ARTIFICIAL INTELLIGENCE AND DESIGN:

A MECHANICAL ENGINEERING VIEW

John R. Dixon

Department of Mechanical Engineering
University of Massachusetts
Amherst, MA., 01003

ABSTRACT

Most AI research into design has been based on or directed to the electrical circuit domain. This paper presents a mechanical engineer's view. Design of mechanical parts and products differs from design of electrical circuits in several fundamental ways: materials selection, sensitivity to manufacturing issues, non-modularity, high coupling of form and function, and especially the role of 3-D geometry. These differences, and the role of analysis in mechanical design, are discussed. A model for design is also presented based on the basically iterative nature of the design process. A brief summary of the related research at the University of Massachusetts into application of AI to mechanical design is included.

INTRODUCTION

"The proper study of mankind is the science of design." (Simon, 1969)

Probably so, but since 1969 the subject has hardly been a major theme of AI research. The Handbook of AI barely discusses it. Now, however, AI has rediscovered design, especially engineering design (Mostow, 1985).

There has, of course, been some attention paid to design by AI researchers over the intervening years. See, for example, Sussman, 1977, 1978; McDermott, 1978, 1981, 1982; deKleer and Sussman, 1978; Bennett and Englemore, 1979; Stefik et al, 1982, Brown, H. et al, 1983, Mitchell et al, 1983; Steinberg and Mitchell, 1985). The vast majority of this research is directed to or based on the domain of circuit design. Unfortunately, one cannot obtain an adequate general model of design, even engineering design, from the circuit domain alone.

Recently some AI researchers have become interested in mechanical engineering design (Brown, D. C., and Chandrasakeran, 1983, 1984, 1985, 1986; Brown, D. C., 1985a, 1985b, 1985c; Brown, D. C. and Breau, 1986; Popplestone, 1984; Mittal, 1985). These initiatives into the application of AI in the mechanical domain illustrate very well not only that AI can contribute important perspectives to mechanical design, but also that studies of mechanical design can enrich the AI view of design generally.

The goal of this paper is contribute a mechanical engineer's view (and model) of design to the AI discussion of design. The view of design and the model presented here are based on the author's engineering experience and also on recent research at the University of Massachusetts into the possible application of AI to mechanical design automation (Dixon and Simmons, 1984, 1985; Dixon et al, 1984, 1985; Dym, 1985; Simmons and Dixon, 1986; Kulkarni et al, 1985; Vaghul et al, 1985; Howe et al, 1986; Libardi et al, 1986; Luby et al, 1986).

MECHANICAL DESIGN COMPARED WITH CIRCUIT DESIGN

The Rutgers Workshop on which Mostow's article is based consisted of mostly electrical engineers and AI researchers. A workshop involving both mechanical engineers and AI researchers has since been held, with quite different results (Cole et al, 1985). Though it may be possible that at some (high) level of abstraction the design processes in the circuit and mechanical domains are similar, design in the two domains is so very different at the practicing level that we are not likely to discover the generalizations until we understand design much more fully in the two domains separately.

There are some important ways that mechanical design and circuit design are alike. Both are engineering, and thus there are bodies of heuristics (e.g., "good design practices") as well as much reasoning from basic science principles. Both domains also use analysis methods of various degrees of sophistication to support design.

Despite the similarities, there are four issues in mechanical design that make it fundamentally different from circuit design. These are: (1) the wide spectrum of material choices available to mechanical designers; (2) the critical role and often hyper-sensitive effect of manufacturing concerns on mechanical designs; (3) the non-modularity of mechanical designs; and (4) the intimate role of complex 3-D geometry in mechanical design.

Perhaps the most significant of these differences between mechanical design and circuit design is in the role of 3-D geometry. In addition to a material specification, a mechanical design is a description of a 3-D geometry. Is. Though Mostow's paper does not even mention geometry as an issue in developing better models of the design process, it is a critical central issue in mechanical design. Moreover, geometry, manufacturing, and function are highly coupled in mechanical design (Rinderle, 1986).

Geometry is the natural language of mechanical design. Mechanical designers "think" in 3-D geometry. There is no mathematical connection between the mental image or concept of a design and its 3-D visual representation in a drawing. Whether on paper or on a CAD terminal, mechanical designers sketch, erase, and sketch again. A mechanical design is seldom the solution to a set of constrained equations; it is instead a representation -- a drawing -- of a 3-D object.

It may be noted that three of the points of difference listed above -- materials, manufacturing, and geometry -- each constitutes a huge body of knowledge. There are also important interactions among these topics. Moreover, this is knowledge that is not naturally represented by equations.

How shall materials be represented so that design programs can reason about them? How shall manufacturing processes and machine tools be represented so that design programs can be written that properly consider the manufacturability of designs as well as plan the production process? And especially, how shall the geometry of a design be represented so that design programs can reason about that geometry, relating it to both function and manufacturability? These are issues that distinguish mechanical design from circuit design, and which must be studied in addition to common issues if we are to develop adequate models of the engineering design process generally.

THE ROLE OF ANALYSIS IN MECHANICAL DESIGN

Before discussing a model of engineering design from a mechanical view, it is necessary to consider the role of analysis in mechanical design. In mechanical design, equations and mathematical analyses enter the design process only after a trial design has been developed. Analyses are used to simulate or predict the performance of a prospective design for its intended use.

It is a fundamental intellectual error, therefore, to believe that analyses, by themselves, can produce designs. Analysis supports and assists design by providing useful information about how a proposed design will perform, but an analysis does not produce a design since there must already be a design in order for an analysis to be performed.

Sometimes parts of a design problem can be formulated as optimization problems, and in these instances, sub-problem optimization methods are very useful. Seldom, however, is a whole, real mechanical design problem expressable as a mathematical optimization problem. The designer's lot will never be such an easy one.

Hopes persist that design can somehow be done directly by some form of "analysis", that is, without iteration. I doubt it. The essential nature of design -- at least mechanical design -- is iterative. Therefore, to learn to construct programs that can design, we need to learn first how to guide iterative processes intelligently so that acceptable designs can be produced efficiently.

MODELLING THE MECHANICAL DESIGN PROCESS

We need a model or models of the design process in order to formulate design problems, acquire and represent design knowledge, and to develop design inference engines. Most mechanical engineers accept that the basic nature of design is iterative. However, there are variations in the exact nature of how a design problem is to be formulated, and just what the process is in detail.

We view design as a hierarchy of nested iterative processes of (1) decomposition and redecomposition, (2) specification and respecification, and (3) design and redesign. Figure 1 shows the decomposition aspect of this model as a simple tree. That is, node A designates a complex problem to be solved. Nodes B, C, and D represent a decomposition of the problem into sub-problems, and so on.

Decomposition continues until sub-problem

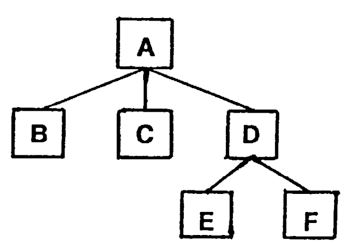

Figure 1. Decomposition into Sub-Problems.

size and complexity is reduced to the point where the problem can be managed intellectually without further decomposition. Usually this is a problem with a relatively small number of design variables, perhaps three to ten or twelve. These sub-problems are then solved (i.e., designs developed) by a process we call "redesign". We shall now discuss this redesign process in some detail and then return to the decomposition part of the model.

Redesign. The redesign model of design is shown in Figure 2. A problem is specified in terms of problem parameters. An initial design procedure generates an initial trial design. (Seldom is this the final design. If it is -- that is, if the initial design procedure is so good that it produces acceptable designs, then the domain is of no further interest intellectually. Such procedures exist in some domains but we are not concerned with such well understood problems.) Next the trial design is evaluated; that is, analyzed to determine its expected performance in terms of performance parameters that may include cost, function, and manufacturability issues. Then a decision is made as to the trial design's acceptability. (Simon coined the word "satisficing" for this concept.) If the design is acceptable, the task is complete. If not, the design is redesigned and re-evaluated, and so on iteratively. Often in practice, redesign ultimately fails and the process returns to the initial step with the information that the problem requirements need to be changed, usually relaxed, in some manner.

A great deal of mechanical design is done by this iterative redesign process. Despite its importance, however, it appears to me that many AI researchers tend to belittle or at least ignore, redesign. There are perhaps two reasons for this. One stems from an association of redesign with "generate and test" (Lindsay et al., 1980); the other from an association of redesign with with process of "debugging of almost right" solutions (Sussman, 1977).

Generate and test is a rather poor process for design if what one means is to generate randomly and exhaustively. But this is not at all what is meant by redesign. In redesign, the analysis results and the reasons for unacceptability are used heuristically to guide the changes made in the design.

The phrase "debugging of almost right solutions" also suggests something rather trivial. After all, if the design is already "almost" right, the really hard intellectual work has already been done, hasn't it? In mechanical design, usually not. When designing a refrigerator, one does not begin with the design of a tractor. When designing an automobile drive shaft, one does not start with an initial design of a fender. In all but the most novel and unstructured design situations (say, starting out to design the first Polaroid camera), getting an "almost" right solution is relatively easy, whereas getting rid of all the unacceptabilities and making all the tradeoffs is excruciatingly hard.

In summary, for sub-problems that need no further decomposition to be managed, design is done by iterative redesign. It is an important intelligent process.

"Domain Independent" Redesign. Our work with redesign has progressed to the point where we have a working prototype of a program (called Dominic) that designs redesign class problems in several domains (Howe et al, 1986). Dominic has designed successfully to date in four distinctly different domains, and other tests are in progress.

Dominic is essentially a hill-climbing algorithm. In this sense it is similar to otimization techniques. It differs, however, in two respects. First, it is guided by heuristic domain knowledge obtained from a domain expert. Second, its input format is a kind of low level language more natural to design problem formulation than the formal mathematics of optimization methods.

Dominic is neither a very strong nor a very weak problem solving method. It lies in-between these extremes. It works "generally", but only on a sub-class of design problems. It makes use of domain knowledge, but also possesses some general knowledge of how to go about solving problems in its class. It may be that such strong/weak methods can be a practical way to apply AI in design.

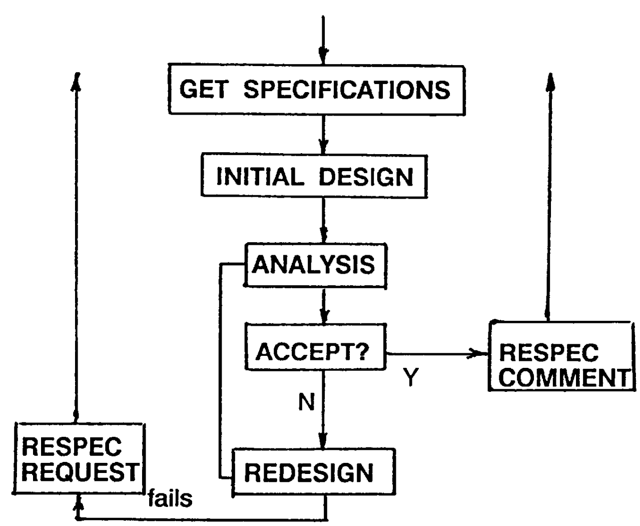

Figure 2. The Redesign Model of Design.

Decomposition. We return now to the decomposition process that leads to the sub-problems solvable by redesign. A tentative architecture of a decomposition node is shown in Figure 3. A problem specification is received from above in the hierarchy. If the problem can be solved by redesign, this is done, and the results returned upward. If not, an intial decomposition is made. Using this decomposition, initial specifications are assigned to the sub-problems created. (This assignment of specifications is a key step; the sub-problem specs are, in fact design variables at this stage.) These problems are then passed to the modules below, which are similar in structure to the one being described. The results returned from the various sub-problems are then integrated and analyzed as a complete system. If the complete system result is acceptable, it is passed upward. If not, new sub-problem specifications are assigned, and the process repeated. If the respecifier must admit defeat, then a new decomposition may be tried. If the re-decomposer must admit defeat, the system reports failure up the line, and asks for some change in the overall problem assignment.

It is to be noted that this model does not allow for passing of information or "constraints" between sub-problems in the hierarchy. Only chaos can result from such communication. Our model is autocratic; information is passed only up or down. What we do include, however, is a mechanism for each sub-problem to pass up a re-specification request. This information is then a part of the information used to determine what the next round of specification changes should be. In other words, the sub-problems can request a change that will affect the other sub-problems, but they cannot impose it. Only the module in a position to tradeoff competing requests has the power to impose or "propagate" constraints on sub-problems. This is as it must be to retain control of this very complex process.

Others are also working on design models that decompose problems for solution. The most advanced is the excellent and useful work by (Brown and Chandrasakeran, 1986).

GEOMETRY

How shall we represent design geometries? Answering this question is key to our future ability to construct knowledge-based systems that can serve to integrate CAD, CAM, and engineering analysis (CAE). Since so much of our knowledge of manufacturing is currently expressed in terms of geometric features, the answer appears to be "In terms of features." But, what, exactly is a "feature", and how shall the desired features representations of designs be obtained?

We have been addressing these questions about features in our research. So far, the definition of a feature is simply "any geometric form or entity whose presence or dimensions in a domain are germain to manufacturing evaluation or planning, or to automation of functional analyses". We have experimented with several different types of features in several domains

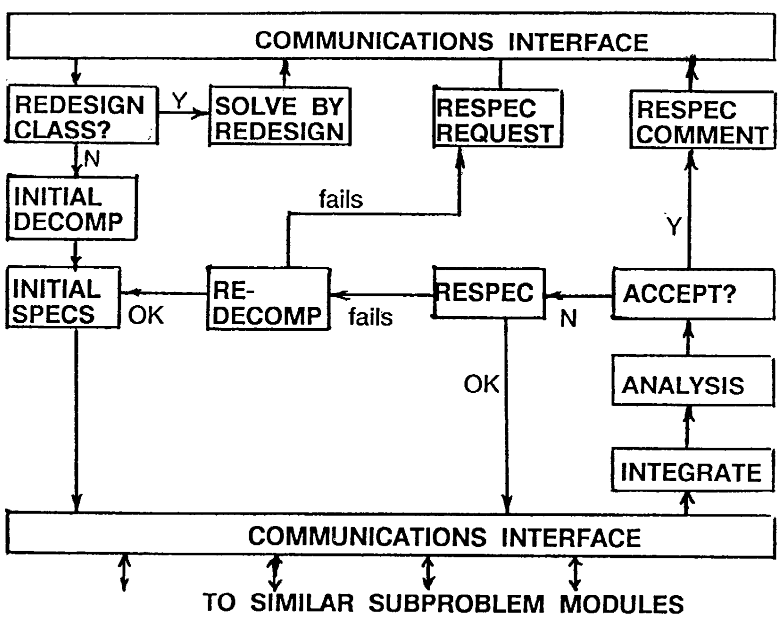

Figure 3. A Typical Decomposition Module.

(extrusion, injection molding, and casting), and have constructed working prototype research programs that provide a "design-with-features" environment for designers (Dixon, 1985; Vaghul, 1985; Libardi, 1986; Luby, 1986). These programs create a features representations of the design, and use this representation to draw the part in wire frame or solid form. In the extrusion program, the features representation is then used to develop an automatic finite element analysis for stresses and deflections in a loaded extrusion. In the injection molding and casting programs, the representation of the geometry is used as a basis for on-line evaluation of the manufacturability of the in-progress designs. These programs function a bit like a manufactururing expert who is looking and commenting over the shoulder of the designer while he or she designs. The programs are simple; it remains to be seen whether adding complexity will create insurmountable difficulties.

Others have been also been working on the features concept in various ways (Pratt, 1984; Latombe, 1978; Popplestone, 1984). Also, rather than designing with features as we are doing, some are attempting to extract or infer features from the points, lines, and surfaces representation created by existing CAD systems (Henderson, 1984).

SUMMARY AND CONCLUSION

The themes of this paper are: (1) that mechanical design is very different from electrical design, and must also be studied in order to obtain general models of the design process; (2) that the differences involve the degree of involvement in the two domains with materials selection, manufacturing processes, and especially geometry; (3) that good analysis is important for good design, but design is not and cannot be done by analysis alone; (4) that the design process is iterative; (5) that design can be modelled as iterative redesign inside iterative respecification inside iterative decomposition, but redesign and respecification are the most important; (6) that learning how to guide iterative processes is intellectually important; (7) that strong/weak methods can be developed for design problem solving; (8) that learning how to represent the geometry of designs is a key issue for applying AI to mechanical design; and (9) that most likely the way to represent design geometry is in terms of features.

If this paper has expanded the reader's model of design by providing useful insight into the nature of the mechanical design process, it has served its purpose well.

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