INTELLIGENT CAD, I

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Preface

In 1963, a paper was presented by an MIT research group proposing a system which is now thought as the origin of computer aided design (CAD) systems that proliferated to a great number afterwards [1]. Their concept was revolutionary and stimulated many other researchers to commence the studies on theories and methodologies for manipulating geometrical shapes in computers. Presently, a new academic field called computational geometry is established on which many of the practical CAD systems are methodologically dependent.

Current CAD systems that are commercially available are mostly based on the original idea proposed by the MIT group, and therefore their main functionality is developing and manipulating the geometrical shapes in the computer. They have been widely applied in various fields of industry, such as aeronautical, naval, architectural, structural, mechanical etc., and proved to be quite useful and sometimes essential for the design activities in these fields. Especially, by combining them with evaluation systems such as the finite element method for computing the strength of members in a design, and also with the computer aided manufacturing systems (CAM), the usefulness of CAD has been definite from the view points not only of the user's convenience but also of economical effectiveness.

With increase of the numbers of users, however, a new demand for CAD has been raised. They are sometimes critical to the present CAD. CAD is just an "automatic paper." CAD systems assist designers only in drawing, therefore CAD is "computer aided drawing." CAD is only useful for inspecting the results of design and has no relation to the designing process. They seem too much exaggerative but not wrong.

It is worth noting that the original aim of the present CAD is nothing but representing geometrical shapes in computers. In other words the originators had defined designing as constructing geometrical shapes. Under this definition, the present CAD should be considered achieving a considerable level of the original aim. Therefore it seems unreasonable to criticize the present CAD systems because they are not useful for other than the geometrical shapes.

This was early pointed out in a literature [2], where the understanding of the designer's designing process is crucial for developing a CAD system that aids designers in their thought process. It was also shown, there, that the designer's thought process to develop a machine in her concept is conducted in topological space and not in a Euclidean-geometrical space. Thus, the CAD based on Euclidean geometry can not be sufficient for aiding the designer's thought process.

There have been many studies that were devoted to describe the design process phenomenologically. Their results were published as textbooks of the design methodology. They are quite useful for experienced designers to consolidate their achievements and for novices to learn how to design. But their descriptions are not accurate enough to stimulate CAD fabricators to construct new CAD by applying them.

Phenomenological observation of the designing process tells us that the designing process s usually domain-specific. Processes of designing ships and of electrical circuits are absolutely lifferent. The naval architecture can be conducted successfully only by utilizing sufficient nowledge about ships, that is hydrodynamical properties of geometrical shapes, strength of material, characteristics of engines, control of complicated systems, stability of floating mass, etc. On the other hand, circuit theory, properties of electrical components are the requisite knowledge for designing electrical circuits. There seems to be no necessarily common knowledge between these domains. Moreover, phenomenological steps of these designs seem quite different from each other.

One way to construct CAD systems that usefully assist designers more than geometrical drawing is to implement the observed designing process directly into the computer. Actually, there are many such systems applied practically. Design systems for some specified electrical motors and certain kinds of ball bearings are typical examples. They are sometimes called automated design.

Actually it is possible to automate design by specifying the design object with a few parameters allowed to change. The automated motor-designing system can design different motors allowing some latitude, but of course cannot design ball bearings. These systems are playback design robots, so to say, and anything but useful assistants in thinking process of human designers. Designing is substantially more than playback. Only when there is some new, that is creative, parts found in a design, we call it a real design.

Creativeness is the intrinsic nature of human beings, and it is very important that the creativeness plays the most important role in driving the designing process of any objects. It is necessary to go into a deeper point of view than phenomenological in order to uncover the common nature of designing processes. If we scrutinize designing processes, we find many common processes operating behind their appearances. The observed creativeness in design can be divided into more elementary processes that are characteristic in design and also independent of the domain-specific knowledge. A general design theory was proposed where a topological model of the thought process in design was dealt with as a theory applicable to any domain of designing [3].

We are also encouraged by the recent development of cognitive science and artificial intelligence. Though no researcher of these fields has been interested in the design, the findings and models in these fields as well as their methodologies for implementing their results in the computer are very helpful for our future development. The significance of artificial intelligence for CAD was early pointed out and actually a Working Conference was held, organized by the IFIP WG 5.2 under the title of "Artificial Intelligence and CAD," which can be said the marriage meeting of CAD and AI [4].

In 1985, a Working Conference on "Design Theory for CAD" was also held by the IFIP WG 5.2, where it was concluded that design theory is requisite for correct utilization of useful results of AI researches when developing new CAD systems, that is CAD that assists designers in creative processes in design [5].

In 1984, the WG 5.2 decided to organize three successive Workshops on "Intelligent CAD." The intelligent CAD defined there was a new CAD that performs as follows:

(1) CAD that assists designers through all stages of the designing process (totality).

(2) CAD that assists designers in the design process of any object (flexibility).

(3) CAD that can be connected with any other information processing system, such as CAM (integration).

This proceedings is the result of the first Workshop held at Cambridge, MA., USA, in October 1987 under the subtitle of "Implication of AI for CAD." The workshop successfully discussed interesting topics and the participants were companying of researchers from various domains; firstly from the design domain in mechanical, architectural, electrical etc., secondly from artificial intelligence and thirdly from researchers on computer science.

The workshop comprised three invited speeches, discussions in three subgroups, and general discussions. Each participant was requested to submit an extended abstract and some of them were presented during subgroup discussions or at plenary sessions. Subgroup discussions were organized to concentrate on topics chosen by the participants, viz. Subgroup 1 on "Representation of Artifacts" chaired by Professor Farhad Arbab of the University of Southern California, Subgroup 2 on "Model of Design Processes" chaired by Professor Manjula B. Waldron of the Ohio State University, and Subgroup 3 on "Architectures for Intelligent CAD Systems" chaired by Professor Fumihiko Kimura of the University of Tokyo.

This book represents most valuable results of the workshop, including reports from the chairpersons of the subgroups and plenary sessions, invited papers, and papers selected from participants' contributions. These selected papers were first reviewed by the Program Committee and chairpersons and then revised based on their comments. Reviewers also picked up key concepts or crucial terms in understanding the papers, which resulted in the Glossary attached to the end of the book.

The Editors would like to thank the Program Committee and the chairpersons of the workshop for their efforts in preparing the workshop, conducting and summarizing discussions, reviewing papers, and compiling this volume. Special thanks also go to people who helped us to organize the workshop and the participants to whom this book owes its greater part. We are grateful to Mita Industrial Co., Ltd. and her President, Mr. Yoshihiro Mita, for their supports in preparation of this series of workshops.

Tokyo, February 1989 — Hiroyuki Yoshikawa

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Chairperson Reports

Design Object Modeling

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Foreword

What follows is the report of the discussions in Subgroup 1 meetings at the First IFIP WG 5.2 Workshop on Intelligent CAD Systems, MIT, Boston, October 1987. As the chairman of the group, I moderated the discussions and it was my duty to produce this report. Rather than a virtual transcript of the sessions, I tried to produce a more coherent document that reflects the essence of the subjects discussed at the meetings. In doing so, unfortunately, some of what would have been obvious in a transcript format has been lost, e.g., the spirit of the sessions, the nature of the discussions, the evolution of the ideas, and more importantly, the credit (or blame, as the case may be) for the key ideas or comments that set the course of our discussions.

The list of topics that we produced in our first session included quite a few important issues that we never managed to sufficiently discuss later on. For the sake of coherence, I have eliminated discussions that did not lead to a substantive result. By doing so, I am afraid, some of the context and the breadth of our discussions has been lost as well. The difference between this report and an account of what actually transpired in our meetings is perhaps a good example for one of our conclusions: the difference between the design of an artifact and a description of that artifact. Schemes used for artifact representation (e.g., the structure of this report) are not usually conducive to reflect their design.

While the ideas presented here came out of the discussions to which all group participants made a contribution, this report does not necessarily reflect a consensus of opinion in the group, nor does it necessarily agree with the personal views of its individual participants. I thank all participants for their contributions, John J. Cunningham for producing and providing me with the notes that are the basis of this report, and Dave Gossard for substituting for me in one of the sessions.

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1. Introduction

The subject of our discussion is the tools and techniques for modeling of concepts, or for the lack of a better term, of "objects." We are interested in the representation and manipulation of the knowledge about concepts that need to be manipulated in an intelligent CAD system. We perceive Geometric Reasoning, Feature Based Reasoning, and Qualitative Reasoning on models as important activities during a design process. Representation of geometric knowledge beyond existing geometric models, modeling of features, and representation of functionality are, therefore, among the topics relevant to our discussion. Each of these topics is an interesting area of research in itself and is also the concern of people in the AI community working on robotics, computer vision, learning, natural language understanding, etc.

Generally, the modeling problem can be decomposed into two subproblems: "what is it that must be modeled?" and "how is it to be represented?" In most applications, these two subproblems can be regarded as "orthogonal" and their solutions can be based on different techniques, quite independent of each other. This leads to a sort of "creationism" in modeling. The basis for this is a static hierarchy of types that captures the essence of the entities of interest in a domain. The representation of each entity in a domain can thus be a "concrete" representation, in the sense that its type determines *all* of its possible attributes, except for their values, of course. This works because in most applications, once it has been decided that an entity is a *cat*, it will always remain a *cat*, although the values of its attributes may still turn it into a Bengal tiger or a Persian cat. The process of deciding what the entity is in the first place, however trivial or sophisticated it might be, is in principle a search through the space of possibilities which in turn is determined by the earlier decision on what must be modeled.

In the context of CAD, however, a new dimension must be added to our representations to accommodate the *design* activity. *Creative*, (as opposed to *parametric*) design, by definition, requires the two subproblems to be considered simultaneously. This leads to a sort of "evolution" in modeling. A designer's concern is to meet the specifications of the requirements of a "new" entity within the confines of a set of constraints. He may not know beforehand that "utility similar to a horse" plus "desert environment" plus "several days between drinking opportunities" eventually leads to a *camel*, or he may wish to ignore that to investigate other possibilities. The "new" entity being designed *evolves* as new properties and attributes, as well as values, are discovered and associated with it. It may by coincidence end up to be an instance of a type in some predefined hierarchy, or it may indeed represent a new type quite incompatible with such a hierarchy. The model of a design entity must then capture the (incomplete) information about this entity, independent of any hierarchy, as it evolves throughout the process of design.

2. What Is Design?

The word "design" is used to denote three related, but quite different, concepts. First, there is design as a verb, which refers to the process of design. Can the activity of design be automated? The answer to this question seems to divide the CAD community into two camps, who therefore see the role and the functionality of Intelligent CAD systems quite differently. On one extreme, an Intelligent CAD system is a substitute for a designer that given the requirements, is supposed to *do* the design. On the other extreme, since creativity of designers cannot be formalized into computer programs, an Intelligent CAD system is only an intelligent assistant to a designer, who is necessarily engaged in the process of design. However, there is an agreement that understanding and even a representation of the activity of design, i.e., of design as a verb, is necessary for both types of Intelligent CAD systems.

Second, there is design as a noun, which refers to a description of an abstraction of an entity. Current practice suggests that a design, in this sense of the word, is represented by a nominal geometry, variational geometry (tolerances), material specification, combination plan (i.e., assembly), functionality, etc. Design, in this sense of the word, is the net outcome of a design activity, an answer to the question "what artifact satisfies the requirements?" Thus, it is more appropriate to refer to this concept as *a description of an artifact*, rather than *a design*.

Third, there is design, also as a noun, which refers to the set of pertinent intermediate results produced while designing (in the first sense) a final design (in the second sense). While design, in this sense of the word, is not necessarily a history of the design activity, it shows the evolution of the final result by capturing the significant milestones in the design activity. It identifies the important decisions that were made in the process and serves as a rationale for the particular derivation that leads to the final result.

It is the last two concepts that are more directly related to our area of discussion.

3. What Must be Represented?

The distinction between a description of an artifact and its design is an important one. It is clear that as the final outcome of a design process, an Intelligent CAD system must have a representation of design artifacts. We understand what is necessary to describe an artifact and have some working methods for representing artifacts in existing CAD systems. Still far from ideal, we feel existing solid modeling techniques provide a good footing for further enhancement of artifact representation.

One can argue that representing an artifact is indeed *all* that existing CAD systems do [1]. The leap from existing CAD systems to Intelligent CAD requires the ability to represent designs of artifacts, in addition to artifact representation. To make the distinction clear, consider the (partial) product cycle shown in Figure 1. Iterations, as shown in the figure, are common in the design phase of a product cycle. With existing CAD systems, the process of finding an artifact that satisfies a given set of requirements is performed entirely by a designer. A CAD system helps a designer only in *documenting* his artifact geometrically. The design of an artifact, however, is more than a mere representation of the artifact itself. Important design decisions, significant features (functional, geometric, etc.) of an artifact, and their derivation and interdependencies encountered during a design process are integral parts of the *design* of that artifact. In principle, much of this design knowledge is still valid and applicable in the next iteration of the same design, if not elsewhere. It should be possible, therefore, for a CAD system to play a very active role in similar situations where this knowledge is relevant, at least in the next iteration of the same design. Without the ability to somehow represent the design of an artifact this information is lost with existing CAD systems. A designer, therefore, has to solve many of the same problems over again in the next iteration of his design.

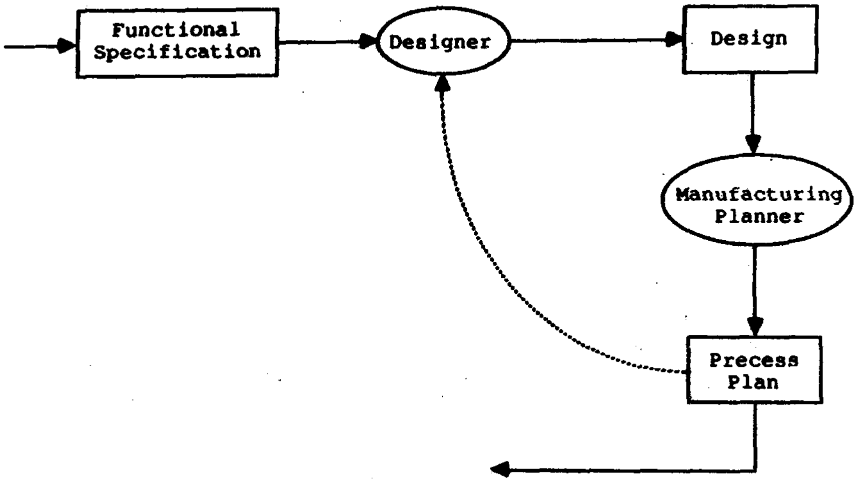

Figure 1

We believe the existing methods we have for artifact representation are inadequate for representing designs of artifacts. Their required level of specificity and the small granularity of their primitive concepts seem to be one problem. Lack of different levels of abstraction is another. More importantly, different views of an artifact and their interrelationships must be represented. For example, in addition to functionality and shape, the relationship between the two must be represented. Indeed, it seems we have difficulty even finding the proper terms to discuss designs of artifacts intelligently. While existing artifact representation techniques still need much enhancement, we need to focus on the problems of representing designs. From a CAD system's perspective, a design activity is a process of deriving an artifact representation from design representations. Without an explicit representation of a design, a CAD system cannot take an active role in a design process.

4. Representation Schemes for Design

The work of several of the participants in our discussion group reflects concerns similar to what has been discussed. Although they may not share the same views and use different techniques to capture design, they are dealing with the same problems.

In their system architecture, Dixon et al [2]. have a "primary representation" for design from which multiple "secondary representations" can be derived for various tasks. Their goal is to have enough knowledge incorporated into a CAD system to enable it to provide online feedback to designers, giving analysis results, manufacturing related implications of designs, etc. Because secondary representations are task specific, they are easier to deal with. By focusing on these tasks and their related representations, they can find what must be included in the primary representation. Specifically, they have worked on manufacturing related issues that must be considered during design. They have found *features* to be the key concepts for raising the level of abstraction in the representations of designs as well as artifacts. They hope to eventually capture designers' intentions with features.

In their view, a feature is an abstract concept that cannot be further defined, except in the context of a specific activity. Features originate in the fundamental principles of an activity. Why is it relevant to talk about *X* is inherent in the activity at hand, and what *X* is depends on the processes involved. For example, manufacturing features have their roots in the physics of the manufacturing processes. Why *X* is a feature in the process of casting, for instance, can be traced to the fundamental principles of physics that describe the flow of the molten metal, its cooling and solidification, etc. Conventional manufacturing heuristics serve a similar purpose by expressing the results of practical experience. They have studied manufacturing practices to find such heuristics and have compiled features for several process-activity pairs, e.g., aluminum casting - cost analysis.

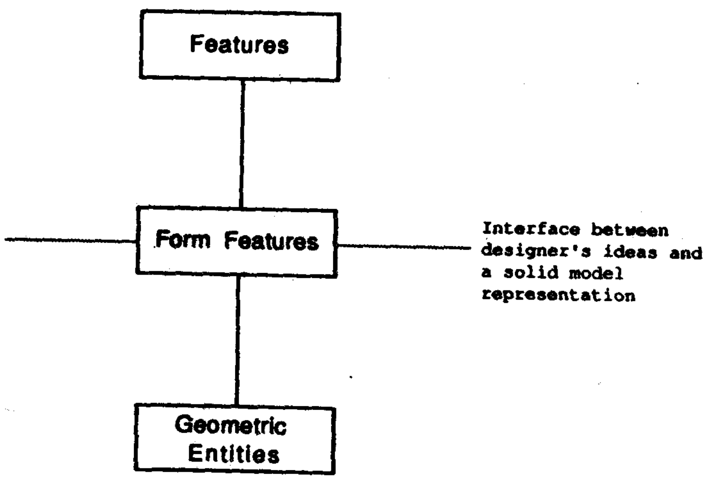

Figure 2

Vosgerau et al. [3] also recognize the need for various levels of abstraction and regard features as the fundamental concepts necessary to achieve it. They define a *form feature* as a surface or a group of surface in the geometric model representing an artifact. Form features are concrete entities that exist in a boundary representation of a solid model of an object. A *feature*, on the other hand, is an abstract entity, a name, denoting some form feature. In their hierarchy of concepts (Figure 2), they see form features as the interface between a solid model representation of the geometric shape of an artifact and its designer's intent. To move out of solid modeling and into Intelligent CAD, they are working on systems