

AN OUTLINE OF THE REQUIREMENTS FOR A COMPUTER-AIDED DESIGN SYSTEM

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HISTORICAL

In the early 1950's at M.I.T. the Servomechanisms Laboratory (now the Electronic Systems Laboratory) devised and developed the first automatically controlled milling machine.¹ The controlling information for the machine was introduced in the form of punched paper tape, on which all dimensional information and instructions for the various feeds and cutter speeds was contained. At first the punched paper tape was prepared manually by some human operator who translated, in effect, the detail drawing of the part to be machined into numerical form and then into appropriate patterns of holes in the tape. This was a tedious and entirely mechanical chore, and it was only natural that short cuts in the process began to suggest themselves. The scope of such short cuts began to spread through the fabric of the technique, and it was not long before the computer was involved in implementing them.

In the late 1950's the Computer Applications Group of the Electronic Systems Laboratory developed in great detail a complete, automatic system for preparing these punched paper "director" tapes from detail drawings. To be sure a human operator was still required, but

the process of converting a drawing into tape was very much simplified, and the combination of the Automatically Programmed Tool or APT System^{2, 3, 4} with numerically controlled machine tools has subsequently proven to be of significant economic importance in many industries, notably in the aircraft and missile industry. The APT System has gone through a vigorous history of rapid improvement and development, partly at M.I.T. and partly with the active participation of industry. Currently maintenance and development are being carried out by the APT Long Range Program at the Armour Research Foundation with over 25 companies participating.

About four years ago there was a meeting of members of the Computer Applications Group with members of the Design Division of the Mechanical Engineering Department to see whether it might be possible to take another important step. At that meeting we discussed the possibility of using the computer in a much more direct and powerful way in the chain of events that begins with the original concept as envisioned by the design engineer and culminates in the production of the finished device. We outlined at that meeting a system that would

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in effect join man and machine in an intimate cooperative complex, a combination that would use the creative and imaginative powers of the man and the analytical and computational powers of the machine each with the greatest possible economy and efficiency.

We envisioned even then the designer seated at a console, drawing a sketch of his proposed device on the screen of an oscilloscope tube with a "light pen," modifying his sketch at will, and commanding the computer slave to refine the sketch into a perfect drawing, to perform various numerical analyses having to do with structural strength, clearances of adjacent parts, and other analyses as well. Based on such analyses the designer would modify his original design concept, and again call for an analytical procedure by the computer. In some cases the human operator might initiate an optimization procedure to be carried out entirely automatically by the computer; at other times the human operator might intervene, as he might do for instance if in a certain iterative process he observed the computer laboring fruitlessly to satisfy mutually incompatible constraints unwittingly imposed, or attempting to find a solution to a problem in a mathematical region which might seem to the computer a likely place to look, but which to the man might be obviously far afield. The different powers of man and machine are complementary powers, cross-fertilizing powers, mutually reinforcing powers. It is becoming increasingly clear that the combined intellectual potential of man and machine is greater than the sum of its parts.

Since this meeting, a formal arrangement was created for the combined efforts of the Computer Applications Group and the Design Division to work together in a broad study of what we call Computer-Aided Design. This activity is supported by a contract from the same Air Force group that sponsored M.I.T. efforts in both numerical control and APT. The investigations under the contract range over the entire spectrum of computer technology and of design philosophy and methodology. Out of the investigation will come the design for a man-machine organism to accomplish the design process in a way far easier than has ever before been possible; but as by-products will come new computer techniques and an enriched understanding of the creative thought process.

THE DESIGN PROCESS

The design process begins with a graphical description of a proposed device or system to satisfy a human need. To say that the description is graphical is to assert that at the very inception of an idea the designer's understanding of his creation is almost visceral instead of intellectual. He perceives his idea at first not in the perfection of a well-turned English word description, nor in the precision of a mathematical formula, but in some nebulous assembly of building blocks of structure, vaguely beheld; he "feels" his creation. The sketch forms the natural bridge between these vague stirrings of the imagination and the subsequent precise statement of the refined details of the concept.

At this early stage, decisions to keep, to modify, or to discard part or all of the original concept are made in a qualitative way, based upon qualitative criteria. The modified concept leads to further qualitative decision making, and to further modification of the concept. While this is going on, the concept which was at first nebulous and incomplete begins to assume a more concrete solid character; it becomes better defined, until at some stage it is well enough defined to permit more precise analytical tools to be applied.

At first such analytical processes are very simple; the mathematical modeling is crude, and the actual calculations need not be carried out in great detail, nor to very great numerical precision. These calculations again lead to modifications of the concept and subsequently to more precise analysis. It is typical of the design process that such iterations—from concept, through analysis, evaluation of the analysis, decision to modify the concept, and finally to a new concept—form loops that are traversed again and again, until eventually the designer judges the design adequate to satisfy some scale or scales of value judgments.

In the design process, the designer is concerned with a large set of variables, some continuous (like the weight of a part) some belonging to discrete "point sets" (like the material: steel, brass, lead, plastic.) Moreover, these variables are interrelated, or cross coupled, in a very complex way. Some of the cross couplings are weak, some are strong. If the relationships happen to be linear, the cross couplings are constant in strength, but usually

the relationships are non-linear, and the mutual influences of the various variables change with their values.

The designer structures such relationships so that he can thread through them, taking advantage of the loose couplings where possible, to obtain hopefully an exact, but more usually a first, or second, or closer approximation to the values of the variables. It is not at all unusual for this structuring to be done graphically, in the form of block diagrams or linear graphs or information flow charts. Thus he uses a graphical form for both the topological and geometric description of the design, and also for its abstract description in terms of physical function.

At the conclusion of the design process, the final result must be carefully defined so that it can be built. This is the function of layout draftsmen and detail draftsmen. If automatically controlled machines are involved in the fabrication processes, programmers are also a part of the system.

When we look at such a design sequence we see a few engineers performing highly creative tasks at the beginning, coupled with a very large number of draftsmen and technicians who perform relatively uncreative tasks over a fairly long period of time. Some of these tasks require high degrees of intellectual effort, such as stress analysis or aerodynamic analysis, but they are none-the-less not in themselves of a creative nature (except in those cases where new mathematical techniques are designed and put to use). Other tasks are obviously of a purely mechanical nature; for example, a detail draftsman does nothing creative whatever. At the worst, he merely traces the outline of a part from the layout drawing, and adds the dimensions. Usually this drawing goes directly to some machinist or patternmaker in the shop, but sometimes it is used by a part programmer and converted by him into symbolic information for use by a computer to prepare punched tape for automatic fabricating machinery. These are all essentially mechanical operations, however, and it is quite clear that at least in principle, the computer can be made to deal with them all.

COMPUTER SYSTEM REQUIREMENTS

A computer system, to work in partnership with a designer, must have several clearly de-

finable capabilities. It must be able to accept, interpret, and remember shape descriptive information introduced graphically. When such a graphical input capability is properly designed, the man-computer combination can manipulate the elements of a drawing in an entirely new way, with a freedom and precision far surpassing what is possible with pencil and paper.

Beyond shape description, such a graphical facility should be an extension of language in general. It should be possible, as has been indicated earlier, to use such a graphical mode to structure abstractions. This has been brought out with great force and clarity by Engelbart,⁵ where he remarks in effect that the essentially one-dimensional nature of symbolic language is not wholly adequate to exhibit the interconnections of ideas.

Coupled to this graphical facility must be a computational facility for unravelling and performing all of the mathematical analyses and computations that pertain to the design process. These lie in the fields of stress analysis, aerodynamics, thermodynamics, electrical network analysis, fluid dynamics, and many others. The computer should also be able to furnish information about standard parts, standard materials, and standard processes. This is essentially an operation of catalogue storage and retrieval.

There are two quite different philosophies of approach to the achievement of these aims. One approach would be to imbed in the computer a large set of special purpose packaged processes, each designed to perform some special task. If the assembly of such a library of special routines could be made complete enough, then the system would exhibit to the user on the outside an appearance of complete flexibility and generality. This would be satisfactory so long as the designer never called for a capability not already rigidly imbedded in the mechanism. But the design process is unpredictable. Indeed part of the design process consists in designing new ways to perform the design function itself. This is a higher order of design activity, a sort of meta-design (like meta-mathematics) that clearly is outside the scope of any rigid set of special processes that can be anticipated at the beginning. This very real consideration leads quite naturally to the

second philosophy, in which the large population of special purpose routines is replaced by a few (perhaps indeed only one) routines of the utmost generality, so designed that it permits of its own modification by the designer, using his own natural language forms, including as we have said, the graphical form.

The Computer-Aided Design System should be capable of carrying on conversations with, and performing computations for several designers at several consoles substantially all at once. In this way each designer can be immediately aware of what the other designers are doing, and thus avoid one of the truly severe problems of intercommunication that designers face today.

The flexibility and ease of communication with the computer will encourage the designer to use more detailed and more accurate mathematical models of the real physical system than he has been willing or able to use in the past. This will result in a more rapid and a surer approach to an optimum design and to a design that may be relied upon, especially in those very new areas where only meager or fragmentary experience has been accumulated from past designs.

It will be possible to design at an exponential rather than a constant rate, because sub-elements of a design, once constructed, will be available on command in their entirety, and can either be incorporated as they exist or can be modified at will. On some far off day it may even be possible to call up last year's automobile on the oscilloscope, to wave the magic wand of the light pen, and in a very short time to create the modified new version from the old. This will be, in a sense, a mechanization of experience.

It will be possible to observe the actual moving action of a mechanical device, or the varying currents and voltages in an electrical device, rather than the static, frozen, time sections of these motions and currents and voltages as we must now do by present methods of analysis.

Finally, the system will be so general that it will be applicable to any creative activity. For example, the *general* problems of the architect, the machine designer, and the electronic designer are the same, but the *specific* details of

their problems bear scant resemblance one to another. Yet an appropriately designed system will be so flexible that it will enable each discipline to modify the structure to fit its purpose.

There is considerable evidence that our intellectual tools influence to a very great extent the form and scope of our intellectual works. It is quite certain that when the computer replaces pencil and paper in this very real way, it will bring about a truly miraculous change in man's intellectual potential.

PRESENT CAPABILITIES

We have already come quite a way toward accomplishing some of the desired ends as outlined. The writer, using Sutherland's Sketchpad Program⁶ on the TX-2, has set up and solved five separate engineering problems in the course of a few hours. It is an extremely flexible and versatile means for communicating with the computer in a graphical language.

Sitting at the console of the TX-2, the writer constructed a geometric figure which represented the cubic algebraic polynomial. The details of this figure are not important; the principle is quite simple and very general. It is easy to construct such a figure for polynomials of any degree, and for both real and complex values of the coefficients and of the variables. Once constructed, the x variable can be manipulated with the light pen, and the resultant value of y is automatically obtained. This happens by virtue of the computer's ability to satisfy the geometrical constraints imposed by the figure.

The second problem was the construction of the general second degree curve based upon a purely geometrical construction, and the third problem was one with which Sutherland had already experimented. A pin-jointed structure is drawn, certain points are fixed, loads are applied, and the deflections of the structure are then automatically calculated, and exhibited on the screen, along with the numerical values of the percentages of elongation of each member.

Fourth, a kinematic linkage was drawn, the driving link was rotated, and the motion of the connected links could then be observed. The linkage could then be modified to yield desired changes in its behavior.

Fifth, a region was drawn in which two-dimensional flow of an ideal fluid was to take place. By invoking the principles of graphical field mapping, the computer adjusted the stream lines and equipotential lines of the field so as to give a good solution to the problem.

These problems are all substantially very different. No special computer program written to solve one of them is of the slightest use in solving any one of the others. But the great range of applicability of generalized constraint satisfaction makes it possible to solve them all. Admittedly special purpose programs can be devised that will solve some of them more efficiently and rapidly than these graphical methods. But on the other hand, the graphical solution is in some cases the most efficient method known. In such cases, since the computer can perform graphical manipulations at least a thousand times faster than a man, such techniques are still highly economical.

Many parts of design are well-enough understood and of general enough utility to warrant special programs. A mixture of general and special techniques is most appropriate for full Computer-Aided Design. Using a different computer, the IBM 709 at the M.I.T. Cooperative Computer Laboratory, together with a special purpose program, it is now possible to draw a cantilever beam on the screen, and to type in its precise length on the flexowriter. Then the vector loads are drawn, and their magnitudes are typed in on the flexowriter. Finally, a section of interest in the designer is drawn, and on this section a particular point of interest is indicated. The computer hesitates for a moment, and then types out on the flexowriter the bending stress, the axial stress, the transverse shear stress, the torsional shear stress, and the combined stress at the point of interest. This is a special purpose program, but its general applicability and efficiency make it well worth while.

In addition to using the generalized constraint satisfaction for computation, the primary purpose of a system such as Sketchpad is graphical communication. In Sketchpad III, as reported in the paper by Johnson,⁷ we have a means for drawing and manipulating figures in three-dimensional space. This is of course essential to the designer of mechanical or structural devices and objects. All of the capabilities of

the two-dimensional version of the graphical input are implicit in the extended system.

The work on the theory of language and operators described in the following paper by Ross and Rodriguez⁸ is directed toward making direct communication with the computer not only possible, but easy, while at the same time enabling the computer to remember and manipulate the many complex details implied by general statements. Then, using these capabilities, the designer at the console can communicate not only the problem itself, but also the problem solution structure, either generalized or specialized, in whatever form and in whatever language is appropriate, meaningful, and most efficient.

CONCLUSION

The historical section of this paper describes our original broad concept of the Computer-Aided Design System. This concept was even at the beginning formed on fairly grand proportions, and it is encouraging that even after the intervening time, its form has not been substantially changed. We have not relaxed our objectives, and as we see the details of the broad framework filling in and taking shape, we are encouraged to believe that however ambitious it might have seemed in those days, our results indicate that practical Computer-Aided Design will indeed, in some not too far distant future be a reality.

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