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EXPERT ASSISTANTS FOR DESIGN

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INTRODUCTION

Christopher Alexander [2] describes architectural design as a process whose objective is to produce a form that has no serious mismatches with the environment defined by its use. Often the environment is incompletely defined and is almost certain to change over time. A similar description applies to nuclear weapon design because specification details vary with refinement of the scenario for using the weapon and with design changes in related equipment such as the delivery vehicle. The form of a weapon might mismatch the delivery vehicle geometry or carrying capacity, the conditions under which it is delivered, or even the effects it is intended to create.

In practice, a design results from many iterations of the process of balancing objectives against constraints. Because for complex designs these iterations are expensive, we are evaluating whether systems using techniques of artificial intelligence (AI) can improve the process and provide corporate memory both of successful designs and of the process itself. In this paper, we describe two such expert programs currently under development at the Los Alamos National Laboratory, PROCON and the Designer's Apprentice. We emphasize the Apprentice because PROCON has been described elsewhere [3,4]. Both codes define interfaces to simulations that provide a wide variety of information about the performance of complex devices. We expect that the systems will help designers understand and use this information more effectively. We also believe that the systems will help users incorporate more factors early in the design process and so avoid attempts to optimize subsystems later. By so managing the flow of information, PROCON and the Apprentice should help achieve better designs.

In section 2 we discuss important factors of the interface. Section 3 outlines how AI techniques can help. In the last two sections we take up PROCON and the Apprentice.

INTERFACES: ACCESS TO THE TOOLS

Computer codes that simulate complex systems play a vital role in understanding and designing those systems. They provide critical information about important characteristics, such as timing [6], strength, electromagnetic field patterns [7], and system behavior [1]. Beyond this, extensive numerical simulation of several versions of a system is often cheaper than constructing even one real version.

But codes to simulate complex systems are themselves complex. To solve his design problem, the designer must cope not only with the complicated phenomena he is trying to understand but also with the complicated tool that simulates these phenomena. Good interfaces to the simulation help the designer build input to the code, run it, and interpret the results, by providing:

- (1) error checks,
- (2) a world model – a model of the thing being designed in its context,
- (3) execution of the simulation,
- (4) a dictionary of synonyms,
- (5) graphics and filtering,
- (6) an assessment of input and output relationships,
- (7) history.

Input that describes the system being simulated should be checked for errors in format and in correlation between variables. This is passive assistance: the designer must create the input from scratch or by changing an existing input file. More active assistance is possible: an interface that has a model of the world being simulated can help build the input. It can convert between units appropriate to the designer and units internal to the code, and can interpret between the designer's terminology and the code's names for variables. On a higher level, the world model establishes contextual information that the interface can use to assist the designer. For example, the designer may specify a material for part of a device. By maintaining a dictionary of terms, the interface can understand that the material has certain physical properties such as density and shear strength. If the interface encodes this knowledge in tables or rules of an expert system, then the system can review a design for inadvertent errors and remind the designer of problems. It is better that the system warn a designer, who may be trying new concepts, than that it prevent innovation by forcing him to correct what it considers to be an error. A dictionary of terms can also be viewed as a starting point for a "natural language" interface [11].

Where the computational environment is complicated by the presence of several different computers, operating systems, libraries, or simulation tools, the interface can help the designer choose properly. If an effective design requires running several simulation codes, the interface can provide synonyms for the different names that codes use for the same variables. Thus the interface provides a single terminology for the designer.

The world model can be the basis for a graphical interaction with the designer – people process pictures better than words. Usually simulation codes can provide a wide variety of output because someone might be interested in seeing these quantities sometime during the life of the simulation code. Most of this output is not something the designer wants to see all the time. The interface can filter the output for the designer in the context of his current needs. Likewise, it can determine when the results are no longer needed.

An area that is often overlooked in design is sensitivity to parametric variation. Even in optimizing codes, there is often an emphasis on point design. In those cases, information about sensitivity is usually expressed through parameters whose meaning is less than intuitive. Because sensitivity analysis can be important, the interface should handle it without requiring specific instructions from the designer. The interface should give some qualitative indication of the effects of changes of input on output parameters.

Finally, a good interface can keep track of what has been done both on the current problem and on related ones. For the duration of the design problem, the system can record design successes and failures and the results of sensitivity studies. For the longer term, the system can log successful designs and compromises and the reasons for them. Recording the successful designs makes it possible to recall past

work, and makes more accessible to designers the details of work in which they themselves may have had no direct part. Thus the interface represents a corporate memory — one not overwhelmed by current design fashions.

HOW AI CAN HELP

To build an interface with all these capabilities AI techniques are essential. We wish to emphasize that not every part of the interface requires AI, and that the concepts we are discussing are broadly applicable to design activities and not just to nuclear weapon design.

AI tools for such an interface come from three areas: expert systems, planning, and natural language processing. An expert system, more properly referred to as a production system, consists of an inference engine and a data base. It can make a decision from a collection of rules that map decision factors to the conclusions and a declaration of what values the decision factors have for the current case. The expert system may be enhanced with the use of object-oriented programming and rules that match patterns [5,8,12]. A planner analyzes a task into a collection of goals. It further analyzes the goals into subgoals until a feasible process can be described. Planning may be extended to learning, in the sense that partial plans may be recorded by the system to help deal with problems too complex for the original data base of procedures. Natural language processors are the third kind of tool we might use. Fortunately, the communications of concern to us are between computers and tend to be more formalized than communications between people, but many of the ideas from this field are applicable. Graphics packages, optimizers, and data base management systems complete the components with which we build the interfaces.

PROCON

PROCON is an intelligent production controller that provides an interface between designers and several simulation codes; it helps the designer set up and submit "production" calculations. PROCON has three major parts: a user interface, an error checker, and a job control stream generator. Inputs to the codes are specified by data base entries in the form of GLISP [9] objects in a Franzlisp environment. Control functions that are part of PROCON use the fields of these objects to provide the interface and checking. However, control is not dependent on the data recorded in the data bases. Adding another code input involves creating appropriate objects describing the input but needs no changes in the functions. Three simulation codes have been interfaced this way. The current thrust to the PROCON development is to provide checking for correlation between input parameters and for legal structure of the input file as a whole. We hope PROCON will eventually replace several programs now used to control simulation codes with a single program that does more than current controllers and is easier to maintain because of the data-driven programming. We plan to put the graphic interface described below into PROCON and to use the job stream generator from PROCON to make the Designer's Apprentice insensitive to change in our computing center's procedures and control languages.

THE DESIGNER'S APPRENTICE

The Designer's Apprentice is a program that will provide a complete interface to the designer to generate initial solutions to the design problem and to help him use appropriate simulation codes. The Apprentice is work in progress. However, we also discuss advanced concepts that are not part of the original Apprentice but are likely to appear in later versions.

Because the Apprentice is composed of many interacting subparts, we decided to use the techniques of structured analysis and design [10] to control development. These techniques have proved valuable for organizing flow of information through the design process, uncovering subcomponent interactions, and learning what sub-processes are contained in each facet of the overall design process. With such an overview in place, incremental code development and prototyping are proving useful. Fig. 1 shows top-level data flow and a task hierarchy for the Apprentice.

Design begins with a set of explicit performance specifications and a set of implicit specifications such as safety, manufacturability, and cost. The specifications might include a nominal yield of the weapon, a range of yields, perhaps a type of

Fig. 1a. Bubble chart for the Designer's Apprentice. This chart shows information flows and transformations of flows. The dotted area represents the current role of a designer.

Fig. 1b. Task hierarchy for the Designer's Apprentice. This figure shows the functional breakdown for a structured analysis.

dominant radiation to be produced, and interfaces for those properties of the weapon that can affect the performance of a delivery vehicle; these properties include limits for the weapon's dimensions, total mass, and location of its center of mass. Safety considerations in transportation and storage are of concern but are likely to be assumed rather than explicitly stated. Availability of materials — particularly nuclear materials — at the time the systems will be manufactured is an important consideration. These factors taken together provide the context for the design. The designer's task is to generate a form — a relation between materials in certain shapes — that meets the specifications. (Alexander notes that fitting a context means eliminating mismatches, not trying to decide what makes a "good" form.)

The designer must make an initial layout that specifies materials and shapes of parts. The Apprentice assists in this task graphically. Because we cannot deal here with internal construction of nuclear weapons, we shall illustrate the interaction with a simple mechanical design example. The desired part is an end plate of an electric motor that holds the bearing and lubrication pads. The plate provides centering for the motor's armature. The bearing can be removed if the armature needs replacement; the plate and armature can be removed as a unit if need be. The plate must extend no further than 1/2 inch beyond the end of the motor housing. Drilled and tapped holes are provided in the motor housing for six 1/4-20 screws. The housing is 1/4 inch thick at the screw radius of 1.25 inches. The motor armature clears the inside end of the housing by no more than 1/8 inch. The armature must be aligned with the axis of the housing to better than 0.010 inch. Several possible solutions are illustrated in Fig. 2.

We assume the designer's computational aids predict lifetime and lubrication needs for various bearings at various speeds with different lubricants, and estimate manufacturing costs of items once the configuration is determined. A data base management code can obtain discrete information such as bearing stocks, design standards such as tolerances, and so on. A more sophisticated program might optimize with respect to cost of materials and manufacturing.

Even with the detailed specification given above, the designer has a wide range of options to complete the task. One is manufacturability — materials and tolerances, manufacturing techniques, edge specification, dimensions of parts. What kind of bearing is required? Which simulation codes need be run and what input information is needed to obtain the desired output? What surface finish is needed? What aesthetic factors should be included? The cost of manufacture will depend on the

Fig. 2. Some design options for an end flange of an electric motor.

decisions made by the designer about all aspects of the design. In the nuclear weapons case, meeting design criteria can lead to a need for developing new materials or new material handling techniques, either of which is likely to be expensive.

The design strategy is to use the specifications to develop a layout, then iteratively run the design codes and redefine configurations until all specifications are satisfied.

The first task for the Apprentice is to determine what the designer is going to do during this session. He may want to continue the same problem he had last time (the default), specify a new problem, or make a radical change in his approach to the current problem. A user profile that keeps track of what a particular designer is doing and what significant problems remain is used to find a starting place for the interaction with the designer.

The second task of design is to collect the specifications. In the Apprentice this is done with a user-modifiable menu. The menu is divided into a main group and a subsidiary group. Although he has access to all specifications, normally the designer is concerned only with the main set. Examples of main specifications are mass, geometry, design context, and yield. Examples of subsidiary specifications are safety issues and special output requirements. The designer may specify some or all of these factors. He may enter physical quantities as numbers with units he prefers. Rather than clutter menus with examples of input syntax, throughout this interaction we use the instruction line to prompt the designer. The instruction line — a standard part of the Lisp machine screen — shows information that helps explain other displays: samples of input syntax, suggestions about what to do next or how to do it, and so on. Fig. 3 shows an abbreviated specification menu as it resides on the designer's screen. Once the designer indicates he is finished with the specifications, an expert system reviews them to see if it can understand what to do next and to fill in values that the designer did not provide. It makes use of limited knowledge to assure that grossly absurd specifications are caught early. (Note that we must distinguish between no specification and a specification of zero for numerical values.)

Next, the graphical interaction to define the layout begins. Merely showing pictures of the design does not suffice. To be useful, they must be modifiable by an interaction with the screen and must scale properly to show dimensional changes in context. Often the designer can spot faults in the design from such pictures and correct the error immediately. Likewise, pictures are an excellent way to advise the designer of potential problems such as dimensions that are too small for mechanical stability. Of course, spotting these defects is one function of an expert program that is assisting the designer. Fig. 4 adds to Fig. 3 a warning that a thickness fault has been spotted by the expert system.

Menus can focus attention on a part of the problem at a particular time. They can also offer proper choices in a particular context. For example, if a plate has been designed, the menu might offer material as an option, and might even suggest appropriate materials. Fig. 5 illustrates how such a menu might look to the designer. Choices of material could be determined by cost, policy, or manufacturability considerations. If the designer can get an explanation whenever he wants, then the system can list choices without comment.

Another aid to the designer is to have always visible the specifications and any values immediately computable from the design. An example of such a computation is the total mass of the object being designed. The dimensions and type of material give the volume of the material. Tables of densities give the mass and the sum of the masses of the parts is the total mass. Such elementary calculations provide the designer with useful comparisons without diverting his attention from the problem at hand. The specifications display also provides another handy method of informing him of mismatches between his design and the specifications.

Specifications		
Item	Spec	Value
Thickness	≤ 0.5 inch	0.5 inch
Screws	1/4-20	1/4-20
Ext Screw		
Length	< 0.375 inch	
Bearing		
Life	10 years	5 years
Lube		
Reservoir	yes	no
Position	0.010 inches:0.040 inches	
Accuracy		

Fig. 3. A sample graphic interface. Flags on the diagram are active. The specifications window is always present; it shows comparisons between the specified values and those derived from the current design. Shading in the window indicates discrepancies.

The CAD features offered by the graphics are underpinned by a program that synthesizes objects (the objects of object-oriented programming). The Apprentice can use objects to do various tasks, such as prepare inputs to codes or make solid models of the forms being designed. One intelligent task is to construct solid figures from lines. Another is to construct cross sections for a composite device based on descriptions of its components. The Apprentice uses data bases of successful devices and designs, as well as heuristic rules, to suggest a solution to the design problem. The data base information and rule output are transformed into weapon-design objects for the duration of the design problem. The objects have subobjects that are the components of the device, with such attributes as dimensions, materials, and locations. By manipulating these objects, the Apprentice generates the inputs to the simulation codes and to the graphic interface.

Specifications		
Item	Spec	Value
Thickness	≤ 0.5 inch	0.5 inch
Screws	1/4-20	1/4-20
Ext Screw		
Length	< 0.375 inch	
Bearing		
Life	10 years	5 years
Lube		
Reservoir	yes	no
Position		
Accuracy	0.010 inches	0.040 inches

Fig. 4. Same as Fig. 3, but with a warning that an expert system in the Apprentice has found a manufacturability fault.

The window system of a Lisp machine can show more than one view of the design. An individual component or an expanded view of a section of the design may be displayed and changed in a second window. The basis for both images is a single object, so the two windows remain synchronized. Because objects are instantiations of an object description (a flavor, for example) the environment can hold several designs at once. By invoking the proper menus, the user can switch between designs.

When the graphic interaction concludes, the designer may choose to run simulation codes on our CRAY supercomputers. For the Apprentice, this entails converting information in the objects on the Lisp machine into inputs to the simulation codes. Data bases of inputs to the design codes — variables, formats, order, correlations — are maintained in the Lisp environment. The correspondence between object attributes and these fields of the input file is kept as well. We note that because the designer communicates with the expert system in terms of the object attributes it is

Fig. 5. Active windows at different levels of the Apprentice are obtained by successively choosing the flag and the item in an associated pop-up menu.

possible to have a uniform interface to several design codes. The designer only needs to be familiar with the terminology used to create the objects, not the stylized input names that the simulation code wants.

Developing the input files that describe designs to simulation codes is the goal of the initial Designer's Apprentice. However, an obvious extension is to make the Apprentice control the computation and analyze its results. Then the Apprentice might be able to provide appropriate graphs of computational results for a particular set of designs, or perhaps merely filter the computer output. Implementing such capability would require adding data bases of computer output variables, drivers to process the information, and expert systems to monitor the status of the computation. Determining what to do next from the status of the computation would take a message-understanding expert system and a planner to create a procedure from scripts and partial plans. Such capability would make the Apprentice a true design partner to the human, but is clearly not easy to achieve.

The test of whether PROCON and the Apprentice can help designers is acceptance by the designers themselves. Few expert systems have had such acceptance. We hope that the combination of graphics, automatic input generation, and a variety of expert systems will prove to be tempting.

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