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Hardware Aspects of Digital Mapping*

Digitizing units, hardware interfaces, graphic displays, and interactive graphic systems are described, and the problems of cost, software needs, data base or information system definition, and implementation in developing countries are outlined.

Abstract: *An introduction sets forth the respective merits of (1) digitizing photogrammetrically-produced graphic plots and (2) direct photogrammetric digitizing. The characteristics of the various types of photogrammetric digitizing units are then discussed, including representative examples of large multi-station systems. With the increasing use of computer-based digitizing units, there has been a strong and welcome trend towards the implementation of standard hardware interfaces which allow designers a wide choice of peripheral devices to use with these units. Another development has been the incorporation of graphic displays into photogrammetric digitizing systems. While vector-driven storage tubes are most commonly used, the recently developed raster-driven refresh tubes show much promise for the future. A summary account is given of the experiences with interactive graphic systems interfaced directly to stereoplotting machines reported by a number of North American mapping agencies. In the general conclusion, the opinion is expressed that the hardware for photogrammetrically-derived digital mapping has been developed at such a speed recently as to outpace the abilities of many users to be able to implement it fully. A final cautionary note is made regarding the difficulties of implementing high-technology digital mapping systems in developing countries.*

Introduction

In the four-year period since the last I.S.P. Congress at Helsinki, a large number of mapping organizations have either entered the digital mapping field or have developed their existing capability substantially. Indeed, there are few agencies of any size in the more highly developed countries that do not have some digital mapping capability, however limited or experimental this may be. It must be recognized however that, in quite a number of cases, this activity is based on the digitizing of graphic documents, even though these are often produced photogrammetrically in the first instance.

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Digitizing of Photogrammetrically-Produced Graphic Plots

The philosophy of those mapping organizations which avoid digital photogrammetric measurements can perhaps be exemplified by the Ordnance Survey, which has a large and well-developed digital mapping system (Thompson, 1979). The basic mapping scales for Great Britain are 1:1,250, 1:2,500, and 1:10,000. Up to the present time, most of the O.S. digital mapping activity has been concentrated on the 1:1,250 scale, which covers urban areas, and on the 1:2,500 scale, which covers the most highly developed rural areas. Both series are planimetric only, i.e., they are uncontoured. At these large scales, there is much alteration and supplementation of the photogrammetrically-plotted data, for example,

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the setting back of the plotted roof lines of buildings to give correct ground lines, the measurement of features obscured by trees and vegetation, etc. (Gardiner-Hill, 1974). As much as 25 to 30 percent of the detail in a single map sheet in urban areas may be of this altered or supplemental character. Thus, it is argued that it is better to digitize only when a thoroughly field-completed and checked document is available, rather than attempt to make the extensive alterations and additions to digital photogrammetric data via an interactive editing process. Obviously, having a fully annotated, classified, and complete map does simplify the digitizing process. On the other hand, it also means an enormous duplication of measurement, with first the basic plotting carried out in the stereoplotting machine and then later the digitizing process carried out on a graphics digitizer. Furthermore, there will almost certainly be a loss of accuracy in digitizing the graphic document as compared with that of the original photogrammetric measurements, which may be significant if the data is also required for a digital data base of terrain information.

The hardware for graphics digitizing has undergone very considerable development over the last four years. For manual digitizing, solid-state tablets based on a variety of measuring principles have almost entirely eliminated previous designs using cross-slides. Also, the first really effective semi-automatic line-following digitizer, the impressive Laser-scan Fastrak (U.K.), has been introduced into several mapping agencies. Finally, several new fully automatic raster-scan digitizers have been introduced, notably the MBB Kartoscan, which has an array of high-resolution photo diodes mounted on a cross-slide which traverses the map laid out on a flat-bed, so converting it into the form of digital data.

DIRECT PHOTOGRAMMETRIC DIGITIZING

At smaller scales and in less complex and developed terrain, a very much lower proportion of the total map information will be produced by field completion and from other sources, and by far the greatest proportion will have been measured photogrammetrically. Given, too, the much more efficient hardware which is now available for interactive editing, the merging of digital data from different sources poses fewer and somewhat less severe problems than was the case previously. Thus, many more mapping organizations have been willing to implement direct photogrammetric digitizing than before.

This paper will concentrate on the hardware aspects of digital mapping and not the more limited and specialized collection of digital height values for a DTM (Digital Terrain Model) or DEM (Digital Elevation Model) or for controlling the production of orthophotographs. Since the paper is to be presented to a photogrammetric audience, it will concentrate on those operations which are mainly photogrammetric in character and, in particular, on the operations necessary to collect the basic digital data. Also, to keep the subject area of coverage within manageable proportions, this paper will confine itself to systems based on analog stereoplotting machines. Thus, analytical plotters will not be considered except in a single instance.

CHARACTERISTICS OF DIGITIZING UNITS

There are a large number of digitizing systems which can be attached to an analog type of stereoplotting machine. Traditionally, these comprise measuring devices (linear or rotary encoders) mounted on the cross-slides of the machine model space with electronic units for the decoding, display, and output of the measured coordinates and the control of the digitizing operations (Petrie, 1972). Increasingly, however, these specially-built hard-wired electronic devices are being replaced by units which make use of computer technology in the form of a microprocessor, microcomputer, desk-top computer, or minicomputer.

HARDWARE-BASED (I.E., HARD-WIRED) UNITS

These are still produced in some numbers, mainly by the manufacturers of photogrammetric equipment. Wild's EK-12, 20, and 22 units; the Zeiss Oberkochen Ecomat 12; and the Zeiss Jena Coordimeter F typify this traditional approach. The pulse counting and display, mode selection (point, time, and distance), the setting of coordinate values, etc., are all carried out using purpose-built electronic components. The more sophisticated of these units incorporate scalers and transformation circuitry to allow the display of terrain coordinates and sometimes digital "planimeters" to give the length of line and the area covered during measurement. Although a few new units have appeared in the last four years such as the Logik 5000 (from Denmark), development in this area is really at a standstill, in that no new concepts have appeared for some time.

Nevertheless, one must not overlook the fact that a good deal of the basic data collection for digital mapping systems is still being carried out using these hard-wired units to which a simple data recording device is attached. An example is the U.S. Forest Service automated mapping system implemented at its Geometronics Service Center (Chamard, 1979). Machines as varied as the Stereoplanigraph, Topocart, Stereosimplex IIC, Planitop F2, Kelsh Plotters, and the SMG 410 approximate instrument are interfaced to individual Altek AC74 digitizing units which perform off-line data collection. These data are later edited on M & S digitizing/editing stations with final output on a large Kongsberg 5000 automatic coordinatograph.

A similar situation is reported by the U.S. Geological Survey (McEwen and White, 1979), which uses Altek AC 189 digitizing units attached to Wild B8s and Kern PG-2s for the stereoplotting component of its Digital Cartographic Applications Program (DCAP).

FIRMWARE-BASED UNITS

By contrast with the situation regarding hard-wired digitizers, an area of rapid development has been that of digitizers based on the use of a microprocessor. In these devices, the various functions of the digitizing unit are executed by the preprogrammed instructions contained in a PROM (Programmable Read Only Memory). Examples of such units produced in the last two years include the Kongsberg PDS-M80 (successor to the pioneering PDS-M8 shown at the 1976 Helsinki Congress); the Kern ER 34 (Roberts, 1979); the series MDR-1, MDR-2a, and SM-1 produced by Surveying and Scientific Instruments (UK); and the Altek AC 90SM. Although the microprocessors used in these devices are often the same—e.g., the ER 34, the SM-1, and the AC 90SM all use the Zilog Z-80—the manner in which they have been configured is highly diverse. Thus, the SM-1 and the PDS-M80 both employ visual display units (VDUs) as standard integral devices for the display of coordinates, text, and prompts and for the entry of commands, data, etc., whereas the MDR-1 (Figure 1) and ER 34 (Figure 2) use numerical LED displays for coordinate display with a numeric pad for data entry and preprogrammed buttons for executing specific functions. The MDR-2a and the AC 90SM occupy an intermediate position with single line alphanumeric displays and appropriate keyboards.

While certain simple functions, such as point, time, and distance modes, event counting, programmable output formats, etc., are standard, the designers of these various units have totally different and opposed views as to how the power of the microprocessor should otherwise be used. Thus, the ER 34 features the real-time display of terrain coordinates, area measurement, and an ingenious algorithm for data collection, while the PDS-M80 has built-in programs for relative and absolute orientation as well as the real-time display of ground coordinates.

Still more elaborate and expensive units have appeared, the best-known being the Kern DC-2B Digitizing/Graphics System (Klaver, 1978) which uses two separate microprocessors (Figure 3). The first is a DEC LSI/11 (termed the General Input Processor) which adds manuscript preparation, control point plotting, building squaring, and spot height annotation to the normal digitizing functions, absolute orientation, and area computation. The second (called the Plotter Control Processor) is a Motorola 6800 which is programmed to perform the main graphics-related operations—the interpolation of lines and curves and the generation of vectors, circles, alphanumeric characters, areas, and graphic symbols—involved in driving Kern's AT automatic drawing table. So a very direct type of digital mapping—described by Klaver as "computer-supported stereocompilation"—can be implemented.

Clearly, the development of these digitizing units based on the use of microprocessors represents a quantum jump in capability and versatility over the hard-wired units. The programs contained in the PROM are instantly available to the photogrammetrist as soon as the unit is powered on. Thus, there is no need to read them in from a peripheral device or to cope with an operating system and the other elaborations associated with many computer systems. However, it must also be recognized that there is a certain lack of flexibility inherent in these units. Once the range of functions and operations has been decided upon by the designer and has been programmed and implemented as the "firmware" in the PROM, there is little prospect of the photogrammetrist being

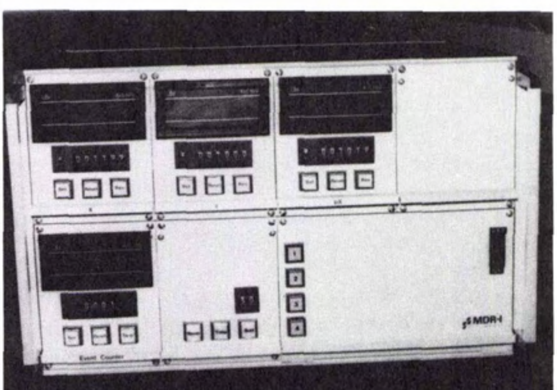

FIG. 1. MDR-1 Digitizing Unit.

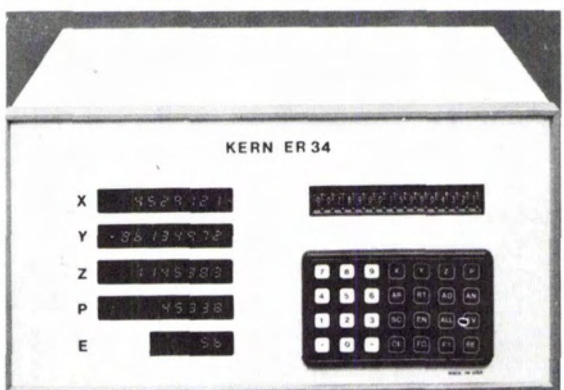

FIG. 2. Kern ER 34 Digitizing Unit.

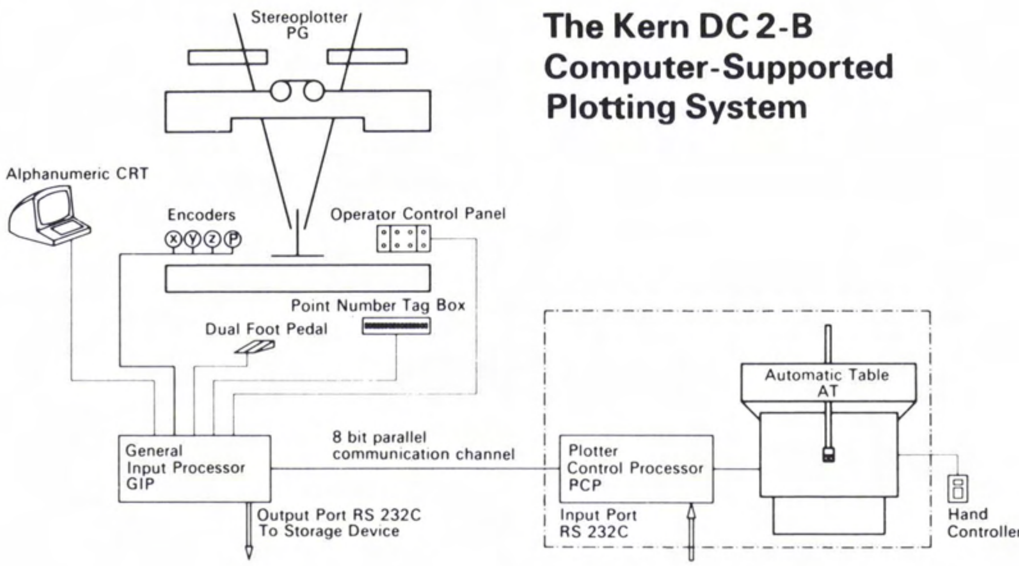

FIG. 3.

able to reconfigure or reprogram the microprocessor with a view to modifying or to altering the functions or to implementing a new range of operations. Such possibilities are, however, present in the next group of devices.

SOFTWARE-BASED UNITS UTILIZING DESK-TOP COMPUTERS, MICROCOMPUTERS, OR SMALL MINICOMPUTERS

The development of these units has been another area of considerable activity in the four years since the last I.S.P. Congress. The computer can be programmed to implement all the functions discussed above and many others besides. Programs may be written to carry out some or all of the following operations: area and volume computations associated with road design and stockpiles; independent model strip formation and adjustment; perspective plotting; etc., besides orientation and map compilation. All of these may be carried out on-line and interactively, with a large choice of possible operations or procedures being offered to the photogrammetrist.

The pioneering efforts of Dorrer and his associates in this field have led to a commercial realization in the CASP (Computer Assisted Stereo-Plotting) package offered by Zeiss Oberkochen at the Helsinki Congress (Dorrer, 1976). Originally implemented in rather restricted form using the Hewlett-Packard HP-9810 programmable desk-top calculator (Figure 4), the package has since been modified, redeveloped, and expanded for use, first with the HP-9825 and very recently with the screen-based HP-9835 and HP-9845 desk-top computers. A parallel development is the HASP package developed in the United States by Hogan, also using the HP-9825 (although an HP-9835 version has also been developed). This is also available commercially, both from HASP Inc. and recently through the Wild organization. The HASP graphics software allows the implementation of direct digital plotting with a choice of characters, symbols, line widths, pen types, etc., in much the same manner as in the DC-2B system already discussed.

Similar university-based developments in this area include the systems developed at the Danish Technical University (Dueholm, 1977 and 1979) and at the University of Glasgow (Petrie and Adam, 1980). The former are based on the HP-9815 and HP-9825, the latter on a screen-based Wang 2200 desk-top computer (Figure 5).

All of these systems utilize similar hardware, with linear or rotary encoders supplying the measured coordinate data to a small controller which then passes it on to the desk-top computer. Quite a number of other mapping organizations have embarked on similar inhouse developments based often on a microcomputer or minicomputer but essentially carrying out the same tasks, e.g., the system using two Wild A10 machines, each connected to a Data General Nova minicomputer, developed by the South Australian Department of Lands (McLeod, 1978).

The work of developing highly-interactive, user-oriented software is extremely demanding for the programmer, especially if it has to be executed on desk-top calculators such as the HP-9810 and 9815, which have rather restricted hardware facilities and have to be programmed in a special machine code. The availability of better hardware such as a larger memory, VDU, etc., and the use of

FIG. 4. Zeiss (Oberkochen) Planitope with DIREC-1 Display and HP-9810 Desk-Top Computer.

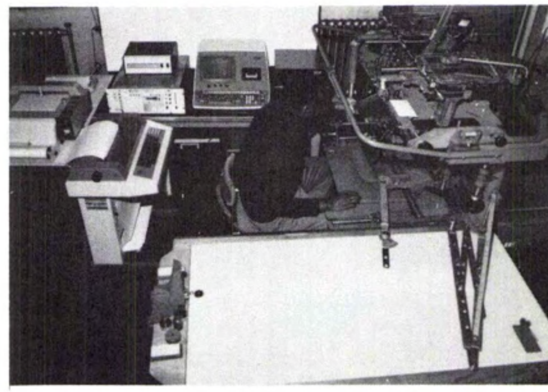

FIG. 5. Galileo Stereosimplex IIC with Wang 2200 Desk-Top Computer for computer-assisted stereoplotting.

a higher-level language such as BASIC (features available on the Wang 2200 and HP 9835 and 9845) eases the problem to a considerable extent. Nevertheless, the experience of those who have undertaken this type of development is that it involves a high degree of knowledge and experience both in photogrammetry and in computer programming for its effective and successful implementation. Furthermore, it does take much more time to develop than can possibly be imagined at the outset. So, although the hardware costs of this type of system may be relatively low, the additional software costs are far from negligible.

When it is implemented successfully, the degree of assistance given to all stages of the stereocompilation process has to be experienced to be fully appreciated. The flexibility is high and the more knowledgeable users can modify or augment the operations rather readily through a change of program, a feature not available when the programs are locked into the firmware of a PROM.

MULTISTATION TIME-SHARING SYSTEM BASED ON A LARGE MINICOMPUTER

It will have been noticed that, in the above account, there has been a steady progression in capability and sophistication from the simplest hard-wired digitizing unit such as the Wild EK-12 to the CASP and HASP developments which are integrated hardware/software digitizing systems of enormous power and potential for digital mapping. The degree of sophistication culminates in the multistation digital mapping systems based on large time-sharing minicomputers which have been developed by a number of mapping agencies. While many of the hardware elements will often be similar to those discussed above, the total hardware configuration and its associated software move into yet another realm of complication and cost. A complete paper could be devoted to this subject alone. Therefore, only the essential elements of a few representative systems will be discussed here.

An early system is that of the Algerian National Cartographic Institute (Vigneron, 1974 and 1975; Boulaga, 1978). This comprises three stereoplotting machines all interfaced to a Data General Nova computer, equipped with a large disk and two magnetic tape drives, which also drives an output drum plotter for the production of intermediate check plots. Final plotting is carried out off-line on a Benson flat-bed plotter. The applications include mapping for road surveys and for agrarian reform projects.

Another larger digital mapping system along the same general lines is that of a commercial air survey firm, Hunting Surveys (Keir, 1976; Leatherdale, 1977; Leatherdale and Keir, 1979). Currently, this utilizes a DEC PDP 11/50 computer, which controls the digitizing carried out on eight Wild A8 stereoplotting machines simultaneously and records the digital information on a central large-capacity disk store (Figure 6). Alphanumeric VDUs equipped with keyboards (Figure 7) are available at each A8 to provide prompts, error messages, header-code menus, etc., to the operator. Final output graphic documents are produced on a Ferranti Master Plotter, again controlled by the large central computer. The range of applications discussed in the papers by Keir and Leatherdale is very wide and encompasses mapping at scales from the largest to the smallest.

That such complex systems can be implemented successfully is a tribute to the abilities of the teams of hardware and software specialists involved in such projects. The sheer skill, labor, determination, and expense should certainly not be underestimated. It is no criticism of those involved in the creation and implementation of these successful digital mapping systems to raise the question of basing such large systems wholly on a single cen-

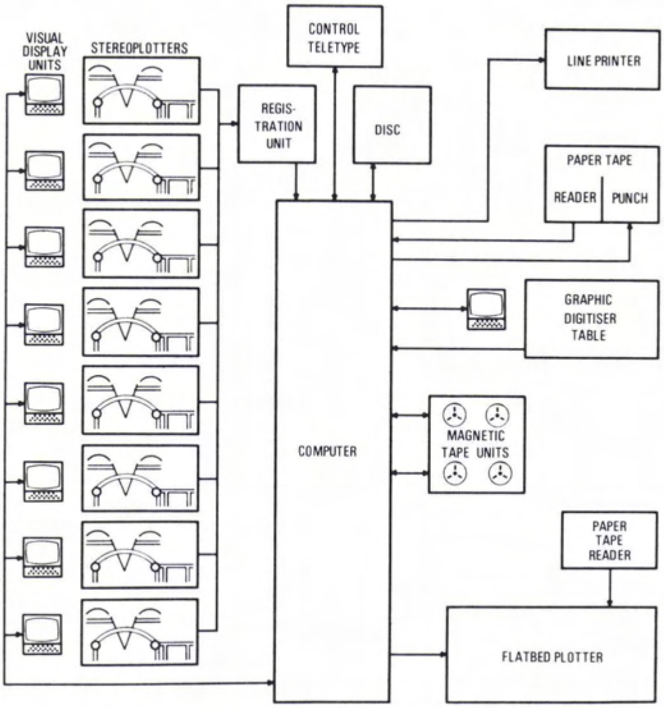

FIG. 6. Hardware of the Hunting Digital Mapping System.

tral computer. A hardware fault or software failure can result in the whole computer system crashing so that all activities come to a halt until a repair can be effected. Therefore, the possibility of distributing some of the controlling/computing operations to individual digitizing units based on a microprocessor or a desk-top computer must be considered seriously as an alternative so that the data collection process is not so heavily at risk.

This leads naturally to a short report on a third digital mapping system, albeit based on the use of analytical plotters, where the idea of distributed

FIG. 7. Wild A8 with alphanumeric VDU for prompts and messages (Hunting Digital Mapping System).

computing power has been implemented to the highest possible degree, at least given our present level of technology. Such a system is that first discussed as a concept (Figure 8) by Helmering (1976) and since reported on as a working system, the Integrated Photogrammetric Instrument Network (IPIN) of the DMA Aerospace Center, by Elphinstone (1979). In this, each OMI-Bendix AS-11A or AS-11B-1 analytical plotter is controlled by a Modcomp II/25 minicomputer. Each of two groups of twelve AS-11 machines is linked to the group's Modcomp II/45 central minicomputer, which is equipped with numerous storage devices and other peripherals and acts as a database storage, transfer, and management machine. A third group of four of these analytical plotters together with several TA-3P stereocomparators is also linked to a third Modcomp II/45. Several more of these powerful minicomputers act as specialized processing systems for height data, file handling, editing, and final output. The sheer daring and scale of the system is quite staggering to the non-military mapper; the cost of actually implementing it must be almost as staggering to the agency concerned, but presumably the gains in speed of output make it worthwhile. One notes that a similar but smaller system involving six AS-11A machines and similar Modcomp II/25 and II/45 computers is being implemented at a civilian agency, the U.S. Geological Survey (Brunson and Olsen, 1978).

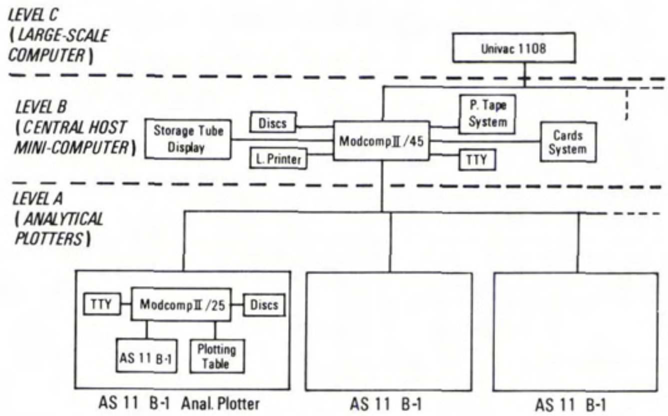

FIG. 8. IPIN Concept (after Helmering, 1976).

HARDWARE INTERFACES

With the advent and rapid growth of digital mapping, a matter of considerable importance to photogrammetrists is the interfacing of the stereoplotting machine to the output electronics unit, microprocessor, desk-top computer, or minicomputer and their further interfacing to a large variety of input/output devices, e.g., tape, disk and diskette drives, printers, plotters, graphic displays, alphanumeric VDUs, etc. Many of these devices have characteristics which make them quite incompatible with one another. Some have differing signal levels (voltage, current, etc.); some use different data formats; some are capable of unidirectional signaling only, while others are bidirectional; most operate at speeds which could slow down computer performance; and many operate at widely different speeds from one another. The job of the interface is to act as an intermediate device or translator which brings any two interconnected devices into a state of compatability so that they are able to communicate with each other.

Unfortunately, the response of many of the photogrammetric manufacturers has been to develop special-purpose interfaces for each specific peripheral device. In particular, the catalogs of the manufacturers of hard-wired digitizing units show a bewildering list of the device-specific interfaces. Inevitably, these have repercussions in their incompatability with other devices, their high initial cost, and in a need for specialist service and repair facilities and personnel.

With the recent development of computer-based digitizing units, the situation may improve and the use of standard interfaces should become more common, thus allowing a much wider choice of peripheral devices and a better matching of system requirements with actual hardware. In practice, it is now possible to find peripheral devices which can be interfaced using one of four standard interfaces: Binary Coded Decimal (BCD); Parallel Input/Output; IEEE-488; and the RS-232C Serial interfaces. A fifth—Direct Memory Access (DMA)—is only of interest to photogrammetrists in very unusual situations requiring ultra high-speed data transfer.

BCD INTERFACE

With this type of interface, the signals or pulses from the measuring elements are encoded in a binary code which represents decimal numerals. Four binary bits are used to represent the numerals 0 to 9. Thus, each digit of a coordinate display, for example, requires four signal wires to transmit it. A group of six digits for a single set of coordinates from one machine axis will need 24 signal wires, and the readings for a full set of X, Y, and Z model coordinates, three times as many. Thus, a direct interface would have an enormous number of signal wires to handle simultaneously. The difficulty may be resolved by first transforming and then serializing the digits into a stream of ASCII characters which are passed through a suitable interface to the computer processor. A notable characteristic of a BCD interface is that it is unidirectional, i.e., information can be sent to the computer but normally it will not accept information from it.

PARALLEL I/O INTERFACE

With this interface, data may be sent bidirectionally between computer and peripheral using a parallel set of data lines. Thus, data are passed between devices at high speed several bits at a time, 8-bit and 16-bit arrangements being the most appropriate for photogrammetric work. Additional control wires carry signals which regulate the flow of data between any pair of devices. In most cases, a single parallel interface must be provided for each device.

IEEE-488 INTERFACE

This is a standard general-purpose interface for instrumentation introduced by IEEE in 1975. In the published standard (which was slightly modified in 1978), the form of signal, logic level, logic sense, and physical connection are all precisely defined without defining the actual use of the interface. Basically, it is a parallel-type interface with a bus structure which allows a large number of peripherals (up to 14 or 15) to be connected through a single interface. Each device has a separate address and is designated either as a "talker" (which is only able to send data to the system), a "listener" (only able to accept data from the system), or a "controller" (able to control the whole system). Thus, the desk-top computer or microprocessor in a digitizing system will act as the controller, the encoders will be talkers only, and a printer will be a listener. Certain devices, e.g., a diskette or cassette drive, may be both a talker and a listener. This type of interface has been adopted by several manufacturers of computers and peripherals, e.g., Hewlett-Packard (as the HP-IB interface), Tektronix (GP-IB), and Commodore, whose products are much used in digital mapping systems.

Since basically it is a parallel-type of interface, data transfer is rapid. However, if there are several active output devices (listeners), these may not all be capable of accepting data at the same rate. Therefore, the speed of data transfer will have to be set at that of the slowest device of the group; otherwise data will be lost.

SERIAL INTERFACES

The antecedents of this type of interface can be traced back through the history of telecommunications to the telegraph and to early radio communication using Morse Code. Data are transmitted over a single wire since the cost of providing several wires in parallel over long distances is prohibitive. Thus, each piece of data is sent one bit at a time, i.e., in bit-serial fashion, instead of bit-parallel as in a parallel interface. A vast number of devices, e.g., teletypewriters and tape punches and readers, had been developed extensively for telecommunications purposes before computers had been devised. These were readily adopted as low-cost data entry and display devices when computers appeared. New and faster versions of these devices have since been designed and produced in large numbers, but they still retain a serial mode of operation.

The most common serial interfaces are those built to the EIA RS-232C standard. This defines the electrical characteristics of the interface and designates certain pins on standard 25-pin connectors as those to be used for passing transmitted and received data, control signals, etc. No specific character codes are designated by the standard, but normally one of the commonly-used telecommunication codes, e.g., 5-bit (Baudot), 7-bit (ASCII), or 8-bit (EBCDIC), is used.

Teletypewriters are available which do not adhere to the RS-232C standard. Instead of using certain positive and negative voltage levels to represent Logic 0 or 1 (as in RS-232C), these use the presence or absence of current for this purpose, hence they are termed current loop devices. 20 mA and 60 mA current loop devices are most usual. While RS-232C devices are limited to 50 ft (15 m) for a direct connection between devices, current loop devices can be used over much greater distances.

It is obvious that passing data through a serial interface one bit at a time is intrinsically a slower mode of operation than doing so with the multiple bits possible in a parallel interface. However, in practice, serial lines and interfaces may be driven at speeds up to 4,800 or 9,600 bits/sec, which is more than sufficient for most digital mapping operations.

DMA INTERFACE

This represents the other extreme in data transfer rates. Most peripheral devices are very much slower in operation than the computer processor. However, there are a few peripherals requiring data rates approaching that of the computer memory, in which case the computer processor which controls the flow of data would be unable to process data as well. The solution is to have a direct connection between the memory and the peripheral device using a DMA interface which may allow up to 400,000 transfers of the data per second. Such rates have not as yet been found necessary in digital mapping work, but they are required in interactive dynamic displays of three-dimensional data which include a change of scale, rotation, and translation of the data. It would appear inevitable that such a requirement will arise in similar manipulations of large data sets in digital mapping operations.

The outcome of the above discussion is to welcome the trend among the constructors of digital mapping systems to use these standard interfaces. Indeed, several digitizing units are now offered with two or three of these interfaces fitted to the unit as standard items of equipment. This has led to a consequent easing of the previously daunting task of interfacing the individual components of a digital mapping system. Furthermore, it has allowed the opening-up of a very wide choice of peripheral devices to the designers and operators of such systems without the previous need to design and build expensive special interfaces for the purpose. To those photogrammetrists who have not been concerned with these problems, this discussion may appear narrowly technical and of little importance. However, those who have been concerned with these problems of interfacing photogrammetric devices to computers and their peripherals can only assure others of its vital nature, second only to that of the provision of software.

Graphics Displays

Over the last two or three years, there have been major developments in graphic displays, largely a consequence of the explosive development and growth of integrated-circuit and microprocessor technology. As a result, there has been an increased capability and sophistication in graphics display hardware accompanied by a dramatic reduction in its cost. Thus, an area formerly of little practical interest to the photogrammetrist is now available for exploitation in the context of digital mapping operations.

Those graphics displays which are of interest to the mapping community are all based on the use of the cathode ray tube (CRT) in one form or another. Their principal characteristics are as follows:

- They employ either (1) the vector or line drawing method, or (2) the raster-drawing method of generating the map image;
- In addition, there is the distinction between (1) the storage tube in which the image, once written on the face of the CRT, is stored or maintained there without need to refresh it from the computer or device memory; and (2) the refresh type of the tube which, as the name suggests, requires the display to be continually refreshed at a speed of 30 to 60 Hz from a display memory.

Of the four possible combinations of these parameters, only three are available as actual devices:

- the vector-driven storage tube,
- the vector-driven refresh tube, and
- the raster-driven refresh tube.

VECTOR-DRIVEN STORAGE TUBE

A single company, Tektronix, has a virtual monopoly of supply of this type of tube. Various models are offered having diagonal screen widths ranging from 28 cm (Model 4010) to 48 cm (Model 4014) and 63.5 cm (Model 4016). Resolution is high, the image is flicker-free, and, although the contrast is rather poor, the quality of the display image is generally good (Figure 9). Also, the cost is moderate, at least for the smaller-sized tubes. Since it is vector-driven, the time taken to write the map image will be proportional to the length of line to be plotted, which can result in a perceptible delay in displaying a complex and detailed plot. Another defect is that, since the image is stored on the face of the tube, any need to alter or edit any part of the photogrammetrically-derived data results in the whole of the existing displayed information having to be deleted. As a consequence, the whole plot has to be redrawn to display the newly revised information.

Whatever these disadvantages, their resolution, quality, and relatively moderate cost make storage tubes the preferred display device for photogrammetric work (Figure 10), since the extent of interactive editing carried out on-line to the stereoplotting machine is often a quite small proportion of the total time spent plotting. However, a quite different situation will be encountered when major editing or revision of the digitized data has to be undertaken after collection of the basic photogrammetric data. Refresh tubes, able to display changes quickly, may then offer significant advantages over storage tubes.

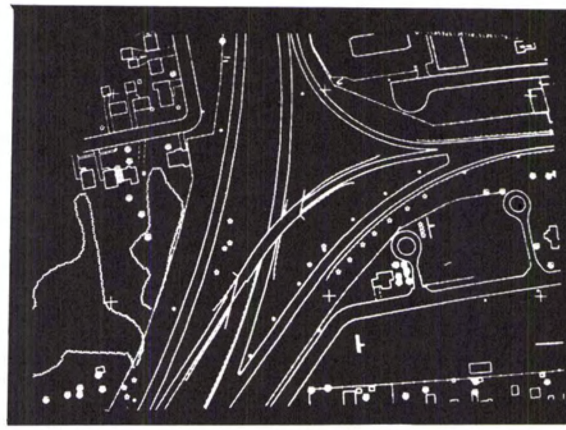

Fig. 9. Tektronix storage tube display of photogrammetric data.

VECTOR-DRIVEN REFRESH TUBE

These devices are the most sophisticated and expensive forms of graphics display. They are available from specialist computer graphics display manufacturers such as Megatek, Vector General, Evans and Sutherland, Adage, etc. All of them utilize high resolution displays designed for highly-interactive graphics work involving the continuous display of complex graphical images

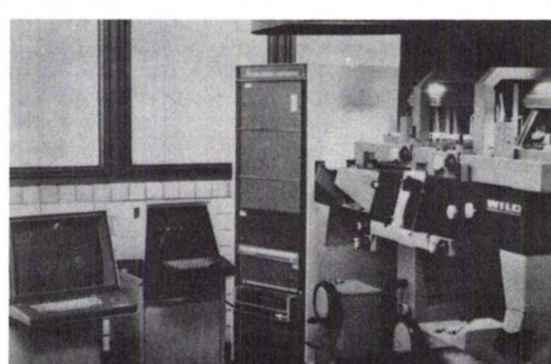

Fig. 10. Wild A10 with Nova computer, Tektronix 4014 graphics display, and alphanumeric VDU (McLeod, 1978).

which are continually changing in position, as required for example in aircraft simulators and the inspection and manipulation of molecular structures in chemical modeling. Facilities include pan, zoom, rotation, perspective plotting of three-dimensional information with hidden-line removal, selective erase, etc. The need for the ultra-rapid processing and transfer of considerable amounts of data for such dynamic displays leads inevitably to a requirement for either a large and fast minicomputer or a special graphics processor dedicated to driving the display and often for DMA interfaces for fast data transfer.

While the capability of being able to see immediately any deletions, additions, or changes after editing would be useful in digital mapping work, this would only be required at relatively infrequent intervals during stereoplotting. This fact combined with the very high cost of these devices ($50,000 to $80,000 per unit) means that there is, at present, little prospect of them being utilized in the photogrammetric stages of the digital mapping process.

RASTER-DRIVEN REFRESH TUBE

Since most digital mapping data are generated, stored, edited, and plotted in vector (i.e., line) form, the need to convert them to a raster format in order to view them on a raster-driven display device is a major drawback. On the other hand, raster-driven graphics displays are well-developed, relatively inexpensive, and well understood, since basically the technology which is employed in the actual display device is similar to that used in domestic television sets. The problem of rasterizing and continuously refreshing the display has recently been overcome with the availability of suitable inexpensive microprocessors. The result has been a dramatic fall in the price of these devices over the last two or three years. Many raster-driven refresh graphics displays have appeared on the market at a price well below that of comparable-sized storage tubes.

Their inexpensive price and their ability to execute selective erasure of information and to display rapid changes in graphics data means that raster graphics tubes need to be inspected closely for their possible application to digital mapping. At present, their principal defect lies in their lower resolution which is typically 512 by 256 lines on low-cost devices and, therefore, well below that of the competing storage-tube technology. However, more expensive devices can already give 800 to 1,000 lines. If the resolution continues to improve and the cost remains low, then this will be of great interest to the designers of digital mapping systems for topographic purposes. Already there is considerable use of these raster-scan displays in the field of thematic mapping where resolution requirements are less demanding.

An especially interesting development with considerable possibilities for digital mapping is the multi-plane capability (Figure 11) now available on a few raster-scan displays. For example, in the Sigma T5670 display (UK), four separate pixel planes each of 768 by 512 bits can be provided at present. These allow the storage of four wholly independent monochrome plots and their display either singly or in any combination. Thus, for example, contours, planimetric detail, hydrology, and vegetation may be viewed either separately or together, which has obvious advantages in digital mapping work.

This type of hardware development has also been exploited to produce relatively inexpensive high-resolution raster color displays which permit each class of feature present in the map to be displayed in a different color. Areas can also be displayed in different colors using polygon fill methods. It will be interesting to see whether these capabilities of raster-scan color displays will be

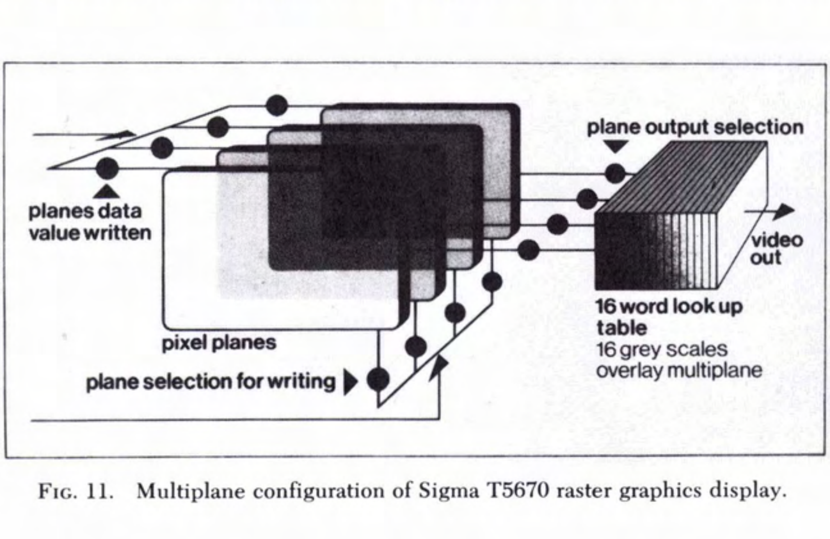

FIG. 11. Multiplane configuration of Sigma T5670 raster graphics display.

exploited for digital topographic mapping operations, as has already started to take place in the fields of thematic mapping and digital image processing.

Inter-active Graphics Systems

Arising from the developments discussed above, a considerable amount of experimental work has taken place since the 1976 Helsinki Congress on the direct attachment of interactive graphics systems to stereoplotting machines generating data for a digital mapping system. While there have been some developments by one or two other firms, the company which has principally been involved in this work has been M & S Computing of Huntsville, Alabama, which has supplied interactive systems to many mapping agencies and firms in North America. Most of these are used as editing devices in large digital mapping systems, the main data collection having been carried out at an earlier stage using dedicated photogrammetric or cartographic digitizing equipment. However, attention will be focused here on the cases where the interactive graphics system is connected directly to the photogrammetric digitizing unit.

Stereoplotting machines interfaced to interactive graphics systems

The M & S system consists of a computer (one of the DEC PDP 11 series is normally employed) with associated disk and tape drives; a workstation which includes a storage tube display, a keyboard, and a small digitizing tablet used for menu commands; and (usually) some type of hardcopy graphics plotter. The system can be expanded so that a single processor can handle several work stations. In the photogrammetric context, between one and three stereoplotters have been connected to a single processor so far. The standard M & S graphics software runs under the DEC RSX-11 operating system. Unique to the M & S system is the use of twin graphics displays. One storage tube is normally used to present an overview at a small scale of the whole area being digitized, while the other gives an enlarged view of the detail in the immediate area of the digitizing operations (Figure 12).

The advantages of using this type of interactive system at the stereoplotting machine providing continuous display of digitized features during data capture are as follows:

- It eliminates the time-consuming remeasurement of a graphic manuscript with its accompanying loss of accuracy;
- It provides the possibilities of checking the digitized photogrammetric data while the stereomodel is still in the stereoplotting machine, thus allowing the detection of errors and omissions leading to the immediate correction of wrongly or incompletely digitized features; and

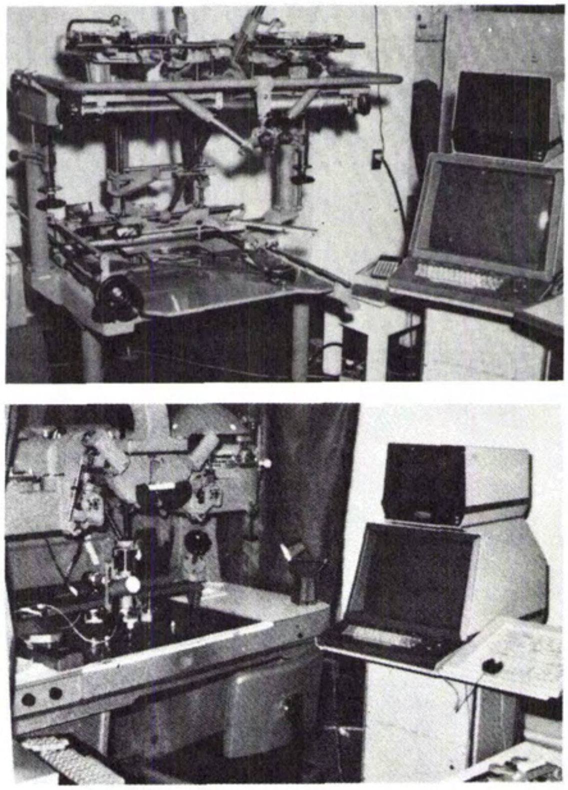

Fig. 12. (a) Stereosimplex IIC and (b) Wild B8 with M&S dual graphic displays.

- It allows the matching of digital map data collected in adjacent stereo-models with that being measured in the current model.

Quite a number of mapping agencies have interfaced M & S systems to a variety of stereoplotting machines—to Wild B8 Aviographs (Topographic Survey of Canada, Minnesota Department of Transportation); Kern PG-2 (Florida Department of Transportation); Zeiss Oberkochen Planicart E3 (Macmillan Bloedel); Galileo Stereosimplex IIC (Michigan Department of Transportation, Chicago Aerial Surveys); and unspecified (M. J. Harden Associates). All of these organizations have kindly provided details of their experiences, as have two other agencies (Texas State Department of Highways and Transportation, U.S. Forest Service) which make use of stereoplotting machines for data capture in an off-line mode with subsequent use of the M & S interactive graphics system in a separate editing procedure.

Experiences with interactive graphics systems

Experiences vary considerably. The most positive responses have come from the Topographic Survey of Canada where the system (Figure 13) comprising three Wild B-8s attached first to a DEC

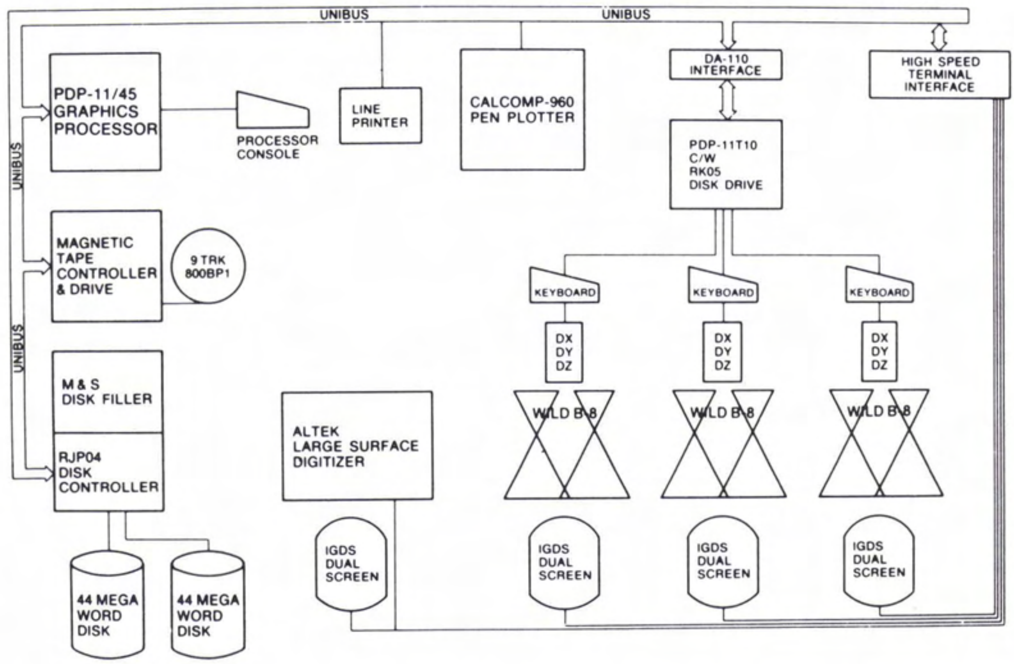

FIG. 13. Hardware of experimental interactive photogrammetric system of Canadian Topographic Survey (Zarzycki, 1978).

PDP 11/45 (Zarzycki, 1978) and later to a PDP 11/70 (Allam, 1979) provides digital data which have been used for topographic mapping at medium to small scales (between 1:10,000 and 1:50,000) to standard map accuracy specifications. A generally favorable experience with large-scale mapping is also reported by the Florida and Michigan Departments of Transportation. On the other hand, in a group of three Wild B8s attached to an M & S system at the Minnesota Department of Transportation, two are in fact operated blind (i.e., without the graphics displays) "so that the operator is not tempted into nonproductive perfectionism." Only the third machine has a graphics capability to allow the detection and correction of errors in the digitized photogrammetric data.

Another respondent, Macmillan Bloedel, reports that "unfortunately, due to the complexity of topographic maps and the large number of users on our system, our photogrammetrist feels that the system response is too slow to achieve the volume of production he needs. Consequently, he has had to revert to manual production of his products which will be digitized at a later time. This is a duplication of effort, but it is the only available remedy to achieve his production rate."

Still other users appear to be quite happy with the intermediate position, i.e., of collecting the digitized photogrammetric data off-line, recording it on magnetic tape, and then editing it later using the M & S interactive system. The Texas State Department of Highways and Transportation makes use of eleven stereoplotters, the digital data from these being recorded on the disk drive of a Data General Nova Computer, which acts as the overall controlling device for all the data acquisition devices. The data are then transferred to an IBM mainframe computer to undergo an initial edit routine, followed by the interactive editing process carried out on the M & S stations based on a DEC PDP 11/35 computer. "Because the number of stereoplotters available for map compilation is usually a limited resource and because of the fact that it has been determined that less than five percent of all errors detected during the edit process require corrections at the stereoplotter station, responsibilities of the plotter operators have been reduced to an absolute minimum and model set-up is not retained during the edit process. A designated person is assigned to accomplish this task for all eleven stereoplotters using model plots obtained from a high-speed drum plotter and the Edit Station of the Interactive Graphics System" (Howell 1979). Obviously, the enormous cost of providing all eleven stereoplotting machines with dual graphics displays of the M & S type must play a significant part in this decision also.

It can be seen from the foregoing discussion that different organizations make quite different use of the same basic system depending partly on the nature of the work and the expertise of the staff, but also on other criteria, not all of which will be given the same weight in different agencies. What is certain, however, is that we are only at the very beginning of an era in which many of the stereoplotting machines engaged in digital mapping operations in the more highly developed countries will eventually have interactive graphic displays attached to their digitizing systems. At present, the cost is still very high ($100,000 for a single station M & S system) but for a given capability this cost may be expected to fall in the future.

Conclusion

As the above account has attempted to show, the whole technology available for photogrammetrically-derived digital mapping has undergone a great advance over the last four years. In fact, one can say that, in many cases, these developments on the hardware side have substantially outpaced the users' abilities to implement them. Several reasons may be offered to explain this phenomenon.

- The present capital costs of the more advanced devices or systems such as vector-driven refresh tubes and interactive graphic displays are enormous—in many cases, they far exceed the value of the photogrammetric equipment to which they are attached. One can be reasonably certain from general trends and developments in the fields of computing and computer graphics that the price:performance ratio of this type of equipment will become much more favorable in the future. But even then, the financial implications will still be a matter of extreme concern, especially to commercial photogrammetric firms which need to recover their cost and make a profit on the enormous investment which they will have to make. However, quite substantial gains in productivity can be made from the much smaller investments involved in the adoption of firmware-based and software-based digitizing systems. These less sophisticated systems also offer the chance for users to gain experience of digital mapping systems in a modest but meaningful manner before adopting larger and more complex systems.
- The second point is that extensive software needs to be supplied, acquired, or developed before the new hardware can be implemented at all. This takes a great deal of time, effort, and money, the extent of which is almost always underestimated in any digital mapping project. Closely associated with these software requirements is the need to have clearly-defined operational procedures and standards, since any failure to implement these or to deviate from them can often have unforeseen but severe effects on the whole digital mapping system (Zarzycki, 1979).
- Furthermore, as Zarzycki has also pointed out, while the technology is now well developed, its effectiveness depends too on the sophistication of the classification system of topographic features, which must not only meet the needs of the digital mapping system itself but also those of geographically referenced information systems.

The final remark must also be a cautionary one. The high technology of the digital mapping system is something which at present can hardly exist far from the highly-developed countries of North America, Western Europe, Australia, and Japan. In particular (and rather sadly), it has virtually nothing to offer the poorer developing countries at this present time. Without large capital investment (of precious foreign exchange) and a very sophisticated infrastructure including such items as reliable electricity supplies, comprehensive technical support, and a cadre of experts in computing, electronics, and analytical photogrammetry, digital mapping cannot be implemented. One reads sad tales of sophisticated and expensive digital image processing systems purchased to make use of remotely-sensed satellite data lying useless and unused in certain developing countries; it is to be hoped that these stories will not be repeated with digital mapping systems.

Acknowledgments

The author wishes to acknowledge the assistance given by manufacturers, mapping agencies, and individuals from many different countries. They have supplied a great deal of relevant and interesting material, much of which has had to be condensed down to a few lines or sentences to fit within the limit and scope of this review paper. Nevertheless, sincere thanks are due to all of those who have contributed information used in this paper.

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