of Using a Diagram Interface to Access an Architectural Knowledge Base) took place in an undergraduate design theory and method core course. Sixty two design students participated in the experiment. They were divided into four groups with variations of task sequence and supplement of text titles. The whole experiment comprised four tasks: making diagrams from stories, writing stories from given diagrams, pairing diagrams and stories and commenting on the existing Archie diagram-story pairs. I found that 1) designers only use a small set of symbols in their drawings and arrange them in conventional and consistent ways (figure 1 shows the lexicon

of symbols they used), 2) designers exhibit different view preference for different concepts (e.g., plans or sections) to illustrate different sorts of problems (e.g., spatial arrangement versus getting light into a building), 3) keywords from the stories are often used as labels in diagrams, and vice versa, and 4) designers mostly agree with each others' diagrams.

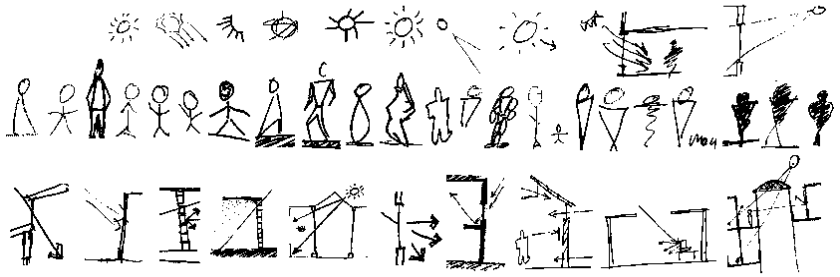

Figure 1. Designers used conventional symbols and configurations for architectural concepts in diagrams.

3.3. PROPOSED NEW EXPERIMENTS -- DESIGN CONCERNS & DRAWING CONVENTIONS

In the previous work outlined above I have already identified several contexts and intentions (Do 1995a). For example, attention to a lighting concern is usually indicated by arrows, visual issues with lines and human symbols. However, this previous experiment did not directly involve design acts. I will conduct a new experiment in which participants will be asked to perform simple design tasks. This empirical studies part of the thesis will identify specific symbols as clues to identify design context. The computer implementation will use these context symbols to activate relevant design tools.

The new experiment is designed to find out what different diagrams designers make when dealing with different concerns in a design problem. For example, when designers think about lighting, what symbols will they use and in what spatial configurations? The purposes of the experiment are 1) to verify the findings of the previous study about drawing conventions in a design process, 2) further investigate design context and intentions as they

are reflected in drawing conventions, 3) establish a digitized record of the experiment results to demonstrate the feasibility of making these drawing convention computable.

For the experiment, I will provide participants a drawing device to draw on. The proposed device is a drawing environment that supports freehand sketching and records the drawing in digital format. A digitizing tablet and a sketching program called the Electronic Cocktail Napkin [Gross, 1994 #300; Gross, 1996 #165] will be used for recording the drawing features and sequence. The reason for choosing a digital device is so that we can play back the actual drawing sequence to reveal how a configuration is formed, also the pressure and time stamp data will be available for future study. This digital recording is proposed because it is less intrusive than tape recording or video taping. Participating designers only need to use design drawing environment without any separate recording equipment. Also, since the drawing program will be the base for implementing the RT^2 manager, it is a test bed of how designer feel about the drawing interface. The experiment will examine what drawing symbols and configurations are used in the design process and how they differ between different design tasks.

The sequence of the experiment is as follows: 1) introduction of the task, where a written instruction sheet of design task will be provided and a brief oral explanation of the instructions, 2) participants are given 5 minutes to get familiar with the drawing recording device, and 3) participants will be given 5 minutes to complete each of the six design tasks while the experiment will take no more than 30 minutes for each participant. In the end participants will be asked to comment on the interface (digitizing tablet and the Napkin program) and the experiment.

I have chosen an architect's office space design for the empirical studies for two reasons: 1) participating designers would either have experience of their own office design or planning

schemes so the exercise would be an easy task, 2) as Wineman describes in "Behavioral Issues in Office Design"(Wineman 1986),the layout and design of office space influence the workers' behavior and that workspace design is more than just simple decoration. I will not discuss the psychological aspects of the office space design in this thesis, however, the finding of design process might yield useful information for future investigation.

3.4. EXPECTED FINDINGS

I expect the experiment will show several sets of symbols occurring within different design contexts. I will interview the participants to verify the my interpretation of their association of drawings and intentions. I will analyze the data and compare them to the symbols and configurations used in various books and discussed above.

I will set up an analysis plan after I have done a pilot study on the proposed experiment. From previous experiments and observations I have already determined that the symbol universe is small and that there is a consistent use of symbols and configurations responding to specific task context, such as lighting, and space arrangements. However, though human examiners can detect the symbols, the drawing styles may differ, for example, a rectangle may be drawn with four separate lines or one single continuous stroke. Therefore, the system implementation part should take this into consideration, allowing designer to customize their own style or use of symbols. However, for the scope of this thesis I would only focus on the identification of the symbol universe and their configuration patterns.

4. PART III -- COMPUTER PROGRAM IMPLEMENTATION

The design computing part, will demonstrate how the results of previous sections can be used to implement a computer program. The purpose of the software implementation is to

demonstrate the practical consequences of the research – if designers can understand each others' drawings, maybe we can train the computer to understand as well. The implementation of RT^2 (the "right-tool-at-the-right-time") serves as a vehicle for formulating and exploring research questions about drawing conventions and design intentions. Implementing a computer program can make more clear the ways by which one might operate about the design intention. For example, it is hard for a machine as well as a human designer to infer which case or story is really relevant without a whole lot more inference beyond symbols and their configurations. (For example, when is it relevant to provide cases from a slide library and when to retrieve a much broader set of tools?) Therefore, one needs to investigate and explore about the "right" timing and the "right" tools for the implementation. The project will then only provide a narrow set of tools based on the investigation and be specific about what the machine might do, such as choosing a functional simulations over case studies of buildings, or whatever.

The design computing part is based on several assumptions. First, in order to be really useful, knowledge based design tools need to be available at the right time. Second, different design activities need different kinds of supporting tools. Third, drawing conventions such as symbols and diagrams can be a clue to activate the right design tools at the right time. I will build a prototype of the right-tool-right-time manager to explore how this manager can help designers use knowledge based design tools. The RT^2 manager will detect the difference between drawing symbols and configurations, and use these discriminations to guess the designer's intent and task context, and provide appropriate design tools to support design decision making. For example, a layout bubble diagram will activate design cases with similar configurations. View lines drawn on a floor plan will bring up a visual analysis tool. The RT^2 manager will employ a freehand sketching environment to allow designers to stay involved in the task -- drawing and thinking, while

providing context-sensitive feedback when it detects different drawing conventions and contexts.

4.1. WHY RIGHT-TOOL-RIGHT-TIME?

Current Computer Aided Design construction tools, though beneficial to design drafting, are often cumbersome to use during the early stages of design (Do 1995a). These tools usually take designers too much time to learn and to become accustomed to their operation. Designers need to be familiar with obscure commands or type in text in order to fulfill their goals. The command and text oriented interface obstruct the flow of the design process. Furthermore, these tools usually force designers to specify more details than they wish at this early design stage (Herbert 1993). Most designers would prefer to sketch their early design ideas and schemes on paper with a pen (Lawson 1994).

Another drawback of the current available design tools is that they all propose to solve design problems with their particular approach. "To the man with a hammer, the whole world is a nail." For example, Case Based Reasoning researchers (Kolodner 1993; Oxman 1993b) see everything about design as issues on indexing and retrieving cases. On the other hand, shape Grammarians see design as generation by production rules (Flemming 1987b; Knight 1981; Stiny 1985). However, design involves different concerns and incremental formulation and therefore needs different kinds of support at different phases.

The design computing part of the thesis asks the questions: 1) how can design studies help computers to recognize design tasks? 2) in what form should information be presented?, 3) how and when should the various design aids be activated?

I argue that current Computer Aided Design (CAD) programs only support design process partially because they do not provide a design task oriented environment. Since the early sixties, many researchers have investigated using computers to help designers. Geometric modeling and drafting programs (e.g. Form-Z, AutoCAD) have been built to help speed the creation of the working drawings, but not the early drawings of conceptual design. These systems help the construction and fabrication phases of a design process. Evaluation tools and expert systems (e.g. (Maher 1985; Pohl and others 1988; Rittel and Kunz 1970) have been developed to help design decision making by providing design rationale or design guidelines. Shape grammar systems (e.g. (Flemming 1987a; Knight 1981; Stiny and Mitchell 1978)) aim to compute geometry information to guide generation and transformation of a design artifact such as a floor plan or facade. Case based design aids (e.g.(Kolodner 1991; Oxman 1993a; Zimring and others 1994) propose using past experience or design precedents to help designers prevent making similar mistakes and learn to adapt old cases into new situations.

No matter how useful these systems are, they all lack the integration into a real design environment where free hand drawing is used. These systems also depend on designers to choose the right computational tools at the right time, and the use of these tools, when not embedded in a design environment, can obstruct the flow of a design. (A usability study of Archie discussed in the Section 4 revealed this finding.)

I propose that designing is a multifaceted activity, and no single tool can serve all tasks. The RT^2 (right tool at the right time) architecture will provides an interface to a variety of knowledge based design tools. Rather than asking the designer to select and apply tools to perform specific tasks (e.g., 'now I want to look at a case library') I am exploring the possibility of automatically (or semi-automatically) invoking various design tools based on design drawing. The marks designers make reflect the task at hand. For example, an

architect often draws an arrangement of spaces, sight lines and viewsheds when working on lighting and visual access, and force diagrams when considering structural stability. The "right tool at the right time" (RT^2) module will infer from the drawing what the user is working on, and will support a tool appropriate to the task at hand.

4.2. A SCENARIO

Imagine a novice designer Lynn designing a public building. Her assistant Arty (RT) sits quietly watching and ready to help. Lynn starts the design from scratch by making a bubble diagram to think about spatial arrangements. From Lynn's diagram (figure 2a), Arty recognizes that she is working on the spatial relations of lobby and other spaces, and calls up a story from a case base, Archie, (Kolodner 1991; Zimring and others 1994) that discusses lobby arrangements (figure 2b).

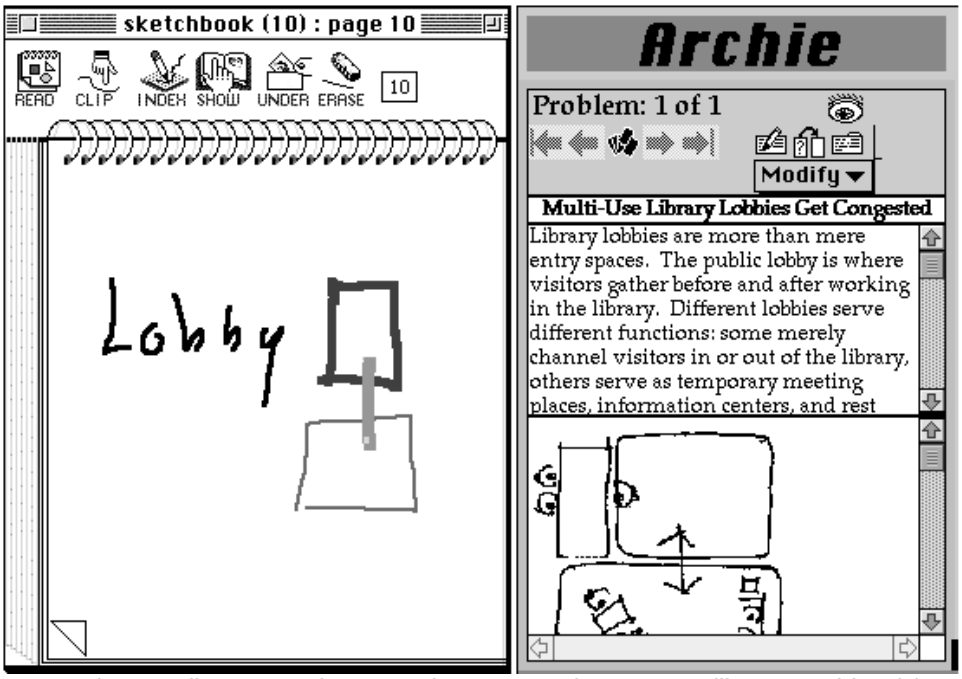

Figure 2. Designer's diagram retrieves a relevant story from a case library, Archie. (a) Bubble diagram of spatial arrangements in a sketchbook; (b) Archie case story of a library lobby with similar configuration.

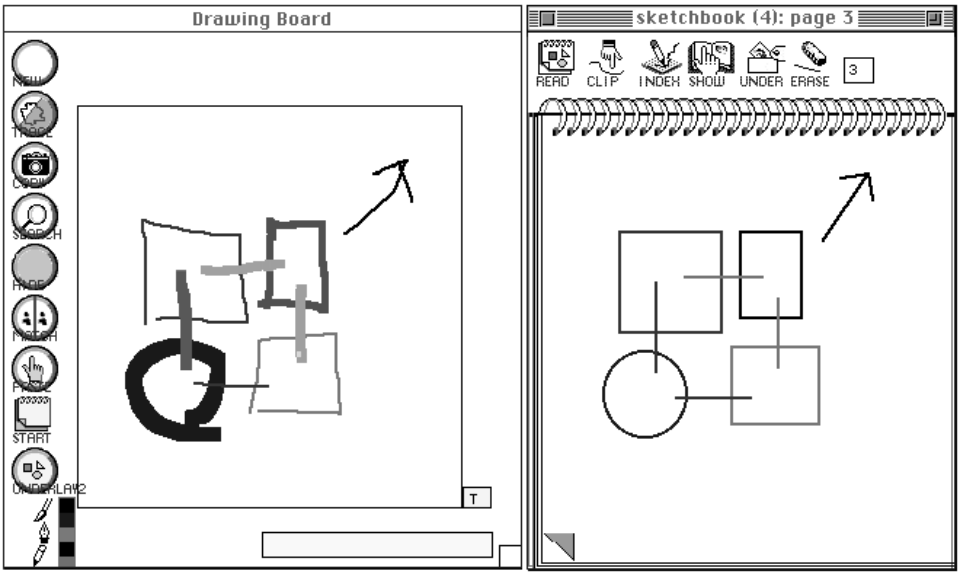

Figure 3. Designer's drawing can be cleaned up and rectified if desired. (a) Sketchy drawing of spatial arrangements; (b) Rectified geometric shapes of the sketchy drawing.

Lynn finds the case provided by Arty useful and incorporates the arrangement into her design (reminded by the Archie case story that lobby can serve as information center, Lynn adds another space bubble into the diagram). She continues to draw. When she stops, Arty hands Lynn a hard line version of her sketches (figure 3). Arty then uses the cleaned up drawing to check the total square footage against the design brief requirements. Meanwhile, Lynn starts to draw diagrams to analyze the sense of visual enclosure in her design from different view points. Arty calls up a viewshed simulation program, Isovist (Do 1993; Do 1995b) to help her with analysis (figure 4).

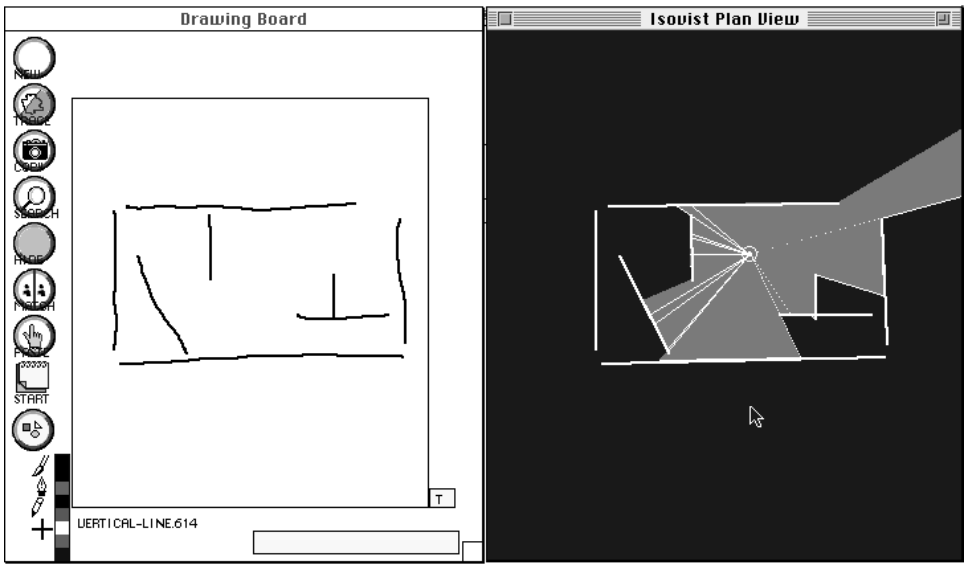

Figure 4. Designer's drawing of visual enclosure brings up a viewshed simulation program, Isovist. (a) Diagram to explore visual access; (b) Isovist viewshed analysis tool.

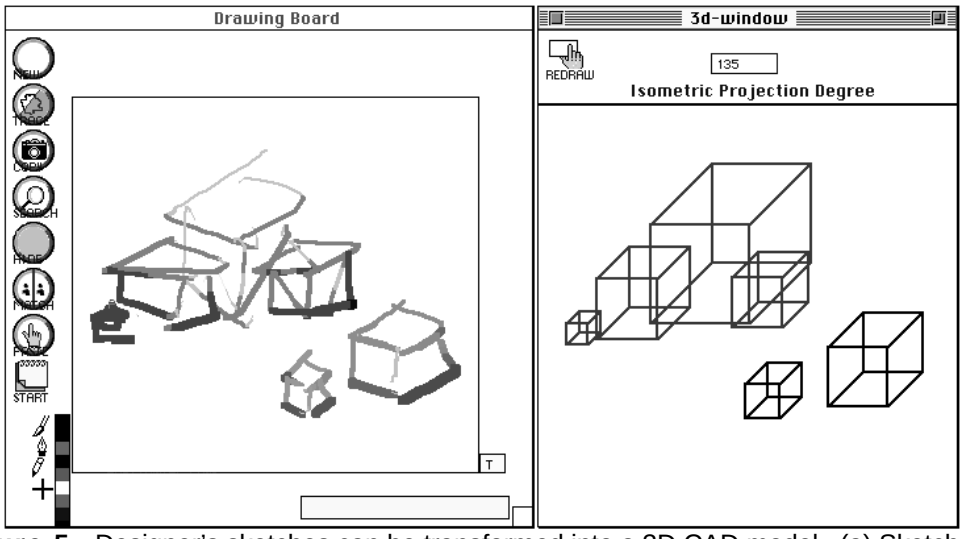

Figure 5. Designer's sketches can be transformed into a 3D CAD model. (a) Sketches of massing study; (b) Translated 3D model of the sketches that allows changes of isometric projection angles.

Satisfied with her basic spatial arrangement, Lynn decides to work on form. She sketches several cubes to examine the massing of her design. Based on Lynn's sketch, Arty quickly builds up three dimensional computer models (figure 5) for Lynn to explore viewing perspectives and perhaps create a walk through animation. To make her building look more monumental (!), Lynn draws a facade composed of a triangle pediment and colonnade. Arty

recognizes the drawing as a temple and finds for Lynn slides and a QuickTime animation of the Parthenon from The Great Buildings Collection CD ROM (Matthews 1994) (figure 6).

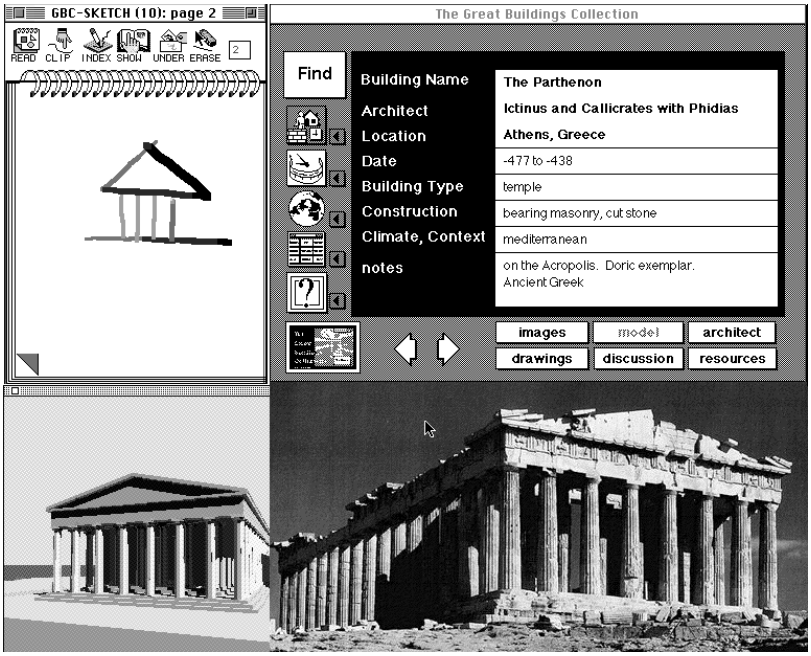

Figure 6. Designer's diagram retrieves information from a multi-media database. (a) Diagram of a triangle pediment and colonnade; (b) Textual information, picture and QuickTime animation of the Parthenon from the Great Buildings Collection (Matthews 1994).

Lynn overlays a trace layer on top of the floorplan, and begin designing. As Lynn works, her assistant Arty observes that Lynn is drawing HVAC devices and wires, and quietly finds a sketchbook page that has similar configuration. Arty goes on finding a product catalogues of thermostat from the World Wide Web through the Netscape program (figure 7).

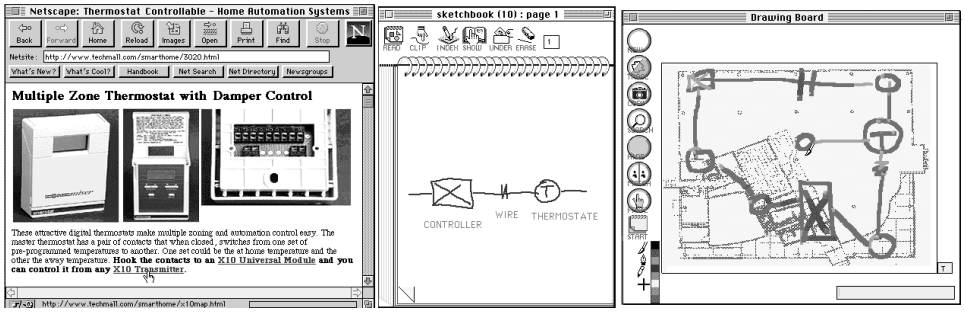

Figure 7. Designer's diagram retrieves information of HVAC production s from Netscape. (a) Retrieved page from the World Wide Web through Netscape program; (b) Retrieved sketchbook of a note on HVAC configuration; (c) Designers diagrams on top of a floor plan.

The story can go on. Though different designers may approach design differently, all design processes have two things in common. First, our designer and her assistant engage in various activities during the design process: finding references, functional analysis, modeling, and visualization. Tools such as design case libraries, drafting and modeling, viewshed analysis support these activities. Second, as she works, the designer makes various kinds of drawings. Her computer based assistant Arty recognizes what she is doing by looking at these drawings and then suggests an appropriate tool.

In summary, I propose to develop an architecture, an application manager for a freehand drawing interfaces that can apply to design by providing knowledge based systems available on the right time based on design drawings. The interactive tool (Right Tool at the Right Time, RT^2) will support design activities such as exploring ideas, finding references, images and information retrieval, while allowing designers to quickly sketch their ideas with a digitizing pen and tablet. The system will allow rough drawings to be produced quickly so that it preserves the important properties of pencil and paper. However, unlike a paper sketch, this intelligent electronic sketching environment is interactive, it recognizes designer's intention by looking at the drawing, and can be trained or modified to fit personal design needs and different design contexts (e.g. define customized drawing and annotation symbols for lighting concerns). Designers can define their own symbols and use these to retrieve right tool at the right time.

4.3. HOW RESULTS FROM 2 & 3 CAN APPLY TO COMPUTER PROGRAM

In the case studies and experiments I expect to find that specific symbols are associated with specific design contexts. Accordingly, my right-tool-right-time manager will employ symbols as identification clues for contexts. The contexts I will try to identify are: lighting and visual analysis, equipment specification catalogue, spatial configuration for retrieval of a precedent case, and check-ups of hand written calculation. The Right-Tool-Right-Time

manager will activate various supporting tools based on the symbols and contexts identified during drawing. Detailed descriptions of various supporting tools are discussed in the following section.

4.4. IMPLEMENTATION BACKGROUND -- ARCHIE, NAPKIN, AND VARIOUS TOOLS

4.4.1. ELECTRONIC COCKTAIL NAPKIN

I have chosen a research tool, the Electronic Cocktail Napkin as a test bed for my experiment and implementation of various ideas about supporting design by drawing with RT^2. The Electronic Cocktail Napkin (Gross 1994; Gross 1995; Gross 1996), as the name suggests, aims to support the kind of activity of scribbling that happen on the back of an envelope or on a cocktail napkin. Designers employed a digitizing tablet and a cordless pen, or a mouse or a PDA (personal digital assistant like a Newton) for their design drawing. The program supports recognizing drawing elements, records drawing pressure and pen paths, registers author information and drawing speed and creates time stamps. Designers can diagram and sketch freely on the drawing surface, and can customize the program to recognize personal defined symbols by combining drawing elements together.

4.4.2. SUPPORTING TOOL I -- THE CASE BASED DESIGN AID "ARCHIE"

Increasingly, architects in practice employ computers for presentation and drafting. However, during the conceptual design phases designers need to access information databases to help make decisions. The information must be easily accessed without stopping the design work flow.

To support design decision making, architectural knowledge bases have been built, such as Archie, a case based design aid for architects (Domeshek and Kolodner 1992; Kolodner 1991; Zimring and others 1994) . I propose to use Archie as one of the supporting tools

for design because I have been involved with the development of the system and with feasibility testing of Archie in simple design tasks.

Archie consists of stories, problems and responses from post occupancy evaluation data collected in field studies. Currently Archie's case base contains post occupancy evaluation data about courthouses, libraries, and tall buildings. These data are organized into categories of problems, responses and stories. Each problem, response, and story is indexed using a set of key features organized along the dimensions of systems, components, design issues, stakeholders, and life cycle concerns. All related items are cross-linked. Each text item is clearly and concisely written, labeled with an explanatory title, and summarized in a one-paragraph synopsis along with scanned in graphic material (plans, photographs, and drawings). However, to access Archie's design information, one must use specific keywords assigned by the system developer. For visually oriented, graphic thinking designers, (Laseau 1980; McKim 1972) this text-based interface may be an obstacle to effective use.

With a team of Computer Science students, I have conducted usability study of Archie using the mockup and lab approach. Paper prototype and monitored laboratory testing of computer systems are common used techniques in usability testing (Hix and Hartson 1993; Laurel 1990). In the mockup version, my team members and I asked designers to perform a courthouse design while a paper mock-up of the Archie interface was available on their desks. We observed and video taped the whole design process. The two designers were asked to speak aloud to explain what they were doing. From the experiment session and the debriefing after session, we found that designers look for information and references from various sources. They would look for case stories from Archie if they knew what's in the database, or if the paper version happened to be handy on the desk.

Both designers expressed the importance of finding useful information to help make design decisions. However, they both enjoyed the act of drawing to explore ideas and design solutions instead of stopping to find useful information. One suggested it would be great if there was an assistant to help find all this useful information for him while he is designing. He then could remain in the design flow, not get interrupted by having to stop to look for material, and have the freedom of having useful information available at the right time.

The other usability studies were conducted with five designers in a closely monitored lab (Do and others 1994). We observed and video taped designer using the Archie program for their design or information searching tasks. Designers were asked to compile a report from the case base for special topics, or to use a case to help design their library or courthouse, or simply asked to find useful information. From this experiment, we found that designers tend to draw and they dislike using keyboard commands when designing. We can conclude from these studies that an assistant that finds information when designers engaging in design drawing would be useful.

4.4.3. SUPPORTING TOOL II -- ISOVIST ANALYSIS TOOL

I have written an Isovist program that aims to help designer understand the visual field of a person in a built environment. An IsoVist (Benedikt 1979) is the area in a floor plan visible from a given view point, bounded by partition walls and other physical environments. The program was written for and partially supported as part of a larger scheme in developing analysis tools for the College (Peponis and Wineman 1995; Wineman and Hodges 1995). The program provides instant feedback and calculation of the visible area from a given origin stand point. It also allows adding, moving, and remove partitioning walls. As the person walk through the floor plan, both the area of the IsoVist field and its perimeter change accordingly.

4.5. SUPPORTING TOOLS -- NETSCAPE, THE GREAT BUILDINGS COLLECTION, CALCULATOR

I have worked with the Electronic Cocktail Napkin Program building a visual bookmarking, or query-by-diagram scheme for several databases: the Archie case based library and "The Great Buildings Collection," (Matthews 1994) a commercial CD-ROM of famous architecture, as well as to FileMaker Pro and HyperCard databases and World Wide Web. While browsing the database, the user draws a diagram on the Cocktail Napkin to link it with the currently displayed database record. To retrieve a record, the user draws a diagram on the Napkin, which compares the query with previously linked diagrams. I am planning to expand the supporting tools list to include a calculator that will be activated when the user writes numbers on a drawing, because there are many examples of number calculations appeared in the design drawings.

4.6. RIGHT TOOL AT THE RIGHT TIME

This research incorporates various design tools into the Napkin drawing environment. For example, I have built a sketchbook that enables users to put visual bookmarks into different databases like Archie, HyperCard, and FileMaker Pro documents. Designers can keep their personal sketchbooks and refer to different information for future use. I would like to expand this drawing environment into a better design decision support interface that allows designers not just to keep notes and sketches but which also detect designers intention and retrieval right information or active design tools at the right time. I would introduce additional design tools to demonstrate the idea of an integrated design drawing environment that activates the right tools at the right time.

I plan to implement the sketching environment to provide information and design tools accessible when design drawing involved. I will come up with drawing conventions in the design phases to map with appropriate tools. For example, the use of visual reference will

more likely happen during the Ideation phase of design. When designers sketch rapidly they tend to engage mainly in exploring physical form alternatives, thinking less about the organization of the site, the architectural program, or the building. On the contrary, in the Organization phase of design, when solving functional concerns or working with the building systems, designers are more likely to access other kinds of information (like the Sweets catalog). For example, designers might draw a diagram of radial lines to indicate visual perception toward the exterior scenery, thus a tool like IsoVist that draws view lines and plots visible areas will help exploring the sense of spatial perception. Or, when designers draw bubble diagrams that connect two ovals with a line, their concerns might be addressed by a case library that deals with circulation problems about how two connecting space by a path.

For my thesis, I propose a system model of a design supporting environment with the RT^2 manager (as shown in Figure 8 below). I believe in early design process a drawing environment that an intention detector might be useful in identifying different drawing intentions and activating different design tools or knowledge bases. For example, when the designer is engaging in analyzing visual access the spatial analysis program like IsoVist would come up. On the other hand, if the designer is exploring analogies and metaphors, visual reference database that has similar configurations such as slide library or a case base should be activated.

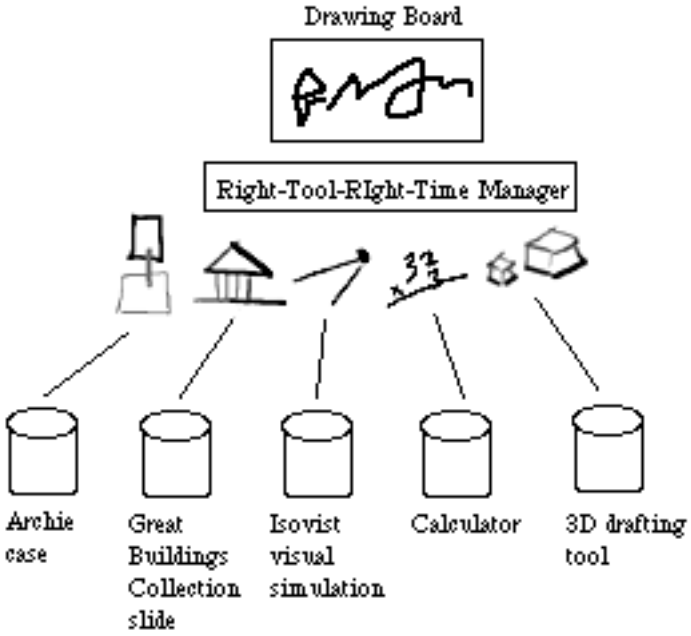

Figure 8. The system model of a drawing environment with the Right-Tool-Right-Time manager that activates different tools based on detected context through drawing symbols and configurations.

The RT^2 is only partially implemented (only with the links to different design aids, the Right-tool-right-time manager that activated different design aids based on drawing symbols will be implemented for the thesis.

5. EXPECTED RESULTS

5.1. EVALUATION OF THE SYMBOL UNIVERSE AND THE RT^2 MANAGER

I will complete the implementation of RT^2, Right Tool at the Right Time, an intelligent application manager that provides design tools targeting the task at hand by recognizing intentions from design drawing. For example, when the machine detects that the designer is working on lighting concerns, it can provide relevant cases, specification of lighting devices, or an interactive lighting simulation.

The thesis will deliver a symbol universe that designers use from the experiments and a prototype computer system architecture on how design tools can support a drawing environment by inferring from the design drawing. The thesis will employ the finding from the empirical studies (conventions of symbols used for different context and intentions) to implement the right-tool-right-time manager in a freehand sketching environment. The main result will show that it is possible to make intelligent guesses about what the designer is up to, simply by looking over her shoulder at the drawing. In particular, this thesis will identify certain conventions of drawing that are often associated with certain task domains in design. The thesis will also show that it is possible to program a computer to make these inferences. In the end I will demonstrate a prototype program that uses this system of inference to support designers with the right-tool-right-time manager.

APPENDIX -- THE PROPOSED EXPERIMENT SET-UP.

Design Brief

An architecture firm just rented a one story warehouse to be used as their new office space. The dimension of the space is 70 ft wide (on north and south sides) and 25 ft long (on west and east sides) with west side entrance facing a main street. All sides of the space are allowed to have opening except the south side that connects to another building. This firm currently has 1 chief architect, 3 designers, 3 CAD operators, 2 contract draftsmen, a secretary and about 1-2 student interns.

The office will be designed to have, besides the area for work groups of designers, CAD specialists and draftsperson, a meeting room, a small kitchenette, a bathroom, and a chief architect's private office, a secretary - receptionist - general affairs section, storage space, printing and plotting area, and space for student interns.

Flexible functional combinations may suit the occupants' various needs. For example, a meeting area can also serve as displaying of past design works, a storage space may include a small reference library, or product catalogue and material samples, print room could include Xerox, blueprint and computer plotting machines, etc.

Task 1

Please take no more than 10 minutes to make a conceptual, schematic design for the above program. Then continue on the following questions on the next page. Thank you!

Task 2

Please start with a new sheet of tracing paper to do a design for the brief. This time, please focus on the zoning of the spatial arrangement for the office.

For example, consider how to arrange a lobby, meeting area, different work groups, service area, etc.

Please take no more than 5 minutes to complete this task. Thank you!

Task 3

Please start with a new sheet of tracing paper to do a design for the brief. This time, please pay particular attention to lighting issue about the meeting and working area.

For example, perhaps introduce skylight or a small courtyard into the office if plausible?

Please take no more than 5 minutes to complete this task. Thank you!

Task 4

Please start with a new sheet of tracing paper to do a design for the brief. This time, please focus on the visibility, noise and privacy concerns between the receptionist, chief architects and the work groups.

For example, consider making each work group commands a fine view to the exterior, and an easy access to the meeting area.

Please take no more than 5 minutes to complete this task. Thank you!

Task 5

Please start with a new sheet of tracing paper to do a design for the brief. This time, you are given the condition that the chief architect has a favorite oak meeting table with dimension 4 ft * 10 ft, and he would like to put that table in the meeting space.
After you consider how the table can fit into the meeting room, please make sure each designer's work space would have at least 800 sq. ft.

Please take no more than 5 minutes to complete this task. Thank you!

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