Trends in Automated Mapping and Geographic Information System Hardware

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ABSTRACT: Dramatic technological advances in computer hardware over the past two decades have directly impacted development in automated mapping and geographic information system (AM/GIS) capabilities. This paper provides an overview of the technological trends in computer processors and peripheral devices important to AM/GIS. The technological trends of computer hardware are discussed to present a perspective on past and current AM/GIS configurations and to explore likely changes in the near future.

INTRODUCTION

TREMENDOUS TECHNOLOGICAL ADVANCES in computer hardware over the past 20 years have provided developers of automated mapping and geographic information system (AM/GIS) software with the capability to perform increasingly sophisticated mapping and geographic analysis functions. Automated mapping systems are those that employ computer technology with an emphasis on computer graphics and map production and with only limited capability for processing nongraphic attributes. These are differentiated from geographic information systems that combine graphic capabilities with strong nongraphic attribute linkages allowing complex query, map overlay, polygon processing, and spatial modeling operations.

During the 1960s, AM/GIS applications used grid-structured spatial databases in batch-mode processing environments. The 1970s can be considered the decade of developments in vector graphics, interactive processing, and output devices capable of generating high resolution displays and hard copy graphic products. In the 1980s, many of the advances in the 1970s were perfected and applied in operational AM/GIS configurations. Interactive query and graphic processing have become an accepted and essential characteristic of AM/GIS. Increases in processor and peripheral device performance have made possible complex database management and modeling, and high quality vector graphics at low cost to AM/GIS users. This paper explores important technological developments in computer processors, mass storage, and output devices, and their relationship to AM/GIS.

COMPUTER PROCESSOR TRENDS

TRENDS IN PROCESSOR PERFORMANCE

Over the past three decades, there have been substantial changes in the architecture, cost, and performance of computer processors. Large, single tasking mainframes of the 1940s and 1950s gave way to multi-tasking computers of the 1960s using third generation programming languages. The 1970s saw the development of minicomputers and interactive processing in many user environments. Distributed computing has been the trend of the 1980s with powerful computers of different sizes being networked for a sharing of computing resources and data. Over the past 20 years, developers of automated mapping and geographic information systems have taken advantage of progress in computer processor technology to build increasingly powerful systems for mapping and geographic analysis.

The past decade has seen a dramatic increase in the performance/cost ratio of computer processors. Processor performance describes the overall efficiency of a processor and includes characteristics like speed of instruction processing and efficiency of input/output tasks (Lieberman, 1987). To illustrate the astounding climb in processor performance, Figure 1 shows the increase in the performance/cost ratio in terms of processor speed (million instructions per second) between 1979 and 1987.

The changes and advances in processor technology have blurred the distinction between the once commonly accepted terms "microcomputer," "minicomputer," and "mainframe." In the recent past, processors could be categorized in this manner on the basis of word architecture (8-bit, 16-bit, 32-bit), processor speed, number of users supported, main memory capacity, mass storage capacity, and cost range. Performance levels for computers falling in the "mainframe" category five years ago are now accepted as being well within the "minicomputer" range today. The increase in the capabilities of desk-top "microcomputers" has further obscured their distinction from "minicomputers." Although the use of these terms to characterize computer processors is still valid, they must be used with care to avoid confusion. For the purpose of this paper, processors commonly used in automated mapping and geographic information systems will be characterized by the criteria in Table 1.

Accompanying the trend of increased processor performance has been a decrease in the size of computer processors and a decrease in environmental controls needed to operate them. Space requirements for housing computer processors of a given performance level have dropped over five times since 1980. Environmental and maintenance limitations have also diminished greatly since the late 1970s. Many powerful minicomputer sys-

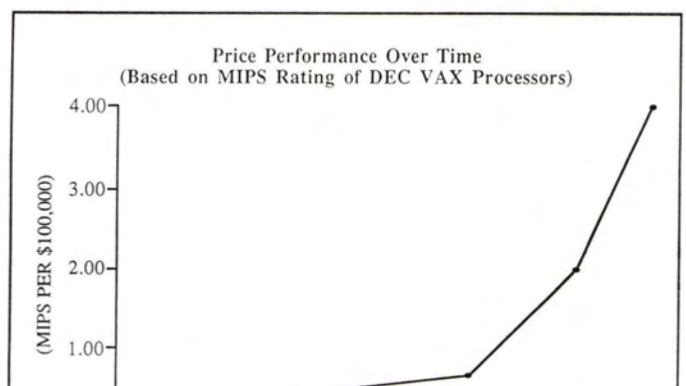

FIG. 1. Computer processing trend.

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TABLE 1. CHARACTERISTICS OF COMPUTER PROCESSOR TYPES

Processor Type	Number of Users	Word Architecture	Main Memory	Cost Range
Micro	Single user	Commonly 8 or 16 bit; recent trend to 32 bit	Commonly 256K to 640 K; recent trend to 1 MB +	$1,500-$10,000
Mini	Up to about 256 devices	Commonly 32-bit	Commonly 2 MB to 64 MB	$10,000-$450,000
Mainframe	Greater than 256	32-bit or greater	Commonly 32MB or greater	Greater than $400,000

tems today are suitable for office environments using existing electrical circuits. A trend toward smaller, low maintenance, easy-to-operate systems will continue in the future.

Major technological developments in processor architecture over the past five years have contributed to the overall increase of processor performance. In particular, parallel processing architectures and reduced instruction set (RISC) processors are resulting in tremendous increases in processor speed for many applications.

Parallel processing involves the use of more than one processor to execute a program more quickly than is possible with a uniprocessor system. Computers using parallel processing architecture execute multiple programs or tasks of the same program simultaneously as opposed to the sequential execution of instructions that occurs in a uniprocessor system (Hornstein, 1986). Theoretically, the overall speed of a system increases proportionally with the number of processors that are included. In practice, however, there is not a one-to-one gain in efficiency because multiple execution of tasks between multiple processors must be coordinated and data must be passed between them, thus entailing some processor overhead. Parallel processing can greatly improve efficiency in executing applications that can be divided into identifiable parts where processing tasks operate on distinct units of a database or with applications using programs with many iterative loops. Various AM/GIS applications involving query or map overlay operations on a spatially distributed database are potential candidates for a move into a parallel processing environment. Programs must often be specially written and compiled to take full advantage of parallel processing techniques (Wilson, 1987).

RISC-based computers use operating systems with simple command sets that allow instructions of a program to execute in one processor cycle. Program compilers on RISC systems are designed to reduce a program's source code into the simple one-cycle instructions that execute very rapidly on RISC systems. RISC-based architecture, although offering increased performance for many applications, is not a panacea. RISC systems require large main memories and special compilers that can translate source code into machine language. Also, some programs that are heavily dependent on floating point operations or other complex functions are not well suited to a RISC environment. (Datapro Research Corporation, 1988.)

Automated mapping and GIS vendors are only beginning to take advantage of developments in parallel processing and RISC architecture. In the future, computer manufacturers must continue to perfect non-traditional approaches like parallel processing and RISC to meet demands for increased computing power at reasonable costs. We can expect that AM/GIS vendors will follow this trend and take advantage of these newer technologies.

TRENDS IN HARDWARE PLATFORMS

Up until recent years, AM/GIS software was almost exclusively run on dedicated minicomputer systems. Although minicomputers are still the primary platform for most installed automated mapping and GIS sites, both mainframe and microcomputer systems are being increasingly used. Table 2 illustrates the trend in processor types supported by vendors of AM/GIS. The acceptance of AM/GIS technology and increases in processor performance have motivated many new software vendors to enter the field in the past two years. In the minicomputer category, the Digital Equipment Corporation VAX series is most frequently used by AM/GIS vendors, although Prime, Data General, Hewlett-Packard, and Wang processors are used as well. IBM processors running the VM or MVS operating systems account for systems supported by mainframe computers.

MICROCOMPUTER TRENDS

AM/GIS vendors have been making increased use of microcomputers as components in their systems. Currently, microcomputers are used in the following manner in AM/GIS:

- "Dumb" graphic workstations attached to a host processor are used to emulate graphic terminals to support digitizing and graphic query questions;
- "Intelligent" workstations attached to a host processor perform some local processing but still require the host processor to perform most complex GIS functions; or
- Independent single-user systems running CAD-oriented mapping or microcomputer GIS packages operate in a stand-alone mode or as data capture stations with batch upload-download capabilities with a host processor.

As Table 2 indicates, there are an increasing number of automated mapping and geographic information system packages being developed for microcomputers. As was discussed previously, the definition of "microcomputer" is changing. Until very recently, high-end microcomputers such as the IBM PC-AT and compatibles used 16-bit chip architectures, relying on operating systems addressing a maximum of 640 kilobytes of RAM, and supporting limited disk storage. These microcomputer systems have been used successfully for database management applications and supporting computer aided drafting (CAD) using software such as AutoCAD, VersaCAD, and other microcomputer CAD packages.

Most current AM/GIS packages running on microcomputers emphasize map entry, edit, and production with limited attribute handling and geographic analysis capability. PC-based packages from GIS vendors such as Environmental Systems Research Institute, Criterion, GeoBased Systems, and ERDAS are scaled-down versions of their minicomputer counterparts. These and

TABLE 2. PROCESSOR SUPPORT BY AM/GIS VENDORS (CUMULATIVE TOTALS)

	Mainframe	Minicomputer	Microcomputer
Pre-1980	0	4	0
1980-81	0	6	0
1982-83	1	12	0
1984-85	1	14	3
1986-87	2	20	16

other microcomputer packages offer impressive database linkages and grid or polygon analysis capability. Their functionality and speed, however, is limited by the power and storage capacity of 16-bit microcomputers and the DOS operating system on which most PC packages are based. Full GIS functionality for complex analysis and mapping functions, which includes ability to handle large, continuous geographical databases, polygon overlay analysis, sophisticated geographic queries, and other spatial analysis, is hindered by the performance limitations of current 16-bit microcomputers, and their operating systems. To some extent, however, the performance of 16-bit microcomputers has been extended through the addition of various co-processors to speed up processing of certain tasks, to drive I/O devices, and to support high resolution interactive graphics (Torres and Shankman, 1987).

The recent development of desktop microcomputers based on 32-bit processors provides a powerful, low cost environment for GIS development. These new microcomputers, using chips from Intel, Motorola, and other manufacturers, provide performance levels that were previously only possible with much more expensive minicomputer systems (Lockwood and Honan, 1987). Several 32-bit processors are now on the market (e.g., Compaq 386, IBM PS/2 Model 70 and 80); however, at this time, they use microcomputer operating systems designed for lower performance 16-bit computers. Operating system software is now becoming available that will be optimized for the 32-bit processing environment and will take advantage of the full capabilities of these new systems.

Although the trend toward more powerful microcomputer systems will not eliminate the need for AM/GIS based on larger computer processors, true AM/GIS functionality will become available, at reasonable cost, to many users who cannot justify acquiring larger systems. The increased functionality of AM/GIS operations on distributed microcomputers on local area networks also will make the microcomputer AM/GIS option attractive to many users.

TRENDS IN MASS STORAGE DEVICES

Significant advances have been made in recent years in mass storage devices using two different technologies: traditional magnetic disk media and optical disk media. For magnetic media, major advances have occurred increasing disk storage density and decreasing data access rates. Since 1980, storage densities of magnetic drives have more than doubled. Over this period of time, removable pack magnetic drives have been nearly eliminated from the market in favor of smaller, fixed media drives which, in many cases, are designed as rack-mountable units in a processor cabinet. For example, the use of high capacity rack mounted drives such as the Digital Equipment Corporatic RA-82 offering over 600 megabytes of storage on a 14-inch disk format is common place in AM/GIS configurations.

Higher processor speeds have required faster I/O rates with mass storage devices, and hardware developers have responded with more efficient read/write mechanisms, higher capacity I/O channels, and intelligent disk controlling devices. AM/GIS developers have quickly made use of these advances to support large geographic databases and real-time processing. Some experts believe that few additional technological advances can be made with magnetic media. Although there may not be additional dramatic advances with magnetic storage media, there will likely be a gradual increase in storage capacity and a decrease in cost over the next decade.

Optical disks represent a new technology in mass storage that has only been employed operationally in computer systems in the last three years. These devices store data by employing a laser to burn small impressions on the disk which are, in turn, read by sensing variations in light reflectance from this surface. Optical disks are capable of extremely high storage densities, as much as two or more gigabytes on a single disk, providing 10 to 50 times the capacity of traditional magnetic storage devices (Dulude, 1988). Current optical disk technology permits a write once-read many (WORM) process in which data can only be written to a portion of the disk once and no data can be erased. WORM technology, which has only recently become cost effective, is most useful for data archiving where large volumes of data must be stored and retrieved but rarely changed. In the AM/GIS environment, WORM technology could prove effective for storing hard copy maps, engineering drawings, scanned aerial photographs, and other geographically-related documents that must retrieved and viewed frequently. Using WORM optical drives, data can be stored and indexed with important spatial and descriptive identifiers for efficient retrieval.

Within the next 12 months, erasable optical disk units will be available. Most of these will likely use a "magneto-optical" technology in which a laser directed at the disk surface shifts the polarity of the magnetic field at that point on the disk. These drives are capable of storage densities as high as WORM drives and allow reading and writing of data (Simpson, 1987).

At this time, the lack of commonly accepted disk format and interface standards and lower disk access rates have inhibited wide-spread use of optical disks in AM/GIS configurations. Optical disk drives will soon begin to augment magnetic disk drives in AM/GIS configurations (McDowell, 1988). Technological improvements and the emerging standards over the next 5 to 10 years will allow erasable optical disks to become popular in AM/GIS configurations.

TRENDS IN AM/GIS CONFIGURATIONS

Automated mapping and geographic information system (AM/GIS) vendors have generally followed three basic conceptual configurations in designing their systems. The three configurations are as follows:

- *Multi-User Centralized*
  The traditional centralized approach to AM/GIS configurations is based on a multi-user, multi-tasking processor to which host-dependent peripheral devices (e.g., graphics terminals, plotters) are connected through local or remote lines (Figure 2a). Users are dependent upon the processing power of the host computer and the database it supports. Peripheral devices are capable of little or no local processing. Some AM/GIS sites using minicomputers connect asynchronous devices directly to the host through RS-232 cables. A more sophisticated and efficient approach used by many installations is to support peripheral devices on a high speed local area network (LAN) controlled by the host. The peripherals are connected to the LAN through device servers which control I/O processing (see Figure 2b). Centralized configurations usually have lower startup costs than distributed configurations and system administration is less complex. However, centralized systems dependent on a single processor are less amendable to incremental upgrades and are more likely to impact user response times than systems dedicated to particular groups of users.
- *Multi-User Distributed*
  Advances in computer hardware, software, and communications have fueled a trend toward distributed computer configurations in which processing power, and sometimes data, are decentralized across a computer network (Figure 3). Users of the network have access to the resources of the entire network. This approach has efficiencies because it allows processing power to be placed at the user's location, thus decreasing delays in response time that can occur more frequently on centralized systems (Hanson, 1987). In a distributed environment, new processors can be added incrementally as new users and new applications demand. Distributed systems can make effective use of high-speed LANs, although processors can be connected remotely. Special network software, usually provided by the hardware vendor, controls transactions on the network. Often, a distributed system has the advantage of being more acceptable in a complex institutional environment where different organizational entities can better justify operating with a distributed processor. The main disadvantages

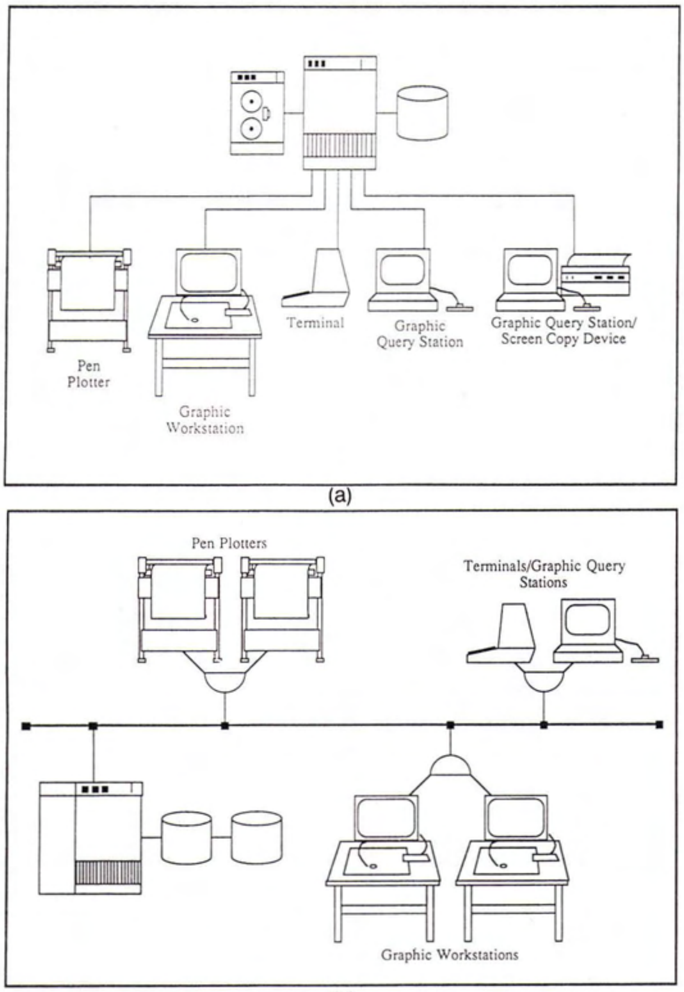

FIG. 2. (a) Centralized configuration using synchronous connections. (b) Centralized configuration using local area network.

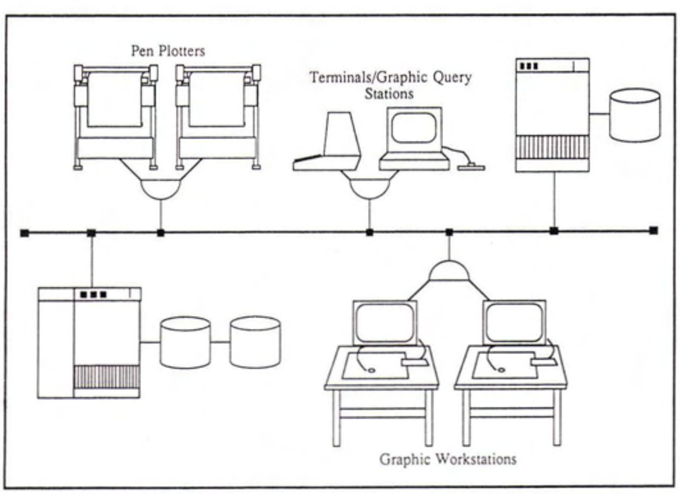

FIG. 3. Multiple processors and peripheral devices on a local area area network.

of a distributed configuration are the higher startup costs, possible duplication of databases and technical resources, and a more complex environment for system administrative tasks.

- *Microcomputer Systems*

Microcomputers have seen increased use in the last three years for CAD oriented mapping applications and more complex geographic information system applications. A number of vendors, notably Environmental Systems Research Institute, Criterion, Inc., and GeoBased Systems, Inc., have developed microcomputer software with many GIS capabilities. New generation microcomputers using 32-bit chips will provide powerful platforms for continued GIS development at the microcomputer level. Most microcomputer systems in use today are single-user systems consisting of the microcomputer with hard disk storage, a digitizing tablet, plotter, and perhaps other peripheral devices attached. Single user microcomputer systems will increase in popularity in the future, but the trend will be toward systems comprised of multiple microcomputer workstations connected on a LAN to allow for efficient access to common data and peripheral devices (Figure 4).

WORKSTATION TRENDS

Over the past decade, there have been major changes in the graphic workstation environment of automated mapping and geographic information systems (Thomas and Croswell, 1987). Workstation trends have paralleled the overall increase in the performance/cost ratio of computer processors. Major workstation trends since the mid-1970s include the following:

- Replacement of vector-based storage tube graphic monitors with raster-based CRT monitors,
- Increase in resolution and color capability of raster-based CRT monitors,
- Decrease in popularity of dual-screen graphic workstations in favor of single screen workstations with windowing capability, and
- Increase in local-processing capability.

In the past three years, there has been a pronounced shift from the use of host-dependent graphic terminals as workstations for AM/GIS data capture and manipulation to intelligent workstations based on 32-bit processors. These intelligent workstations, used either in a stand-alone mode or as part of a network, have considerable local processing and, usually, local mass storage capability (Figure 5).

This increased popularity of intelligent workstations is part of the trend toward distributed system configurations. Developers of software for AM/GIS have made effective use of high-performance workstations (multi-tasking 32-bit processors) such as the DEC VAXstation/GPX, VAXstation 2000 and 3000; Hewlett-Packard 9000 series; Apollo Domain series; Sun 3 and 4 series; and others (Burdick, 1987). These intelligent workstation platforms are differentiated from older microcomputer workstations using 16-bit processor technology and single-tasking capabilities. As AM/GIS vendors take advantage of 32-bit micro-

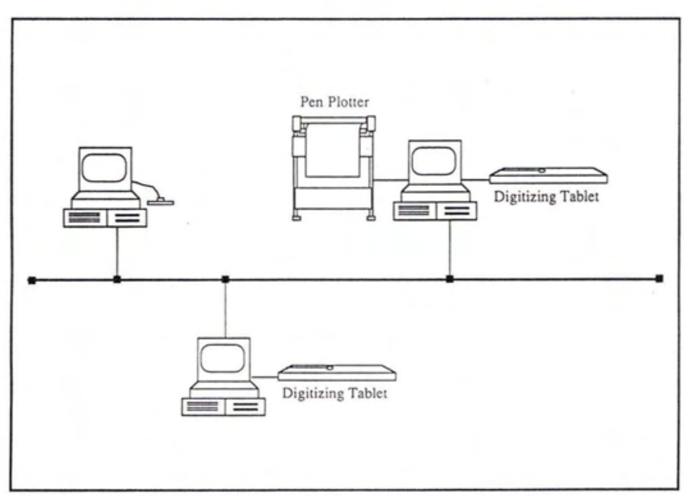

FIG. 4. Microcomputer workstations on a local network.

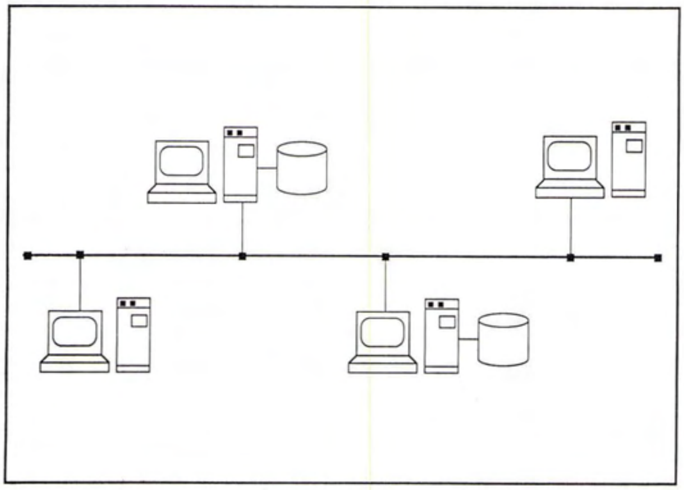

FIG. 5. Intelligent workstations on a local area network.

computers as workstation platforms, the clear distinction between "high-performance" (intelligent 32-bit) and "microcomputer" workstations will diminish.

As the cost of computing power continues to drop, there will be an increased use of high-performance graphic workstations in AM/GIS configurations. This trend toward workstations with local processing and local storage capability, however, will not eliminate the use of host-dependent graphic terminals in AM/GIS configurations. Host-dependent terminals with little local processing capability are inexpensive and provide an effective platform for many graphic query and editing tasks not requiring local processing or large data storage.

TRENDS IN HARD COPY GRAPHIC OUTPUT DEVICES

Common devices for generating hard copy graphic output in AM/GIS include pen plotters, large format electrostatic plotters, and screen copy devices producing output from images on workstation monitors. Advances in the capabilities of these devices accompanied by a reduction in cost have kept pace with the increasing demands of AM/GIS users (Laroff, 1986; Victor, 1987).

PEN PLOTTERS

For most of the history of AM/GIS and computer graphics systems, pen plotters were the only commonly used devices for generating large-format hard-copy vector graphic output. Common frustrations voiced by users of pen plotters in the 1970s and early 1980s include the slow plotting speed and the tendency for pens to clot, requiring considerable monitoring of the plotter during operation. While pen plotters are still slow in comparison to raster-based plotting devices, significant advances have occurred during the 1980s:

- Shift from flat-bed plotters to drum-feed plotters accepting cut sheets and roll media
- Increase in average plot speed from about 10 inches per second to over 24 inches per second
- Use of on-board vector optimizers to increase the efficiency of plotting operations and off-load processing from the host
- Ability to accept a wider variety of plotting media
- Advances in plotter inks combining quick-dry, low-viscosity properties and increased color choices
- Increase in the number of pens supported
- Features for easy maintenance like automatic pen-capping
- Average drop in cost of about 30 percent since the early 1980's.

Large format pen plotters commonly used in AM/GIS configurations are manufactured by Calcomp, Houston Instruments, Hewlett-Packard, and other companies. List cost for drum-feed plotters capable of generating 36-inch width plots typically sell for about $7,000 to $12,000.

Although there are no major technological advances that can be expected in pen plotters in the near future, they will continue to be important components in AM/GIS configurations. Their ability to provide high quality, color graphic output at relatively low-cost will allow them to maintain an important place in AM/GIS configurations. The ratio of pen plotters to electrostatic plotting devices in AM/GIS installations, however, will gradually decrease in the future.

ELECTROSTATIC PLOTTERS

Electrostatic plotters produce hard copy plots from vector files that have first been converted to a raster format. The image is plotted by passing the plotting media through an array of nibs that selectively apply electrical charges to the media's surface. It then passes through a liquid toner which adheres to the charged portions of the media. Electrostatic plotters have the advantage of producing large format, hard copy plots quickly in comparison to pen plotters. Also, electrostatic plotters require relatively little attendance by an operator. Traditionally, the disadvantage of electrostatic plotting devices has been their low resolution as compared to pen plotters ("stair step" appearance of raster format apparent on the plot), lack of color capability, and relatively high cost. The popularity of these devices among users has provided the impetus that, in the last three years, has greatly diminished these disadvantages and made electrostatic plotters a viable alternative to pen plotters in many AM/GIS environments. Advances in electrostatic plotter technology have been exhibited in the following areas:

- Increase in resolution from a standard 200 dots per inch in 1985 to an average of 400 dots per inch today,
- Development of color plotting capability,
- Standard use of on-board rasterizers to remove the load on the host computer for processing vector files for plotting, and
- Average decrease in cost of about 50 percent since 1986.

Most color electrostatic plotters available today require multiple passes (one for each of three primary colors plus black) through the charging and toner process. Steady improvements in the color electrostatic plotting procedures will soon make single pass devices popular and eliminate problems that sometimes occur with color registration and distortion of the plotting media.

SCREEN COPY DEVICES

Screen copy devices connect to the port of a graphics workstation to produce a hard copy (usually page size) of the graphic or text image on the workstation monitor. Screen copy devices are used both to generate proof plots for use in editing and also for final plots to be used in documents or presentations. Trends in screen copy devices have been toward the use of a larger variety of technologies to generate the screen output. Today, screen copy devices use impact, electrostatic, thermal transfer, and ink-jet printing technologies to generate output. Screen copy devices using all of these different approaches will continue to be available to users at decreased cost.

Trends in screen copy devices have included higher resolution, increased use of color, and a gradual drop in cost. Over the past year, devices employing color electrostatic, ink-jet, and thermal transfer technologies have seen the greatest increase in popularity among AM/GIS users. Manufacturers such as Tektronix, IBM, Versatec, Benson, and Seiko offer screen copy devices using these technologies with a typical cost range of $4,000 to $7,000. Resolution ranges from about 150 dots per inch to about 300 dots per inch. Cost reductions in the 30 to 50 percent range and increases in resolution up to a maximum of about 400 dots per inch can be expected over the next two years. Although laser printers have not yet been adopted generally as screen copy devices for AM/GIS workstations, their use will likely increase in the future as color laser technology becomes available at a reasonable cost. Color laser printers have become available over the past year and, within two years, their cost will likely be competitive with other color hard copy devices.

Color hard copy devices employing new technologies such as light sensitive micro-encapsulation media will begin to emerge over the next several years. Several companies are experimenting with this technique in which capsules of colored dyes on a coated paper are exposed to light forming a color image. This technology is inexpensive and may extend the range of colors available in hard copy output. AM/GIS vendors will likely take advantage of these devices when they become available.

Other Output Devices

There are several recent developments in computer output devices, seeing only minimal use in AM/GIS applications today, that will likely have an impact in the future. These include so called "softplot" display devices and output devices producing non-traditional products like microfilm and 35-mm slides.

Softplot systems produce large format (up to 34 inches) high resolution displays. They can be used in the editing process to reduce the need to repetitively generate hard copy output on pen or electrostatic plotters. These devices use a laser driven, liquid crystal "light valve" approach to produce color displays at resolutions in the 2000 line/inch range. Plotting times are very quick, thus allowing this device to be used in a dynamic graphic editing environment. Greyhawk Systems, Inc., now offers a reasonably priced unit using this technology (Stepner and Kahn, 1986).

Other output devices that are beginning to see use in the mapping and GIS community are computer output microfilm (COM) devices and various color film recording devices. COM devices can directly convert digital map files into high resolution microfilm media. Maps can be efficiently stored and archived in microfilm format, and producing large format hard copies through specialized microfilm printers is inexpensive. For presentation purposes, devices are available to directly produce color slides from digital map files (Gelatt, 1986; Kinnucan, 1987).

CONCLUSION

The technological advances in computer hardware have directly impacted development in automated mapping and geographic information systems. These advances include a dramatic increase in computer processor performance, the development of powerful, low-cost workstations, higher-density storage devices, and increased capabilities for producing cost-effective, high quality hard copy outputs. Users will continue to be offered flexibility in processor configurations that are customized for particular environments and demands on performance.

Incremental improvements in the power and flexibility of processors and input/output peripheral devices will continue. As software vendors respond to this dynamic hardware environment, users will be offered greater performance at a lower hardware cost.

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