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DESIGN HISTORIES: ARCHIVING THE EVOLUTION OF PRODUCTS

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ABSTRACT

This paper is an introduction to and a brief overview of research on the development of design histories for mechanical devices. A design history is a representation of the evolution of a product from initial specifications. Currently, design records usually include the initial specifications and drawings representing the final configuration. A Design History adds a record of all the critical decisions and constraints that maps these two design end points together, providing information critical in product redesign, design failure recovery, and design progress explanation.

Keywords: Design History, Design Representation, Design Capture, Redesign support.

1 Introduction

When the design of a mechanical product is completed, it is usually recorded as a collection of initial specifications and final drawings with attached notes. This information, representing the two end points of the design process, is then used to support two major activities: Communication (with other designers, manufacturing, management, marketing, etc.); Support of redesign or the design of similar products; and Explanation of the design sufficient enough to support the modification of a product that does not meet the specifications. In current practice these activities often fail because there is not enough information recorded to answer all of the questions raised.

Several researchers have speculated that redesign, design communication and failure recovery would be significantly improved if the final design included more information about the "history" of the design process. [1; 2; 3] This history would be a mapping from the initial specifications to the final drawings of the product.

A major project at Oregon State University has been an effort to develop a computer-based Design History to test the hypothesis that such a system can aid design understanding and redesign. There are four questions that have been addressed in this research:

- What kind of information should be included in a Design History?
- How should the information be represented?

- How can the information be easily recovered?
- How can the information be captured during the design process?

The results, to date, for answering these questions is discussed in the sections below.

2 The Information Needs in a Design History

In order to develop a usable Design History, it is necessary to determine the types of information needed by designers when they attempt to understand a design. It is not immediately clear what information must be represented in a history complete enough to explain a mechanical device's evolution. On first thought a record of CAD drawings of the object and changes to them might be considered sufficient. However, much of the important information about a product is not contained in the evolution of the drawings alone. For example, some information is too abstract to draw on a CAD system, [4] some is about the function or behavior of the product and some is about the rationale contained in the decisions that shaped the product. To expand on the information needs four studies are discussed.

An engineer, when trying to understand a product by looking at a piece of hardware or a drawing of it, asks many questions and makes many conjectures. This is even true with designers reconstructing their own reasoning for earlier design decisions. Thus, the first study to be discussed focused on the information needs of design engineers. In order to identify the questions and conjectures used to understand a product, three professional engineers were video-taped performing a redesign task. [5; 6] The task involved making changes to a design (represented by its final set of drawings and the initial specifications) that was produced by a different subject in an earlier study. The video tapes were analyzed to develop a taxonomy of questions and conjectures, a small part of which is presented here.

Results show that questions asked by the engineers are of four kinds: Construction (How is this built?); Location (Where is this?); Operation (What does this do?); and Purpose (Why is this here? or Why is this built this way?). Although these questions are often interrelated, the first two can be answered by knowledge about the form or structure of the design. The last two require functional information about the design. Finally, all may require information about the original designer's rationale.

Besides the nature of the question, the topic or focus of the question is also important. This is divided into four groups: 1) components; 2) assemblies; 3) interfaces; and 4) features of components, assemblies and interfaces. Data from the video tapes showed that 47% of the questions (358 total) were oriented toward the construction of components, assemblies, interfaces and features. Another 22% were oriented toward their location; 20%, their operation; and 11%, their purpose. These findings help define what types of information an engineer might look for in browsing a Design History tool.

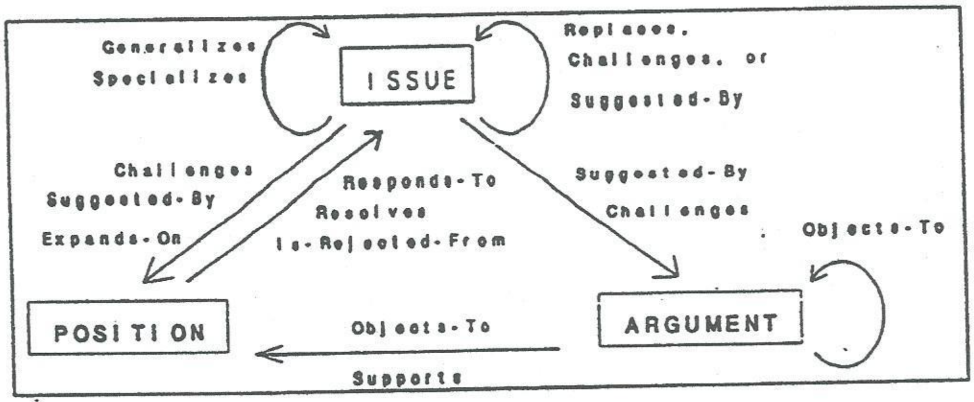

Figure 1
The IBIS Data Element Network

Where the above study focused on the type of information that engineers need, a second study has concentrated on the organization of the design effort. Researchers at MCC have refined the IBIS model of decision organization. [7] This model is organized around three elements: Issues; Positions or proposals for the resolution of the issues; and Arguments in support (refutation) of the proposals as shown in Figure 1. MCC has implemented this model on a computer for ease of posting the issues, proposals and arguments. The resulting tool, called gIBIS ("graphical" IBIS), allows the development of tree diagrams that relate text string instances of the three types of elements. IBIS (on paper) and gIBIS (on computers) were used to support a recent software development project at NCR. [8,9] The entire project addressed 2,260 issues and is by far the largest study of its type. Some of the results from this study are:

- The IBIS and gIBIS tools provided a shared memory for the design team. The history of decisions made and recorded in the tools was easily reviewed and utilized by members of the design team and management.
- The use of IBIS and gIBIS helped the design team detect design issues that had "fallen through the cracks". It was estimated the resulting savings were 3-6 times greater than the cost of using the tools.
- The use of these tools helped the team to more quickly understand the problem they were trying to solve.
- The tools aided in making team meetings more productive by structuring the information (issues, positions, and arguments) and helping establish and focus the agenda.

- The use of the tools supported communication with other levels of the organization. People not at a design team meeting could easily discern what was discussed – not just what the final decision was.

A complete Design History of a mechanical device must be a super set of the M-CC/NCR effort in that it must be able to record, organize and play back all the important information generated during the design process. Thus, not only must the decision structure be modeled, but also the entire development of constraints, functions and structure need to be recorded and available for browsing in order to answer the questions and support the conjectures. Additionally, the data required must include not only text strings, but graphical representations of the artifacts.

To more fully understand the information needed, a third study is referenced. In this study the evolution of a single component in an assembly from its initial inception to its complete detailing was analyzed. [10; 11] The data for this was taken from a video tape of a designer. [12; 13; 14; 15] The product designed was a device to hold aluminum plates for dipping into a water bath (Figure 2). The component analyzed was the outer frame assembly shown in Figure 3.

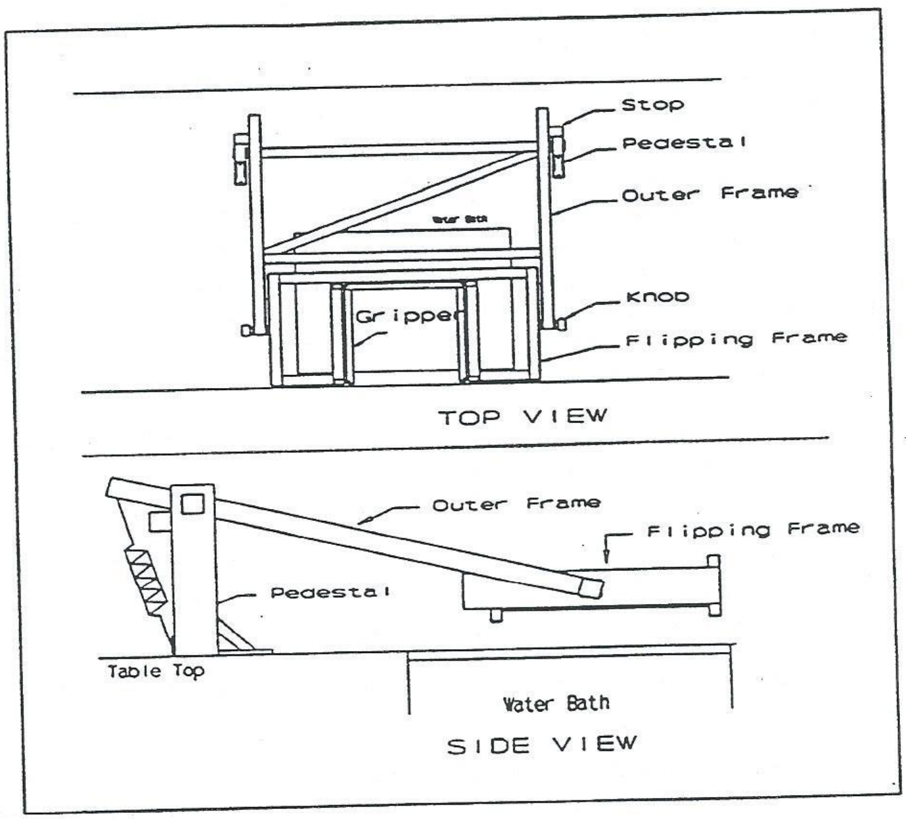

Figure 2.
Top and Side View of the Flipper-Dipper Assembly

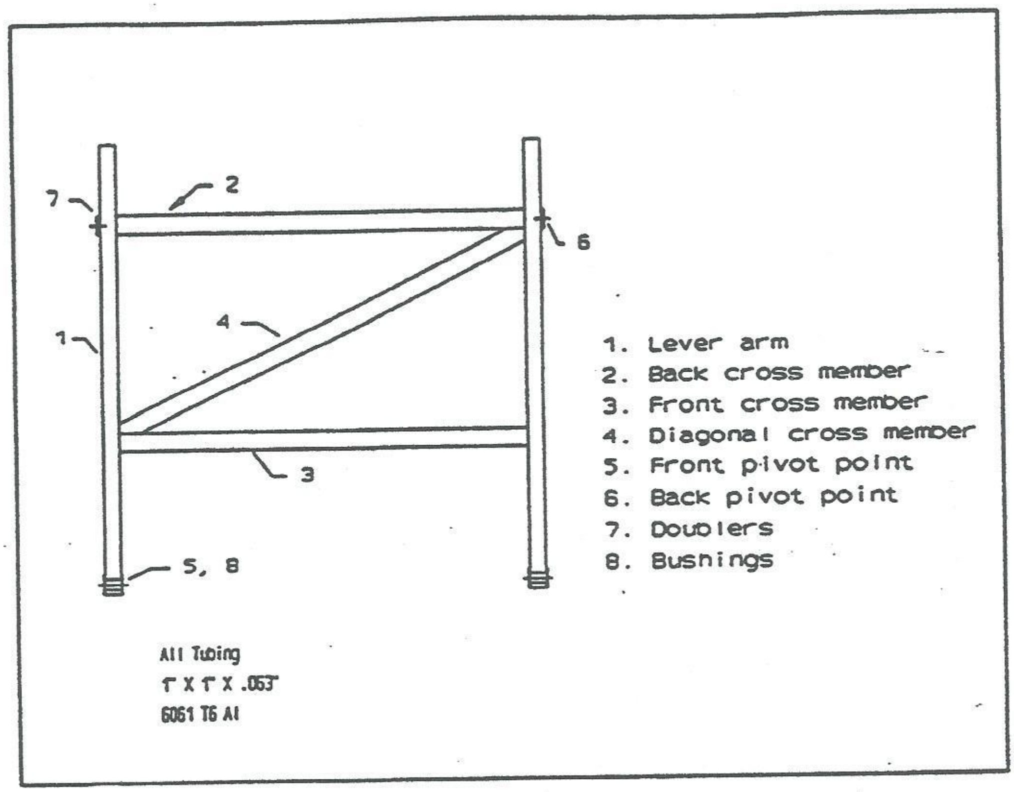

Figure 3.
Top View of the Outer Frame Assembly

The study included 38 design objects with 277 different features (both form and functional features). Of these approximately 30% of the objects and features were necessary to describe the design object itself. The eight objects that make up the outer frame are listed in Figure 3 . Relating these objects and features were 725 constraints which have been categorized in many different manners in the representation.

One breakdown of the constraints is by their source: Given external to the design, as in original specifications; Introduced through domain knowledge; or Derived through a design decision. Design decisions are viewed as transducers of constraints. They input some collection of existing constraints and produce new, derived constraints as output. In this study, fully 75% of the 725 constraints were derived from decisions (Figure 4).

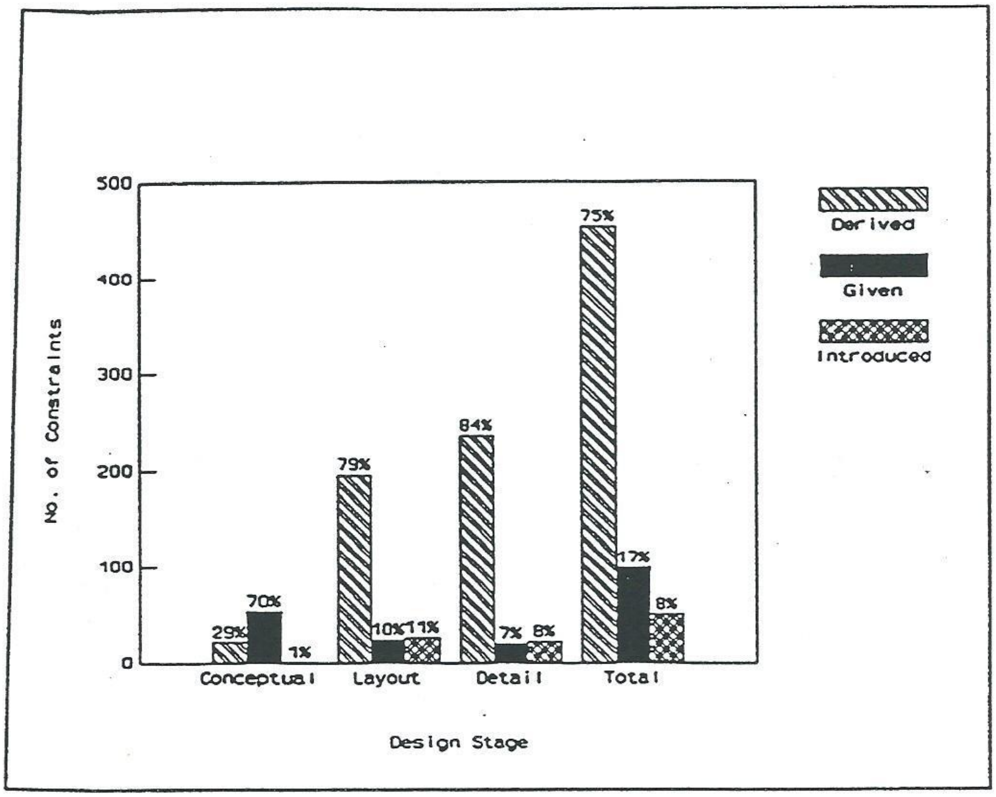

Figure 4.
Sources of Constraints in the Development
of the Outer Frame Assembly

As part of this study, the development of the features important to the designer, the necessary data representations for those features, and the relationship of constraints and constraint development to the features were identified. It is in this last area that the greatest contributions have been made. The traditional approach of considering only those constraints given at the beginning of the problem and of considering only quantifiable constraints is too limiting for future tool development.

The forth study was an effort to combine the research discussed above into one data element network as shown in Figure 5. [16; 17] In this figure, the issue, proposal and argument model used by MCC (Figure 1) has been extended to be dependent on constraints as indicated by the OSU research. The basic relationships between these elements are also shown. As shown, an issue is "Resolved - By" a decision, which is "Based - On" arguments. Also decisions have relations amongst themselves. One "Precedes" another giving temporal order to the Design History. Also a previously made decision can be "Continued-By" another which alters the original outcome.

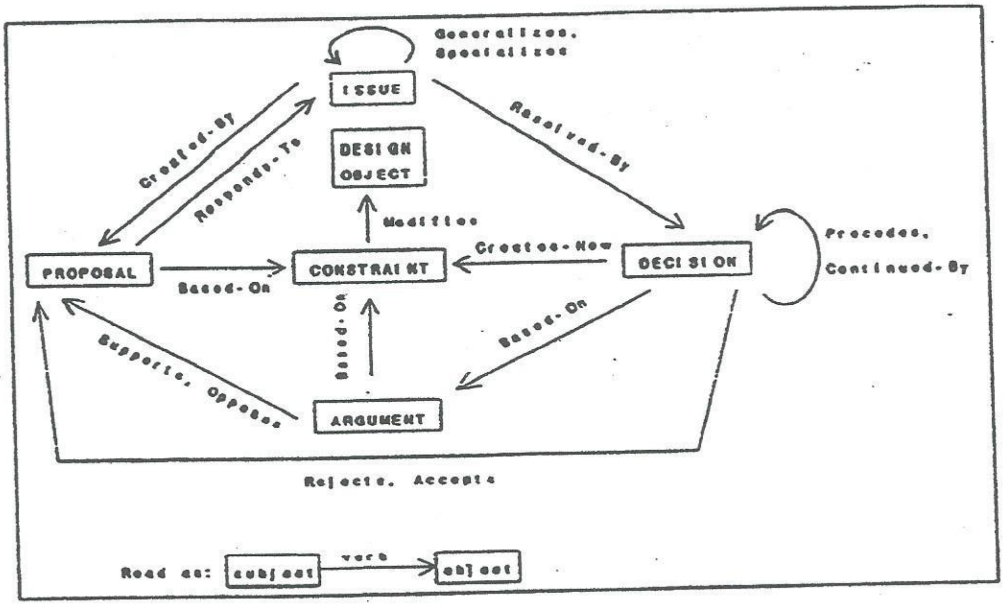

Figure 5.
The Data Element Network for a Design History

Although the temporal order of a Design History is mapped by the sequential relationship of decisions, the intellectual focus of the history is seen through the issues addressed and their relationships. Specifically, sub-issues are developed to "Specialize(s)" issues and super-issues are established to "Generalize(s)" the focus of the design effort. Also, proposals are generated to "Respond(s) - To" issues and new issues are "Created - By" proposals. Thus, the net of the relationships between specific issues can get quite complex during the design process.

The constraint based nature of the model can be seen in the figure. Decisions "Create(s) - New" constraints while proposals and arguments are "Based - On" them. Design objects are defined (Modified(s)) by constraints.

The material in this section has outlined research to identify the types of information needed in a Design History. A challenge has been to develop a computer based data representation of this information.

3 Data Represented in a Design History Tool

Since the Design History must represent all the data elements (Figure 5) the computer representation of these must be quite robust. Furthermore, the information needs to be represented at varying levels of abstraction and both in textual and graphic form. The graphic needs range from tree structures of decisions as in the IBIS model to sketches and drawings of components, assemblies and form features.

Both the gIBIS project and the work at Oregon State University have used object-oriented knowledge representation techniques to handle this information. [11; 18; 19] The gIBIS project used a Hyper-text tool to build its representation. The O-SU effort uses the Hyperclass object-oriented programming environment, developed at Schlumberger; and Vantage, a solid modeling tool, developed at Carnegie Mellon University. With this environment, all information about the evolving design can be represented as constraints. The first level of classes of information in the model are as shown in Figure 6. Most of the classes of objects have been discussed in the previous text. Other classes need to fully describe the decisions and the constraints are included. Additionally, there are many sub-levels to this representation.

* Issue
* Argument
* Decision
* Decision-operator
* Evaluation
* Constraint-source
* Constraint-role
* Constraint-expression
* Design-object

Figure 6
The Top Level of Classes of Information
in the Hyperclass Design History Tool

An unexpected outcome of the studies discussed in the previous section and the effort to codify their results is a general purpose representation for exchanging design information. This representation addresses issues that need to be understood as standards like PDES mature from the representation of geometry to the representation of all the information generated during the design process.

4 Playback Requirements for a Design History Tool

In order to access the data in the Design History an engineer or another user must be easily able to browse the information. Based on the studies described in Section II of this report a Design History system must provide at least four basic types of browsing capabilities. [19] These are partially enabled in the current, Hyperclass tool.

- Browsing design artifacts
  This type of browsing allows the user to traverse the hierarchical structure of the form features of a product. Details on assemblies, components, interfaces and features can be easily searched. Much of this information is graphic as shown in Figures 7 and 8 from the current implementation. In Figure 7 a component is shown with one feature of it high- lighted. This feature is shown in reversed text in Figure 8, a tree diagram of the structure of the component. In Figure 9 the feature itself is shown and a feature of it (the highlighted slot) can be further investigated. This type of browsing can be used to answer construction and location questions.

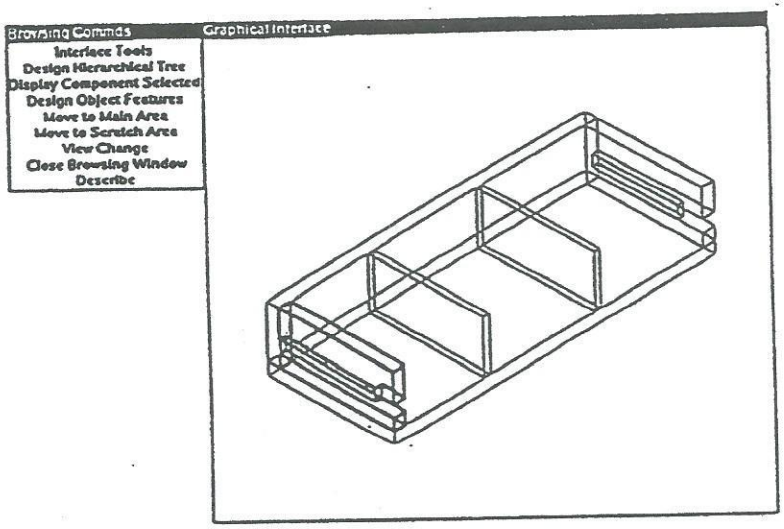

Figure 7.
A Graphic Window from the Hyperclass Design History Tool

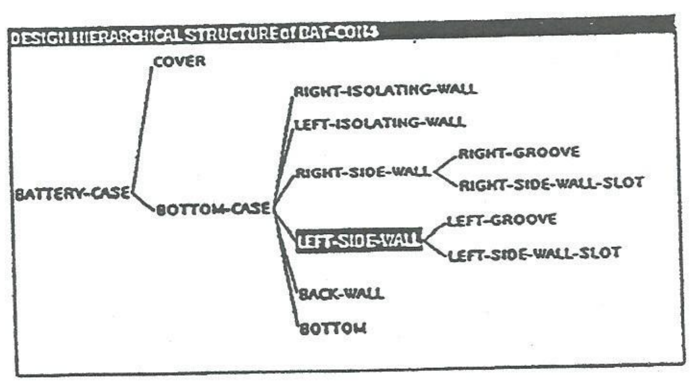

Figure 8.
A Design Feature Tree from the Hyperclass Design History Tool

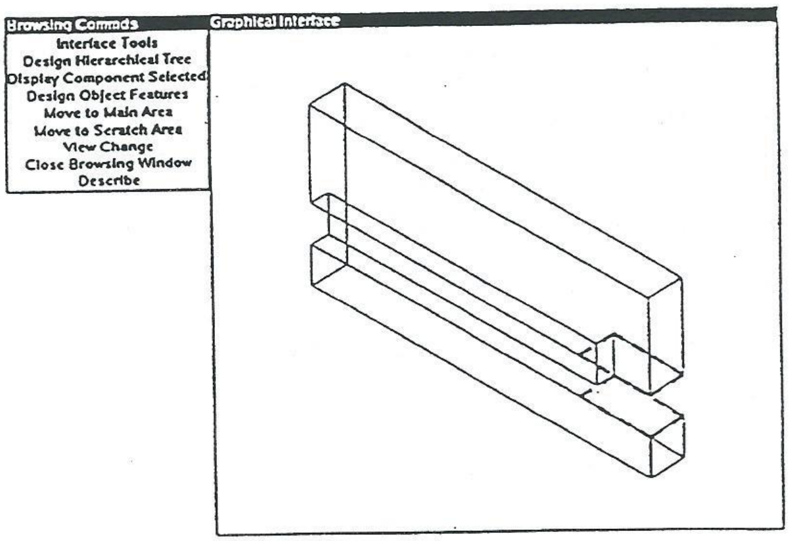

Figure 9.
A Feature Detailed from the Hyperclass Design History Tool

- Browsing design evolution
  Browsing the design evolution allows the user to relate the initial specifications (given constraints) or introduced information (introduced constraints) to the development of any aspect of the product. This aids in answering purpose questions if they are directly dependent on the given or introduced constraints.

- Browsing constraint dependencies
  This type of browsing allows for exploring all types of constraints. It is a generalization of browsing the design evolution as it allows exploration of any type of constraint relationship. Since 75% of all the constraints are derived constraints, this type of browsing can lead to the decision that initiated or modified a design object. It can also show which constraints were used in making a decision. This type of information helps answer purpose questions. A typical window from the current system is shown in Figure 10. Here the effect of the given constraint, the diameter of the bottom of the battery, on a number of downstream derived constraints can be seen. For example, the battery diameter was one of the constraints that was used in the decision that resulted in the initiation of and the reconsideration of the isolating wall length. This relation can be seen in the two instances of the object "Isolating-wall Length" which is labled as a derived constraint.

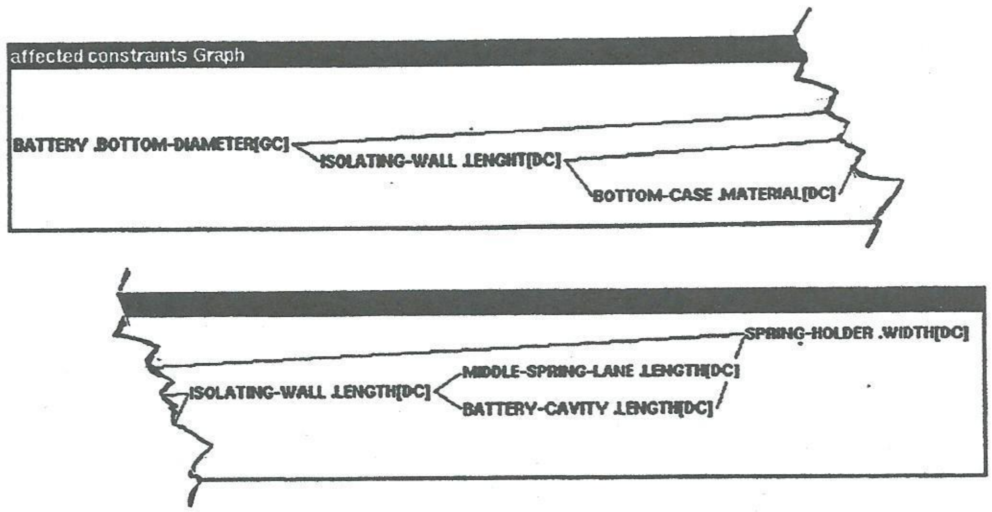

Figure 10.
Example of Affected Constraints Graph

- Browsing design rationale and alternatives
  An important type of browsing is the consideration of design rationale and alternatives. These can be in support of any of the questions mentioned in the above browsing tools. However, instead of the result of a decision (the state of the constraints) the user wants to know more information about the decision making process. Here data about the issue, alternatives and arguments must be available to the user.

To meet these browsing needs a user interface for the Design History system has been developed. [18; 19] A large-screen display contains several windows of information. The main window shows an isometric drawing of the final design (see Figure 7). By buttoning (with a mouse or stylus) on a component or a feature in the drawing window, the user can determine which original requirements affected the design of that feature. The user can also obtain a detailed explanation of the purpose of the selected component or feature and the decisions that led to its creation and refinement.

To test the value of a Design History in aiding redesign and design communication a controlled experiment in which subjects are asked to carry out a redesign task is planned. The task will involve making changes to a design that has been entered into the Design History representation. The performance of two groups of subjects will be compared. One group will have access only to the final drawings and notes of the original design. The other group will have access to a computer-based Design History browsing tool which should provide them with easy and convenient access to the information stored in the system.

5 Design Capture

In order to build a Design History, data must be captured during the design process. This data must include information about the design objects, the constraints and the other elements in the decision structure shown in Figure 5. A sufficient capture system must meet two criteria - the data must be complete enough to fully represent the design and it must be captured in a manner that has minimal intrusion on the designer(s). Currently the data for the Design History representation at OSU is hand crafted from the video recorded data. This is checked by a second researcher before being entered into the Design History representation - a very time consuming process. It is estimated that it takes approximately thirty minutes to extract and prepare each minute of video data. With refined methods the time for capture from videos may be reduced to ten minutes per minute of data - still clearly prohibitive for any usable system. This method is best suited for very fine grained data. Currently, data is logged with the average of one decision every two minutes. This fineness was thought necessary for initial tests of the efficacy of Design History systems, but may not be warranted for operational systems.

A second method has been suggested for recording the Design History data. This is through a "design historian", a role that Hales played in his study. [20] Hales was a part of a team that designed a coal gasification test rig. During the three year design process, he chronicled the flow of the design process focusing on the interchanges of information between members of the design team. On the average, he recorded one decision every hour. This level of fineness may be sufficient, however, many important decisions made by individuals might have been overlooked.

To formalize Hales' methodology, it can be imagined that a member of the design team could be assigned as design historian. This individual would be much like a knowledge engineer, interfacing the knowledge gained about the design to the history software. The historian would be a part of meetings and would interview project engineers on a regular basis (daily?) to gather the data needed.

The gIBIS system use by MCC/NCR in their study gives a template with which the design historian or members of the design team can record a limited Design History. However, during the MCC/NCR experiments design team members were not eager to use the system as it required "extra" effort on their part.

To surmount this problem the ideal design capture system would be part of an on-line engineering design environment. Such an environment would allow the designer to do all his/her design work on a computer terminal. This would include not only drafting and the results of analysis that is now possible, but also notes, sketches, decision matrices, quality function deployment matrices and other parts of an organized design process. Such a capture system would have two primary goals. First, it would need to be able to collect a consistent data base. Second, it would have to be supportive yet not invasive to the designer. In other words, while capturing the needed design information, an ideal design capture system would give the designer tools that would aide in his/her execution of the design process without causing excess paper work or information generation.

In an effort to develop one sub-set of this ideal system, a research project at Oregon State University has been focusing on the capture of geometric information during the early phases of the design process. There are three reasons for focusing on this kind of design capture. First, current CAD tools have difficulty capturing abstract geometry. Second, our research on the role of sketching and drawing during the design process has shown that these activities are critical during the early design phases. [4] Third, decisions made early in the design process control the cost and quality of the final product. [21]

The goal of this project has been to develop a computer-based drawing system that will not only allow the computer to capture sketches made by the designer,. but will, based on the sketch, build a feature model of the artifact. This system, called the design capture system (DCS), [22] currently runs in C on a Micro VAX-Tek 4129 system and on a HP 9000-370 work station.

The operation of the system is as shown in Figure 11. The user sketches on a tablet with a stylus. Input is in the form of isometric sketches, but any 3-D sketch made can be accommodated. The sketched primitives are recognized as line segment primitives such as straight line, arc, circle, etc. These are stored as data for 2-D primitives displayed on the screen "cleaned-up" (i.e. the straight line, sketched not too straight is now straight). From these primitives the system attempts to recognize 3-D features, the heart of the system. As the designer sketches 2-D primitives, the system interprets the 3-D features in the order the designer adds them to his/her sketch. This capturing of the sequential order of the designer's addition of features, is fundamental to parametric changes that will be made later on in the design.

Next, based on the relation of each new 3-D feature to the existing design, a feature based solid model is developed and displayed. Figure 12 shows a component sketched into the DCS. This component took the designer less than two minutes and is a parameterized solid model representation.

To date this system is showing itself to be supportive but not invasive in its aide to the designer. It produces a feature based solid model while affording the designer a capability that has not been previously available.

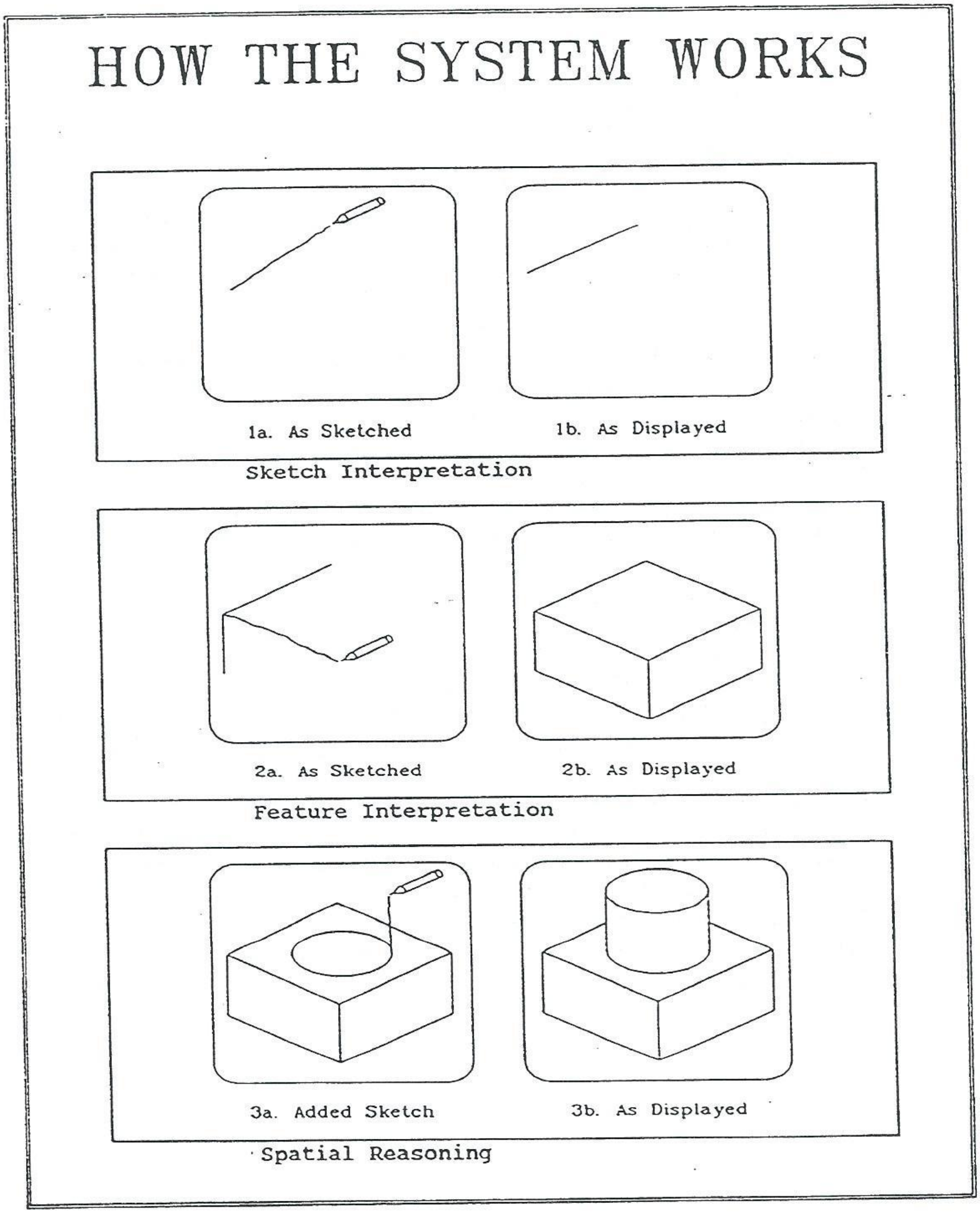

Figure 11.
The Operation of The Design Capture System

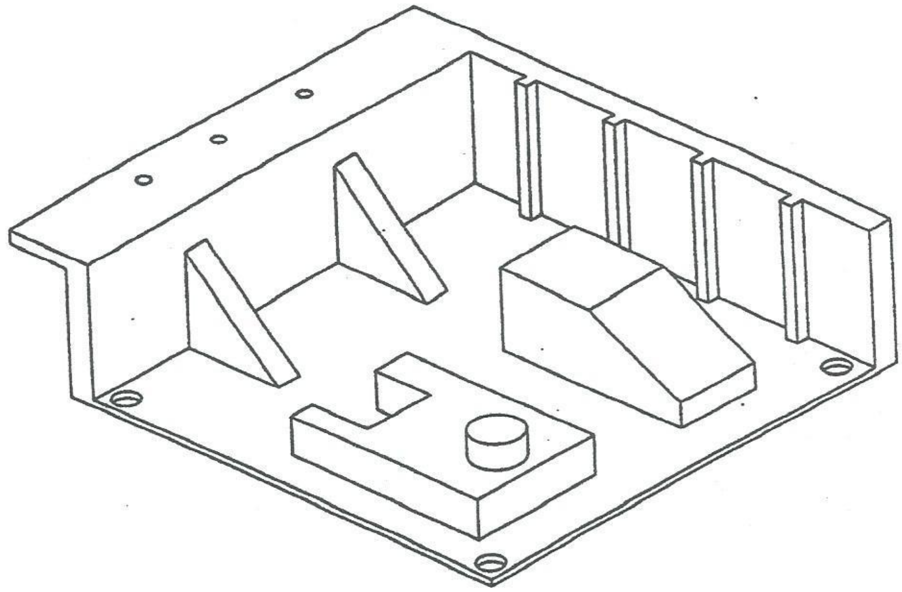

Figure 12.
A Sample Component Sketched into the Design Capture System

6 Summary

In this paper research issues important to the development of a Design History have been developed. These center around: 1) The need to determine what should be in a Design History; 2) The need to develop adequate representations for such a history; 3) The generation of adequate playback and query systems; and 4) The need for systems to enable the capture of the historical information. Although research is well under way in all four of these areas there are many open issues that need to be resolved. Primary among these are:

- Research is needed on representations of function and operation of a physical object. Additionally, integrating this data into the representation of form is not well understood.

- More effort is needed to verify the types of information needed in a design history. This will happen naturally as tools are developed and utilized. Additionally, studies specifically focused on this issue are needed.

- The capture of design data is critical to the development of a Design History. Increased effort needs to be made to develop an environment that supports all phases of the design process and transparently captures a Design History.

- The work discussed in this paper is focused primarily on the design of mechanical devices (OSU) and software (MCC). Extension of the concepts to electronic design and other fields is necessary.

- Work has barely begun on the needs for a browsing environment. An interface that allows the needed information to be rapidly found is essential.

7 Acknowledgements

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