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CAN ENGINEERING BE AUTOMATED?

Presidential Address by
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(Presented at Annual Meeting of Boston Society of Civil Engineers, March 14, 1967)

The effects of the current technological advance are profound in all fields of endeavor, and civil engineering is no exception. One of the most important manifestations of this progress is the electronic computer. In my opinion, the computer is much more than a rapid computational device, and will have a far-reaching and basic influence on the practice of civil engineering. By attempting to answer the question posed by the title of this paper, we may be able to predict the nature of this influence.

The advent and increasing use of computers over the past few years has been the cause of considerable discussion, and even debate, among engineers. Many of us tend to be rather emotional on this subject and to take one of two extreme views. On the one hand, some engineers seem to believe that a computer can do everything, and that eventually the primary requisite for a good engineer will be a knowledge of computers and computer programming. This point of view overestimates the capability of the machine and, more seriously, underestimates the intricacies of engineering and the unique contribution of the human engineer.

At the other extreme are those who believe that the computer, and particularly its human proponents, are degrading professional practice. They are afraid that mechanization will produce sterile engineering, and perhaps even dangerous design, because of a lack of human judgment. They also feel that computer-oriented engineers are too dependent on the machine and incapable of knowing when the computer results are wrong.

It must be recognized, however, that the fault in such cases, when they exist, lies not in the machine but in the individual engineer. Those who fear the computer for such reasons fail to recognize that human progress matches technological progress, and that engineers are capable of not only using but also controlling this new and powerful tool.

Both of these extreme viewpoints are of course wrong. In fact, we have advanced beyond this level of argument. Computers are now universally accepted, although with some lingering doubts, by the engineering profession. But it is still not clear how far we can go with computerized engineering, and what its impact will eventually be.

Before we can attempt to answer the question in the title, it is necessary to define our terms. Engineering, in this context, is not merely problem-solving, but rather a creative process which involves an experimentation with ideas. It includes, but is not limited to, the analytical techniques of testing and evaluation. Although the decision as to which of the available techniques should be used (or perhaps the formulation of new techniques) is engineering, the mechanics of executing these analyses is not. In other words, computation per se is not engineering. Most importantly, engineering requires the synthesis of all the factors (tangible and intangible) which contribute to the success of the total project. Basically, engineering is conceiving alternative solutions to the problem, and selecting the most appropriate on some rational basis.

Automation, as used in the title, does not merely imply computation but rather the execution, without human intervention, of the complete engineering process from the initial collection of raw data to the final specification of the project ready for construction. One frequently hears the term "automated design", but this is usually restricted to only a part of the design process, an optimization of a concept already qualitatively formed. Automated engineering, in the present context, means not only the execution of formalized analysis but the mechanical creation of alternatives and the pre-programmed capability of decision-making.

Within the ground rules established by the definition of the two terms above, it seems apparent that engineering cannot be automated. However, it is equally apparent that some parts of the process which are normally considered to be engineering, can and have been automated. Structural analysis, to take an example, is now seldom done by hand except in rather trivial cases. This automation of analysis might have been thought impossible a few years ago, and we should therefore not jump to the conclusion that engineering, in the broad sense, cannot be automated.

If engineering is to be automated, the machine must be programmed to make the decisions now made by humans. The extent to which this can be done is the subject of studies in the field of artificial intelligence. A review of some of the current thinking in this field may give a better insight into the possibilities of engineering automation.

The beginning of the modern concept of artificial intelligence is usually associated with the introduction of the term "cybernetics" by Norbert Wiener in 1943. Since that time, numerous investigators have pursued this idea with increasing success due to the expanding capabilities of computers. The generality of this work indicates that the questions considered in this paper are not unique to engineering. Although engineers tend to look upon the group working in this area as rather far-out, abstract, and addicted to unintelligible jargon, closer reading of their work reveals that they are really interested in the same problems as are engineers. Basically, artificial intelligence means the ability of a machine to make judgments or decisions which, when made by a human, are considered to indicate intelligence. But here we encounter a problem in semantics: What is intelligence? It is this ambiguity which makes it difficult for us to understand those promoting the concept of artificial intelligence. However, such efforts are to be commended, and if such a thing exists, it is certainly applicable to engineering.

One of the first experiments in this field involved a mechanical mouse which, when placed in a maze, could always find its way out by trial and error. Furthermore, the mouse had a memory, and if placed at the same starting point, would immediately find its way out without trial and error. Is this intelligence? I think not. Whatever intelligence was involved was exercised by a human in designing the mouse. The fact that the mouse performs better than a human placed in the same circumstances is irrelevant.

Another frequently cited example is the computer which plays checkers. It is said that the computer consistently defeats the man who wrote the program. Again, this does not prove intelligence. What both of these examples do indicate, and this is important in the engineering problem, is that the computer has a much greater capacity than man for data processing, i.e., the storage, sorting, and retrieval of information.

These experiments were only the beginning. A more recent computer program displays what is called "analogical reasoning" by recognizing similarities between geometric objects. On the basis of a college admission test involving such recognition, and intended to test human intelligence, it is believed that the computer program could score at about the tenth-grade level. Although this is impressive, it must be realized that geometric recognition is the only function which the program can perform. It may also be significant that this single-minded program stretches the capacity of available computers.

It is sometimes said that a computer has the ability to "learn". The mechanical mouse certainly learned in a narrow sense. It has also been suggested that a computer could "learn" structural design. A structural engineer learns by experience, and a successful solution to some previous problem is remembered and applied to a new problem. It is argued that similarly a computer could be given a large number of successful designs to be stored in its memory (somewhat analogous to a student being taught structural design) and recalled for use when a new problem is supplied. By matching problem characteristics, it presumably could produce a reasonable design. Although this seems at least feasible, whether or not it is "learning" depends on one's definition of the word.

So, what is intelligence, and can it be created artificially? One suggested test is to place a man in one sealed room, a computer in another, and communicate with both by telephone. If, after a series of questions and answers, we could not tell which room contained the machine, then artificial intelligence is indeed possible. Although this is not as far-fetched as it may seem, my own belief is that we could always detect the man because of his wider scope of responses and ideas. However, the capability of computers is expanding rapidly and in the future they will be able to perform tasks in a manner unbelievable today. But man also improves, and the human will always be ahead of the machine. In our context this means that the engineer will be working at progressively higher levels. This will be demanding on the talents and efforts of future engineers, but it also represents a great opportunity for better engineering.

Considering now the immediate future, and coming a little more down to earth, there are several current developments in the computer field which will affect engineering in a more basic sense than did previous use. We have passed the stage in which engineers are for the first time becoming acquainted with the computer, and have reached the point at which we are primarily concerned with improving current procedures. An evaluation of these efforts may give us some clue as to the possibility and degree of eventual automation.

Most of the current developments are in the general area of improved man-machine communication. The objective is to make it possible to integrate the computer into the engineering design process, and not merely to use it as a large calculating machine. Man and machine can be coordinated so that the shortcomings of each are compensated by the other. The potential of such a combination is much greater than the sum of its parts. The most significant of the new developments in man-machine communication are (1) improved languages, (2) time-sharing, and (3) graphical input-output.

There has been a continuous evolution of languages (i.e., the format of computer input) since the advent of computers. Originally, machine language was used. This was extremely tedious, time-consuming, and degrading to an engineer. It required, for example, an instruction to move number A from memory location X to Location Y. In effect, the user was forced down to the machine's level. A quantum step forward was made with the introduction of FORTRAN. This language permitted the use of macro statements, each one of which would cause a whole series of internal machine operations. For computation it was possible to write arithmetic expressions in much the same form that a mathematician or engineer would normally use. Although FORTRAN was a major improvement, it was not engineer-oriented and required substantial programming efforts for the solution of non-standard problems. Perhaps the most serious disadvantage was that it required the engineer to have considerable computer expertise.

The latest in this continuous evolution is the development of the Problem-Oriented Language which, as the name implies, permits the engineer to communicate with the computer in his own terminology. The individual input statements (or commands) in such languages are extremely powerful, and each causes a whole series of internal computer operations. As an example, consider the very successful STRESS (or more recently STRUDL), a computer system developed at M.I.T. for the analysis of structures. A single command like MEMBER PROPERTIES 14WF30 stores the properties of a member in a frame for whatever purpose may be subsequently required. STIFFNESS ANALYSIS causes the complete elastic analysis of a structure and stores all results for future reference. It is also possible to SELECT MEMBERS from tables of standard sections after an analysis has been made. A system like STRUDL might be considered to be automated engineering. A more correct view is that it represents an easy means for the engineer to accomplish mechanical operations. The engineer is then free to devote his efforts to the more difficult and intangible aspects of design. The machine makes no decisions unless the rules for such decisions have been pre-programmed. If these can be rigorously codified, then the making of the decision is no longer engineering.

A second significant current development is the hardware and software embodied in the concept of time-sharing. Normal computer operation (batch processing) is inefficient for engineering purposes because the engineer has no direct contact or interaction with the machine. He must prepare and submit a program, wait several hours (or even days) for someone else to run the problem, evaluate the results when they mysteriously appear, redesign and start the whole process over again. With time-sharing, many engineers may use the same computer simultaneously through remote terminals (currently teletypes). Each engineer is said to be "on-line", which means that his instructions are immediately executed by the computer and the results are quickly returned via the teletype. When the engineer has such a terminal in his own office, and when powerful problem-oriented languages are available to him in this mode, he will have achieved a major step increase in his capacity to do engineering. Time-sharing systems with engineering capabilities now exist experimentally and will in a few years be available commercially (commercial remote-computing systems are now available but these do not have the capacity or software required to do "engineering" in the present context). The potential value of time-sharing for engineering is enormous since it will enable the engineer to use the computer at his convenience, thus permitting him to truly integrate the computer into the total design process.

Graphical input-output is a third significant development in the area of man-machine communication. Engineers naturally use graphical representations, both to crystallize their ideas and to communicate with other engineers. It is now possible to communicate with a computer in the same way. Sketches may be drawn on the face of an oscilloscope, and the geometric information contained in the sketches transmitted directly to the computer's memory for use in stored programs. Computer results may be displayed in the same way or they may be automatically plotted for permanent records. Computer-controlled drafting is now a reality, although not yet economical for most purposes. If the preparation of design drawings and other documentation is considered to be a part of engineering, then this phase of engineering certainly can and should be automated. It might also be noted in passing that the quantity of hardcopy drawings will surely decrease since such information can be stored and retrieved much more efficiently on tape or disk.

The advances in man-machine communication which I have cited above, and which in my opinion represent the most significant progress being made in the computer field, are definitely not leading us toward automated engineering. On the contrary, the whole purpose is to give the individual engineer a more important role in the design process. By using the power of the computer, he can more effectively apply his judgment to the problem, exercise his options with respect to alternatives, and more thoroughly control the progress of the whole project.

It is apparent that there are many ways in which the computer can assist the engineer in addition to mere computation. Most engineering requires a great deal of data and data manipulation, and this is an area in which the computer excells. Modern computers are essentially enormous storage and retrieval devices and they should be viewed in this light when we consider proper engineering use. Recent hardware developments in large, random-access storage devices are particularly significant for engineers. For example, the entire steel handbook, complete with tables and specifications, can be stored in less than one percent of the space available on some disk packs. Furthermore, any item of information thus stored can be efficiently retrieved either for the engineer's inspection or for use in a program.

When mention was made of the large amount of engineering data, I was not primarily thinking of collected raw data (e.g., traffic data), but rather of the temporary data which is created and used during the design process. If one analyzes the numerical work associated with design, it is surprising to find how little is actual computation. The major part of the effort is in collecting and organizing the numerical data in preparation for mathematical operations or for display and evaluation. In other words, much of what is normally called design is in reality bookkeeping. To verify this statement one has only to look through the hand computation sheets for the analysis and design of a structure. It is apparent that the data processing power of the computer can be brought to bear on this kind of manipulation without disturbing the engineer's prerogatives and without automating engineering in the true sense.

The concept of the computer as a public utility is gaining wide credence. The idea is that a network of interconnected computers could be made available to the general public in much the same way that the telephone system is now available. A commonly cited example of use is the housewife who employs the system from her kitchen for such chores as balancing the checkbook, making up shopping lists, and checking her household budget. This may not come to pass for economic reasons, and some husbands may not even find it desirable, but it is certainly feasible. Along the same vein, there is now a program in the MAC time-sharing system at M.I.T. called the MAD DOCTOR which is a reasonable facsimile of a psychiatrist. When the user asks a question through a remote terminal, the computer responds with another leading question somehow related to the first. Although this is very entertaining, and the computer seems to display some intelligence, I doubt that the psychiatrists are in serious danger. The purpose of these somewhat facetious remarks is to emphasize that, if such things are feasible, there must be an enormous, untapped potential for the use of computers in engineering.

Whether or not the great advances being made and about to be made in the computer field constitute the automation of engineering, it is clear that so far we have only scratched the surface and engineering is entering a period of drastic evolution. I am convinced that the significant advances over the next decades will not lie in improved theories of analysis and design, but rather in the organization and management of the design process itself. The computer will play a dominant role in this development.

The change now taking place in the information processing field, including engineering, has been compared to the industrial revolution. This is not a far-fetched idea. What will be the effect on the engineering profession? Some fear that it will result in technological unemployment. I do not share this concern. It is true that better engineers will be needed because they will be operating at a higher level. They will be doing a better job of engineering in a more comprehensive manner, leaving the routine operations to the computer. This will not only benefit society but will result in a higher status for engineering - a goal which we all seek. None of this necessarily implies fewer engineers since there are many important aspects of engineering which are not now given proper attention. However, it may mean some dislocation of engineers at the lower levels, and this is a transition problem which the profession as a whole must face.

Lest we be too optimistic, it should be noted that there are certain dangers created by the computer revolution which must be recognized and met by the engineering profession if it is to continue serving its proper role. The engineer must assert himself and not allow his position to be usurped by the so-called "computer expert". This can only result in poor engineering, but could happen if engineers fail to make full use of the tools available to them. For this and other reasons, I believe that there is a threat to the engineering consulting firm as it is now constituted. If such firms are slow to accept and implement new ideas and methods, they will find themselves in a position of declining importance. It is disturbing to hear of an Avco or a Dow Chemical receiving contracts for what is essentially civil engineering work.

Although the computer may be responsible for some of these problems, it may also provide the answer. The machine is a great equalizer. The smallest consulting firm has access to the same computer as the largest organization. If it properly uses the computer, the small firm can undertake large projects, and do them well, without overtaxing manpower resources. The difficulty in the past has been the lack of access to a large computer and the high cost of program development. However, the advances being made in computer technology, e.g., improved languages and time-sharing, and the general availability of large-scale programs for engineering purposes, will remove these obstacles to extensive computer use by small organizations. In my opinion, the automation of appropriate parts of the engineering process can be a boon to the engineering consulting firm in its traditional form, and can preserve for the public the advantages of this type of engineering organization.

In passing, I feel compelled to comment on engineering education with respect to computers. Educators have been criticized in recent years for placing too much emphasis on the machine and producing graduates who were excellent programmers but knew little about engineering. This criticism may have been valid a few years ago but I do not believe it is now appropriate. The emphasis, at least at the better schools, is on engineering in its true sense, with the computer relegated to its proper role as servant to the engineer. Little time is devoted to computer programming per se. In fact, by using the computer for routine engineering chores, the student has the time to study in depth the more profound aspects of engineering design. He is exposed to a wide variety and large number of engineering problems, and by actually obtaining solutions to these problems gains experience which would previously have taken years of post-graduate practice.

To summarize these remarks, let us return to the original question, "Can Engineering Be Automated?" In my opinion, engineering will never be automated. However, this statement is based on the recognition that the meaning of "engineering" constantly changes. Much of what we previously considered to be engineering has already been automated. Undoubtedly, much of what we now call engineering will be automated in the future. Whenever a step in the engineering process becomes so well developed that the decisions involved can be pre-programmed, that step is no longer "engineering" and is a proper subject for automation. However, engineering in its true sense is decision-making on the basis of incomplete information. This fact, plus the ever-expanding scope of engineering, indicates that the total process will never be automated.

Current developments in computer technology, e.g., improved languages, time-sharing, and graphical input-output, are of great importance to engineers. However, these advances are all leading to computer-aided engineering rather than automated engineering. The difference is not merely semantics but is actually rather profound. The intent is not to replace the engineer, but to relieve him of the routine so that he is better able to cope with the real engineering problems.

The amazing progress being made in the computer field is in no way a threat to the engineer or the engineering profession. On the contrary, it will permit the engineer to move to a higher level of activity, thus permitting him to make a greater contribution to society and, at the same time, giving him a higher status in that society.