Proceedings

OF THE NINTH U.S. NATIONAL CONGRESS OF

Applied Mechanics

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U.S. NATIONAL CONGRESS OF

Applied Mechanics

HELD AT
CORNELL
UNIVERSITY
ITHACA, NEW YORK
JUNE 21-25, 1982

PUBLISHED ON BEHALF OF THE CONGRESS BY

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
UNITED ENGINEERING CENTER
345 EAST 47TH STREET NEW YORK, NEW YORK 10017

Library of Congress Catalog Card Number 55-5938

FOREWORD

The Ninth U.S. National Congress of Applied Mechanics was held at Cornell University, Ithaca, New York, from June 21 to June 25, 1982. The Congress was organized by the U.S. National Committee on Theoretical and Applied Mechanics of the National Academy of Sciences, representing ten scientific and professional societies. In 1982, the Society of Naval Architects and Marine Engineers was admitted to the Committee.

At the Ninth Congress a new feature, symposia on current topics of theoretical and applied mechanics, was introduced into the scientific program. Twelve symposia were selected by the Scientific Committee, which also appointed a chairperson and co-chairperson for each symposium. The fifty-one symposium papers, together with the traditional five general lectures are contained in their entirety in these Proceedings. In addition, two hundred eighty-four contributed papers, which were presented at thirty-six sessions, are represented here by brief abstracts of the extended summaries. These papers were selected by the Scientific Committee for presentation at the Congress.

We wish to gratefully acknowledge here the financial support of the agencies, industries and universities listed elsewhere in these Proceedings.

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(The views, opinions, and findings reported in this Congress are those of the author(s), and not those of any of the above sponsors.)

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GENERAL LECTURES

INTERACTIVE COMPUTER GRAPHICS FOR APPLIED MECHANICS

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ABSTRACT

Interactive computer graphics is about to transform computational mechanics by enhancing dramatically the perceptions and capacities of engineers and scientists. While computing and computer graphics are but tools for the mechanician, interactive graphics is able to make the computer more nearly a direct extension of the mind through improved communication between the person and the machine. In this active partnership, both the machine and the person do what they can do best: the machine takes on the tedious calculations, the data manipulation, and the figure drawing, and the person visually integrates and evaluates patterns of behavior. The result is not only increased effectiveness but also improved control over analytical and design processes.

Structural mechanics research and teaching involving computer graphics demonstrate how these techniques will affect the broader sphere of computational mechanics. Examples from current Cornell University work illustrate how various endeavors of the applied mechanician can be enhanced. Finite element preprocessing of shell structures shows how graphics may be used to input problems, and color finite element postprocessing illustrates how graphic output can enhance interpretation of results. The high level of interaction and the ease of use that characterize well designed systems are demonstrated by new instructional programs.

Finally, the concept of *interactive-adaptive* techniques is introduced. This approach builds upon the graphical input and output and the rapid person-machine communication described earlier. Interactive-adaptive methods are those in which system characteristics, models, analysis parameters, and algorithms are selected or changed by the user during the analysis itself. These capabilities enable the engineer to accomplish computer-aided system design and the researcher or student to study more effectively mathematical models, numerical formulations, solution algorithms, and system behavior.

INTRODUCTION

Interactive computer graphics is on the verge of transforming electronic computing in a way which will dramatically enhance both the perceptions and capabilities of engineers and scientists.

Clearly computing in itself is not the primary occupation of most engineers and applied mechanicians; instead, it is a tool with which we accomplish research, development, and design. Nevertheless, it is not an ordinary tool in the same category as, for example, an hydraulic jack which we might use in testing a structure or model. Richard Hamming discussed the nature of computing as a tool in his 1972 book, *Computers and Society* [1]. Hamming argues that, of all the inventions of man, the tool-making animal, very few are tools of the mind rather than devices to enhance or amplify our bodily strength and senses. Besides computing, the other principal tool of the mind discussed by Hamming is language, and I feel that his analogy is worth recounting.

Both spoken and written language have gone far in developing the intellect of man. However, they are communicated in an essentially sequential manner and in this they are similar to digital computer processing which is also largely sequential. Other forms of language, such as mathematics, involve patterns of interrelated symbols, but an even better example mentioned by Hamming of a language communicated nonsequentially is cartography. Nevertheless, except to contrast nonsequential map interpretation to sequential digital computer processing, he does not relate cartography to computing.

I find this analogy compelling because language, as an intellectual tool, promotes nonsequential interpretation. I contend that any tool of the mind worthy of this name should likewise nurture the intellect by including nonsequential or graphical modes. Because our minds obtain and interpret information fastest visually, a large porportion of our knowledge is acquired through our eyes. Therefore, the effectiveness of the computer as a tool or extension of the mind is fostered by graphical communication between person and machine. The traditional means of man-machine communication – punched cards, formatted listings, sequential formatted files that we edit at a keyboard – are more geared to the "convenience" of the machine rather than to the person who uses the computer.

Basically, computer graphics is the use of computers to draw pictures. However, much of computer graphics is *passive,* that is, the desired drawings are specified before computing is done and are executed some time after the information is produced or recorded. For truly effective man-machine communication, a more dynamic mode is necessary, *interactive computer graphics.* In our view, interactivity has two distinguishing features. First, the responses by the computer should be rapid, that is, within a matter of seconds or fractions of seconds. This implies a rather large amount of computational power devoted to driving the graphical display devices. Second, in addition to visual output from the computer, as much input from the person as possible should be graphical or analog as this too is a more natural and reliable mode of communication. This second feature implies that graphical input devices are necessary.

To convey the potential impact of interactive computer graphics on computing in general, many people have made an analogy between doing computing and driving an automobile. In the early days of automobiles, a specialist was required to operate a car. Starting was manual, shifting and braking were difficult, and the throttle and spark were advanced separately. However, with the development of automatic starters and chokes, power brakes and steering, and automatic transmissions, virtually any adult can drive. Well designed methods of interactive graphics promise to provide similar enhancements to digital computing. Within the next decade, nearly all computing will be associated with interactive graphics. The hardware technology already exists – for example, much of it draws from the video industry. The breakthroughs that are occurring now are in the economy of the equipment, especially the reductions in price of memory and VLSI's. And perhaps the most convincing forerunner of this dramatic expansion of access to computing is in the entertainment industry where in 1981 $5 billion of quarters were expended on video games in the United States [2].

What are the implications of this computing revolution for engineering and applied mechanics? It seems to me that there are two main challenges regarding computing that face us. First is the often voiced concern about *productivity.* For example, in structural and mechanical design with computers a large proportion of the engineer's time is spent on the tedious and error-prone tasks of preparing detailed input for the computer and interpreting voluminous output. These are tasks that are significantly speeded by interactive graphics, and thus the engineer can perform analysis more quickly or can perform many more analyses in a given time to optimize a system. The second challenge relates to sufficient *control* of computing so that is remains in its proper role as a means or tool rather than an end in itself as some young engineers seem to perceive it. It is the engineer who is indispensable in the decision-making cycle, and interactive graphics can provide the opportunity not only for real-time choices but also for effective utilization of computers as unobstrusive but vital tools in this process.

COMPUTER GRAPHICS HARDWARE

Before I illustrate how responses to these two challenges are evolving, I will briefly describe some of the principal types of equipment used in interactive computer graphics. Although space limitations prevent a more comprehensive introduction to hardware, there are already a number of excellent textbooks which describe not only the hardware of computer graphics but also the mathematics, basic techniques, and software [3, 4].

There are three main types of display devices in wide use today. The first of these is the direct view storage tube (DVST). This is a "vector" display because all images are drawn by straight-line segments written onto the cathode ray tube. Moreover, the images are stored on the display as they are generated, and thus very complex images with many thousands of lines may be presented. This very popular type of device has been widely used for over a decade and is relatively inexpensive. However, the drawing speed is rather slow, and portions of the image cannot be erased without erasing the entire screen; therefore, motion or change of the object displayed cannot be simulated except for very simple images.

More suitable for dynamic displays and interactive response times is a second type of vector display, the fast vector refresh device. With this, several thousands of

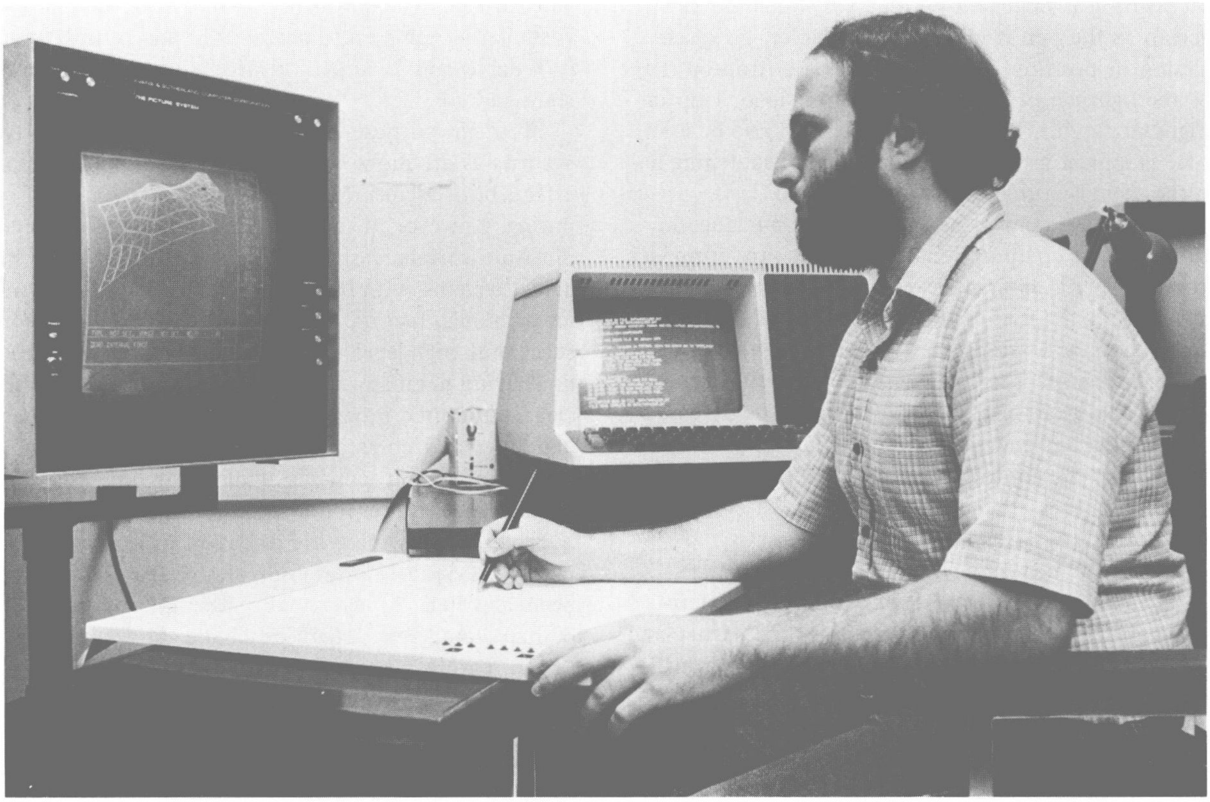

FIG. 1 AN INTERACTIVE GRAPHICAL WORKSTATION CONSISTING, IN THE THIS CASE, OF A VECTOR-REFRESH GRAPHIC DISPLAY, A DIGITIZING TABLET WITH PEN, AND AN ALPHANUMERIC TERMINAL WITH KEYBOARD.

lines can be drawn every thirtieth of a second. If the display is altered at every redrawing, selective erasure is possible, and slight successive changes of view can simulate dynamic motion. Moreover, the equipment usually includes hardwired capabilities for translations, rotations, perspective transformations, and diminution of line brightness with distance from the viewer (called "depth cueing"), all of which make the two-dimensional display seen three-dimensional to the viewer. The two main disadvantages of this type of display are the relatively high expense and the possibility of flicker if one attempts to draw an image with too many lines.

The third device, now most rapidly growing in popularity and availability due to decreasing costs, is the raster video display terminal, which is capable of displaying halftone or color images as well as vector figures. The price decrease is understandable, for these units consist primarily of a large memory (called a "frame buffer") and a high-resolution TV-like monitor. The frame buffer stores the image as a rectangular array of picture elements ("pixels"), each of which is mapped to a corresponding location on the screen. Each pixel may be illuminated or not and, if illuminated, may have a color determined by a mixture of red, green, and blue. The number of possible colors is determined by the "depth" of the frame buffer, i.e., the number of bits of memory available per pixel; a one-bit frame buffer is simply black and white, while an 8-bit memory system permits 2^8 or 256 different colors. Typical resolutions of modern, high-quality monitors range from 512 X 512 pixels to 1024 X 1024. Therefore, with 8-bit resolution, the memory required for a single image ranges up to a megabyte. Although selective erase and changes of the image in the frame buffer are possible, true dynamic display of complex, high-resolution raster images is not yet economical because of the difficulty of revising the image data in the buffer fast enough.

As mentioned previously, a graphical dialogue between the person and the machine requires graphical input devices as well as display equipment. Although there is a variety of input hardware – joystick, paddle, button, knobs, mouse, trackball – the two most common and versatile devices are the lightpen and the digitizing tablet. Each can be used to point at displayed objects or commands or to place objects on the display; moreover, through software, they can be used to simulate and thus replace other input devices such as joysticks, knobs, and keypads. The lightpen is moved over the screen, and its position is tracked by means of a photocell within the pen. With a digitizing tablet, the user works on a flat surface (Fig. 1) within which is embedded a grid of wires that electronically detects the position of a pen; the tablet may be considered a map of the screen, and the stylus' position is indicated by a cursor which moves on the screen as the pen is moved on the tablet. To specify a selection or position, the user presses a button on the tip of the lightpen or depresses the spring-loaded tip of the digitizing stylus. Both types of pen can also be used to enter graphical information by tracing or sketching in much the same way that a drawing is created.

These displays and input devices are put together with sufficient computational resources to form a "workstation" for interactive computing (Fig. 1). The effectiveness of the user of this station depends not only on the choices and arrangement of equipment but also on proper human-factors engineering of the physical environment. For example, the lighting should be designed to avoid reflections and to provide an illumination level appropriate for the contrast levels of the displays.

COMPUTER GRAPHICS SOFTWARE

Of equal significance to the quality of the workstation is the adequacy of the software system for the particular application. "Applications software" is to be distinguished from low-level graphics software or graphic languages, which are sets of basic commands to draw lines, fill rectangles, draw characters, etc., and which are the basic building blocks of graphical programming. Applications programs also differ from the newly emerging body of intermediate-level graphics packages, which are tools for software developers to, for example, lay out graphical displays of commands ("menus"), select color palettes, and remove hidden lines or hidden surfaces from displays. Instead, we are concerned with high-level programs for users to accomplish specific tasks without further programming, e.g., a system for the complete design of some specific product, object, or structure. It is the applications software aspects that I will emphasize in the remainder of this paper through several examples of programs written at Cornell University.

Since 1975, we have been doing research at Cornell involving interactive computer graphics as applied to several disciplines and with special emphasis on three-dimensional problems. The focus of my descriptions is on the work with which I have been most closely involved: the development of computer graphics techniques for research in structural mechanics. Although the programs we have produced are research software and therefore perhaps not as robust as commercial products, the work does push the state of the art and thus anticipates and demonstrates how these techniques will dramatically improve engineering practice.

In addition, since 1980, the College of Engineering at Cornell has developed an instructional computer graphics facility. The objectives of this center are to enhance teaching of undergraduates by providing the graphical tools for student exercises and to expose students to modern methods of computer graphics and computer-aided design. The software developed for these purposes is similar to commercial products in that it must be highly reliable and be easy for large groups of students to learn and use.

My main purpose in describing the example software systems is to show how interactive computer graphics affects both engineering productivity and control of computing. However, at the same time, I hope to convey and illustrate certain desirable characteristics of these interactive systems, with particular emphasis on the ergonomics or human factors. There are several design features of successful high-level applications software – a rational underlying database; modularity to foster expandability; clear, structured programming; a system for anticipating, handling, and correcting errors; transportability to the maximum extent possible while maintaining necessary performance and response; and thorough documentation. Such features as these are discussed in various texts and papers [3-5]. However, somewhat less attention has been devoted to systematic descriptions of what is perhaps the most significant and difficult-to-achieve design feature – proper human factors, sometimes called "user friendliness." Because the effectiveness of interactive graphics in meeting the challenges of productivity and control depends heavily upon the ergonomics of the software systems, it is worthwhile to summarize some of the important and desirable human-factors characteristics [6]. Among these are:

1. *Completeness of Function.* For the particular application, all reasonable functions associated with that application should be available.
2. *Flexibility in Sequence.* The user should be able to follow any feasible path he wishes through the complex of functions inherent in the application.
3. *Cancellation.* The user should be able to reverse or correct any previous action which is erroneous or, in retrospect, ill considered.
4. *Recovery.* If a fatal error is committed by the user or if the computer "crashes", resuming work without repeating much of the previous effort should be possible.
5. *Varied Data Entry Options.* To ease the input of numerical information, the user should be able to choose a mode of input most suited to his needs and preferences. For example, numerical values can be entered by graphical keypads, alphanumeric keyboards, or files.
6. *Rapid Graphical Feedback.* Every user action should be acknowledged either by a visual response signifying either the nature of a completed action, or if completion requires more than a few seconds of computing, by a message that the computation is in fact underway.
7. *Checking Options.* The user should be provided the means of reviewing graphically any previous actions, assignments, or definitions.
8. *Selected Quantitative Specifics.* Using graphical control, the user should be able to cause selected numerical values to be shown on the graphical display, at an