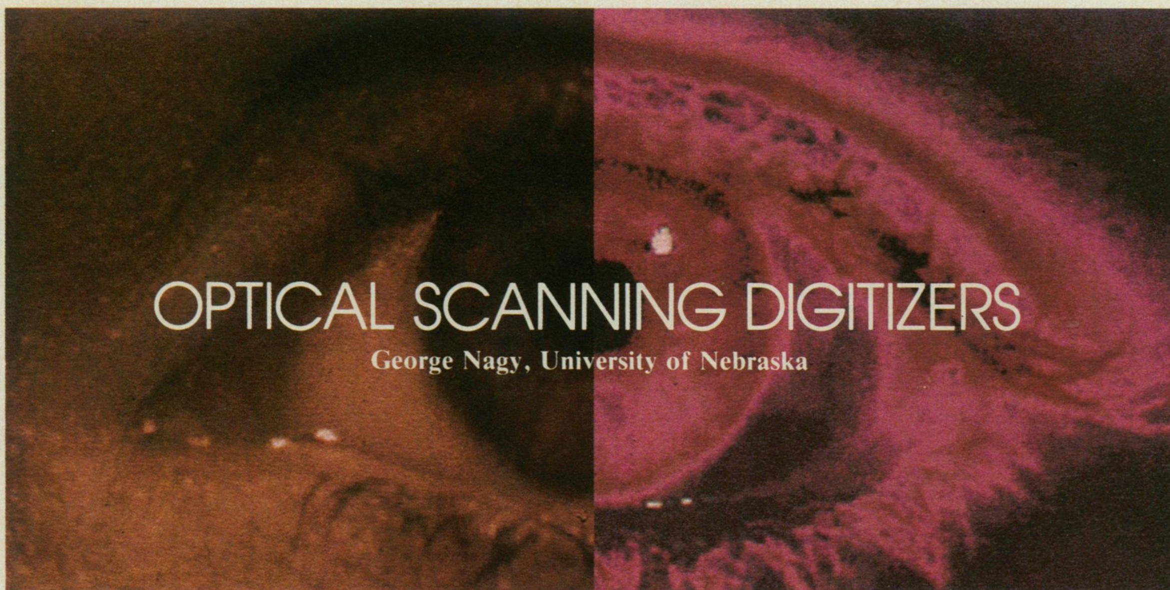
Electronic eyes are everywhere, scrutinizing documents, blood slides, even pizza crusts. With this potpourri of applications, scanners may become as commonplace as today's photographic camera.



OPTICAL SCANNING DIGITIZERS

George Nagy, University of Nebraska

Optical scanners, or scanning digitizers, are used to convert a picture into an array of numbers representing the positional distribution of optical density within the picture. The relation between the computer-readable output of the optical scanner and the original image is critical to automatic pattern recognition and digital image processing.

Optical scanners can be thought of as eyes for computers. They are used in optical character recognition; computer-aided design and drafting; biomedical applications; geographic data processing, including remote sensing; facsimile communications; printing and publishing; and experimental physical science. (See center insert on applications.) Commercially, the most widespread application of optical scanners is optical character recognition. Virtually all earlier products were based on mechanical scanners, but the current trend is solid-state transducers. At the same time, the implementation of recognition algorithms is shifting from special-purpose, hard-wired logic to microprocessor-based software. Consequently, large, high-speed OCR systems designed to displace several hundred data entry specialists are gradually giving way to devices that can be cost-justified even in organizations employing only a few data entry personnel. OCR input devices may eventually be attached to even the smallest computer systems, complementing the standard keyboard for alphanumeric entry.

To recognize a single character, we need only examine a 30×30 picture element array; the exact spatial relation between successive characters is unimportant. Optical scanners designed for character recognition are, therefore, generally not suitable for image input. Image scanners are, however, finding their way into OCR systems designed for less restrictive applications, such as the processing of documents containing gray-scale illustrations, line drawings, and a mix of type fonts.[1]

Engineering applications require the digitization of line drawings with predominantly straight-line segments, such as detail, assembly, structural, and architectural drawings; logic, circuit, and wiring diagrams; printed circuit, wafer, and chip layouts; and utility maps (in-plant and cross-country cabling, piping and pipelines, conduits, ducts, transmission lines). Ink on mylar has sufficient contrast to allow use of a scanner with only binary (black and white) amplitude output, but variations in reflectance make pencil drawings difficult to scan.

Many engineering applications require a scanner capable of handling a wide range of drawing sizes and a mix of line and alphabetic information. A typical floor plan for a telephone company central office, for example, may contain more than 6000 alphanumeric symbols. No systems currently available can convert such drawings to computer-readable form without extensive interactive editing, but simple logic diagrams, drawn according to carefully prepared specifications, are tractable. The conversion of existing drawing files, some of which have a useful life of up to 50 years, is likely to take on additional importance with the proliferation of CAD/CAM technology.[2]

Inspection and robot vision differ somewhat from other applications because 3-D objects form the target. Since this topic was the subject of an excellent special issue of *Computer* in May 1980, nothing further will be said about it here.[3]

The most publicized biomedical applications of scanners are in tomography. Here, the transmittance of body

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parts to X-rays or ultrasound in various directions is converted directly to digital form for subsequent 3-D reconstruction. Cell counters are used routinely in hematology and cytology. Less specialized equipment, usually based on television-camera technology, is used to convert radiographic film, histological sections, or microscope slides for research and diagnostic screening.[4]

In geographic data processing and natural resource management, both line drawings (such as topographic maps, soil surveys, bathyspheric charts, and maps of stream or transportation networks) and image data (usually in the form of aerial photographs) must be entered. In many geographic applications, color is an important element. The multispectral scanners and vidicon cameras used to obtain digitized representations of large segments of the earth's surface are also specialized optical scanners. In some respects, satellite scanners represent the acme of scanner technology.[5]

Among the major contributors to optical scanner technology is the printing industry. Since color illustrations are produced as a sequence of impressions with printing plates inked in various colors, large, high-speed scanners were developed many years ago to prepare color-separation plates for gravure, letter-press, and offset printing. Although these analog instruments simply reproduced each color component of the desired illustrations, the addition of an analog-to-digital converter transformed them into high-performance, relatively fast image-digitizing devices. With the advent of high-resolution digital matrix printers (laser typesetters) and the rapid introduction of computers in other segments of the industry, most publication operations became eligible for all-digital technology.

Analog facsimile transceivers have been in widespread commercial use for many years, transmitting black-and-white images over the telephone network. The optical scanners used in this application generally have fairly low spatial sampling rates (three to eight elements per millimeter), but the trend is towards higher sampling rates and end-to-end digital transmission through public data networks. With the obvious commercial (and perhaps domestic) appeal of digital facsimile, we should soon see a large variety of economical page-format scanners.[6]

Wherever photographic observations are used in physics, chemistry, and biology, optical scanners can increase accuracy and reduce drudgery. An early high-volume application was quantifying the immense amount of data obtained in bubble-chamber, cloud-chamber, and spark-chamber experiments in high-energy physics. Scanners are also used in astronomy, spectroscopy, crystallography, gel electrophoresis, and photomicrography. With relatively inexpensive commercial scanners, we may see less effort devoted to constructing a specialized instrument for each application.

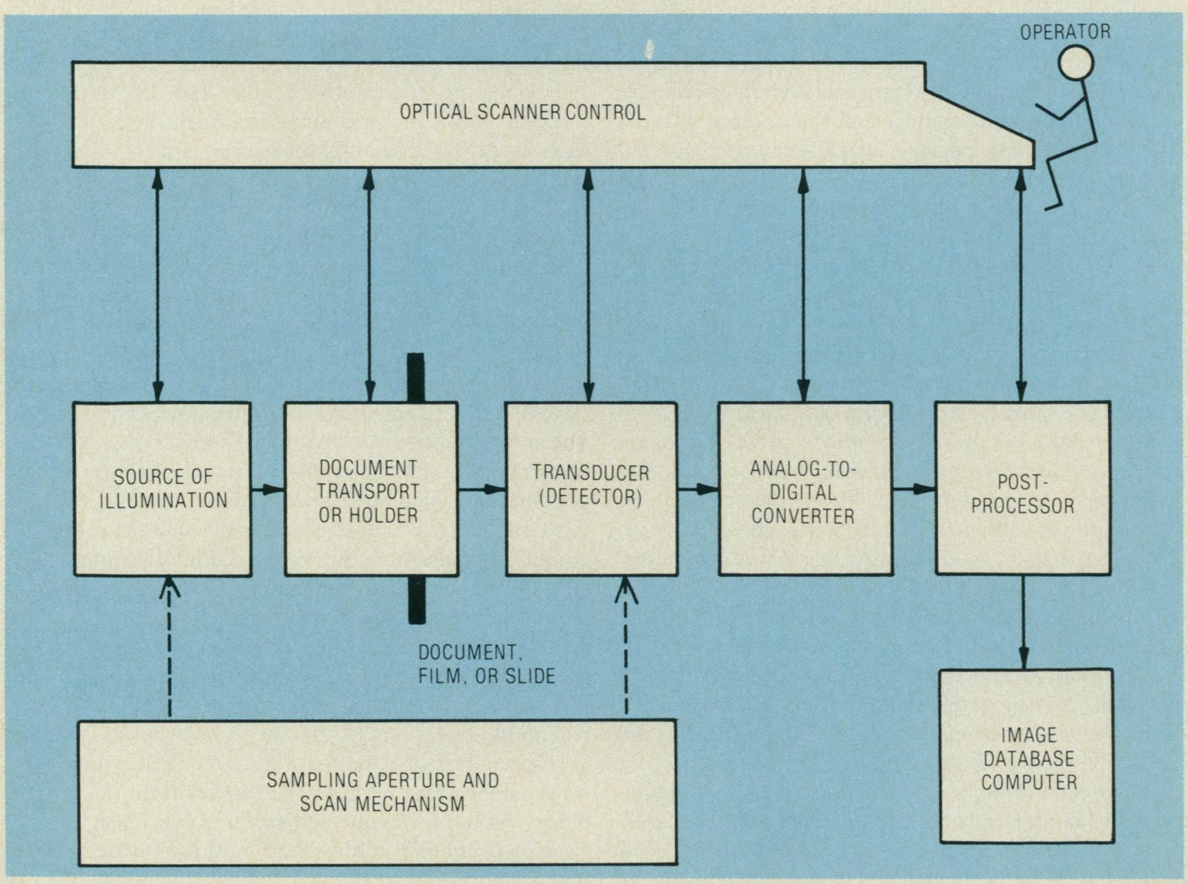


Figure 1. Functional components of an optical scanner. Regardless of the type of scanner, these basic functions stay the same.

In short, we have a bewildering array of potential applications for scanners, in addition to the many well-established uses. Since few services for optical scanning are available, those who wish to digitize an image must acquire a scanner. The purpose of this article is to give information on the mode of operation, specification, evaluation, and limitations of various automatic digitizers, with an eye towards providing some kind of selection criteria.

Scanner anatomy

Although scanners come in a wide variety of sizes and shapes, every scanner has the functional components shown in Figure 1. The spatial sampling intrinsic to image digitization is performed by measuring the light transmitted through or reflected from a small part of the image. The sampling-spot-distribution function determines how the image contributes to each element of the digital output array. The distribution this "aperture" function represents is due either to the intensity of the illumination or to the sensitivity of the light detector. The output of the detector is the convolution of the *point-spread* function (which is the mirror image of the sampling-spot-distribution function) with the image (Figure 2).

The transmittance or reflectance must be determined separately at every sample position in the image. The duality between the source of light and the detector, mentioned above, also applies to the scanning operation, which may be performed in one of two ways. The first is to move the spot of light from picture element to picture element and measure the entire amount reflected or transmitted. The second is to illuminate the entire image and observe only the light reflected or transmitted from one picture element at a time. If the sampling aperture and the scan mechanism, or driver, are associated with the light source, the device is called a *flying-spot* scanner (Figure 3a); if the sampling aperture and the scan driver are part of the light collector, it is called a *flying-aperture* scanner (Figure 3b).

A CRT scanner and a LED array scanner are examples of flying-spot scanners. The beam in a CRT is deflected to illuminate each picture element in turn. Television cameras and photodiode array scanners are examples of flying-aperture scanners. Here, the entire object is externally illuminated. We can, of course, construct scanners where the field of view of the illumination source *and* the light detector are effectively restricted by an aperture and scanned relative to the image. High-precision microdensitometers typically use this hybrid approach.

The role of the optical system is to channel the light from the source of illumination to the light collector or transducer by way of the image. The optical system consists of lenses, mirrors, prisms, or optical fibers and may also constitute an integral part of the scan mechanism

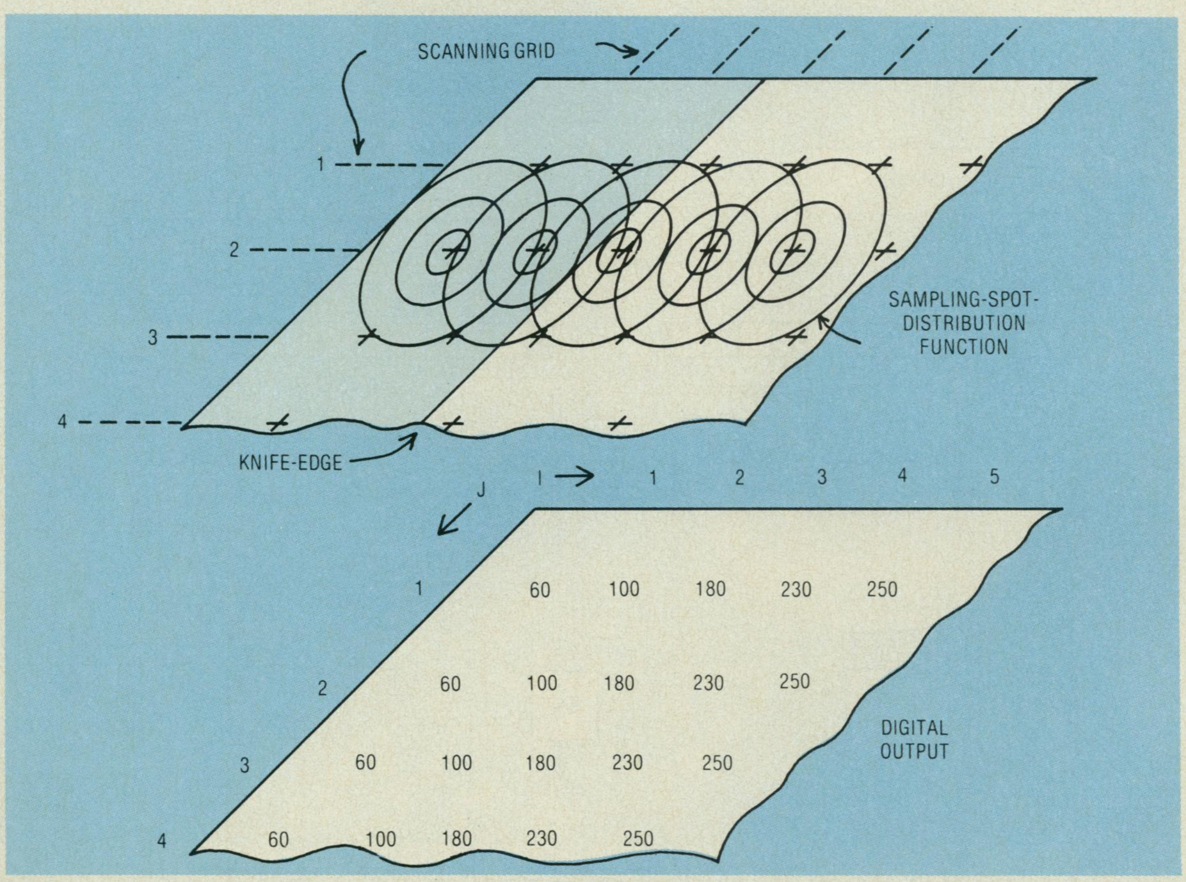


Figure 2. Spatial sampling across a "knife-edge," showing the equal-intensity contours of the spot distribution. A knife-edge is a sharp black-to-white or white-to-black transition.

itself, as in the rotating-mirror and moving-fiber scanners used in OCR. The optical system is commonly used to compensate for size differences between the field of illumination, the image, and the transducer. Some variable-format scanners accommodate 35-mm camera lenses.

Transmission scanners, also called film scanners, minimize light scattering. Consequently, they are generally more accurate and have simpler optical paths than reflection scanners. Uniform illumination is also easier to obtain with film scanners. However, the distortion introduced in converting opaque images to film may outweigh the gain obtained by using a film scanner.[7]

Flying-aperture scanners require a uniform and accurately controlled field of illumination. Linear rather than point sources of light, condenser lenses, light boxes with multiple reflections, and diffusers such as ground glass are used to achieve the desired uniformity. The most accurate photometric results can be obtained only with microdensitometers. With these scanners, the relative positions of the illumination source and the detector are fixed during digitization, and the optical path is constant.

The transducer converts the light impinging upon it into an electrical signal (charge, voltage, or current). Ideally, the amplitude of the electric signal is proportional to the intensity of the light, but all physical detectors have a *dark threshold,* below which no measurable signal is generated, and a *saturation threshold,* beyond which a further increase in light produces no increase in the signal. The relation of the signal amplitude to the light intensity is usually nonlinear even in the working range of the device. Examples of photoelectronic sensors used in optical scanners are the photosensitive surfaces in television cameras, photomultiplier tubes, and photodiodes and phototransistors, including charge-coupled and charge-injection devices.[8]

The analog-to-digital converter circuit quantizes the analog electrical signal into a digital form suitable for storage, transmission, or processing. Depending on the application, either the *differential* (step-to-step) or the *integral* (overall) linearity of quantization may be more important. With some ADCs the conversion is virtually instantaneous; with others, the signal is integrated to increase the signal-to-noise ratio. In many television cameras and solid-state detector arrays, the transducer itself integrates the light input over the entire scan cycle prior to quantization.

The ADC may contain a digital buffer for parallel output. For gray-scale operation, an eight-bit (256 level) output is common, even if the photometric accuracy of the system does not warrant such precision. The numerical output may bear either a linear or a logarithmic relation to the light intensity, depending on whether the reflectance, transmittance, or optical density of the im-

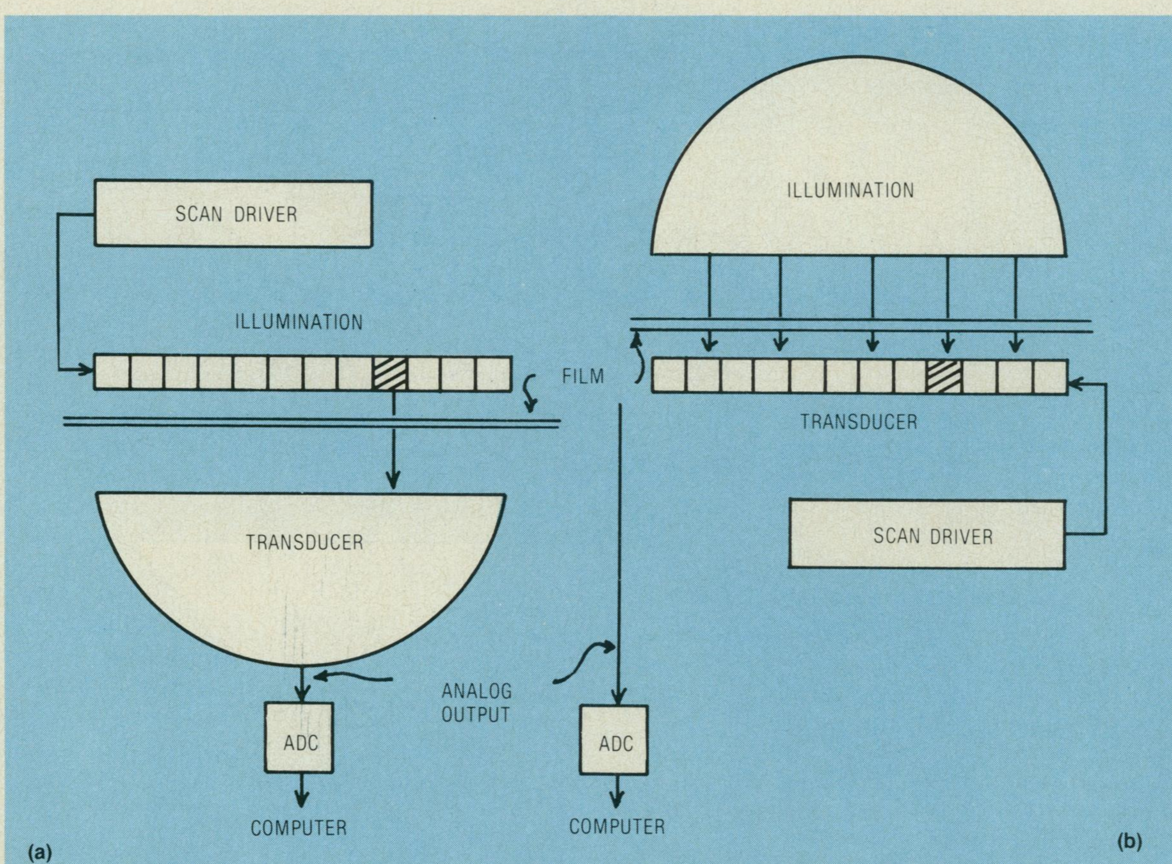


Figure 3. Schematic of a flying-spot transparency scanner (a) and a flying-aperture transparency scanner (b). In the flyng-spot scanner, the sampling aperture and the scan driver are associated with the light source. In the flying-aperture scanner, they are associated with the light collector.

age is of interest. The conversion can also compensate for the nonlinearity of the detector.

In low-volume or large-format applications, each document is manually positioned for scanning. In such systems, we need a means of accurately positioning the document. Repositioning is easier when the entire document is (1) scanned in a stationary position, as with most television-camera-based devices, or (2) mounted on an accurately controlled platen. Ease of mounting the image is important; with some devices positioning the document correctly takes longer than scanning it.

In high-speed document transports, such as those used in OCR, one scan direction is usually obtained by a stepped friction feed through rollers, which may introduce skew or scan-to-scan variations in spacing. In drum scanners, the document can be held in place by a vacuum. The document transport, like most other components, is generally simpler in transmission, or film, scanners, where a sprocket drive can be used for positive positioning.

Selecting a scanner

Services for optical scanning are not yet widely available, so if we wish to digitize images we usually have to acquire a scanner. Specifications for scanners are presented in terms of I/O characteristics only; the contribution of an individual scanner is not described. This functional rather than device-dependent approach is preferable because we can then measure scanner characteristics with only appropriately selected test patterns and the digital output of the system itself.[9]

Spatial sampling characteristics. How much detail will be lost by digitization? The answer depends on the picture to be digitized, the spatial sampling rate, the spot size, and the sensitivity, linearity, and signal-to-noise ratio of the detector and associated electronics. The word *resolution* generally refers to the spacing of the sampling grid, the size of the sampling spot, or the smallest object capable of being discriminated. (The third definition is based on a concept of resolving power borrowed from the tradition of image-forming devices such as lenses and electro-optical image intensifiers.)

The spacing of the sampling grid is usually referenced to the object being scanned, although in applications involving telescope optics, such as airborne or star scanners, an angular specification is more appropriate. Another measure of the sampling grid—one that is independent of optical system magnification—is the number of scan lines and the number of samples per scan line per frame. For documents normally viewed without magnification, the useful range is from 25 to 250 microns. Fine pencil lines are approximately 100 microns wide. At a 25 micron spacing, a letter-size document generates 100 million picture elements; anything finer than that is impossible to process and store. We can recognize typewritten characters when reproduced by facsimile devices with 200-micron spacing, but OCR requires about double the sampling rate. Below one micron, diffraction phenomena impose a limit to digitization using visible light.[10,11]

The sampling spot can be characterized by its two-dimensional *modulation transfer function*. The MTF is the modulus of the complex Fourier transform of the point-spread function, which is the output of the transducer corresponding to an infinitely small, infinitely bright spot in the image (a Dirac delta function). The MTF represents the sinusoidal spatial frequency response of the analog components of the scanner, and it should extend beyond the highest spatial frequency of interest in the image. The spatial sampling rate, in turn, must be above the Nyquist frequency (*twice* the maximum image frequency) to avoid aliasing. The unit of spatial frequency is cycles per millimeter (line pairs per millimeter); in the television industry, lines per millimeter (half-cycles per millimeter) are sometimes used.[12-17]

The response to an infinitely thin line is called the *line-spread* function. Its integral, the *step response*, is the convolution of the sampling spot or aperture with a Heaviside step function. The step-response after sampling and quantization can be measured directly by translating a *knife-edge* (a sharp, black-to-white or white-to-black transition) under the field-of-view corresponding to a single element of the digital output array and plotting the output corresponding to each position of the test pattern. The step-response can be estimated much more rapidly and conveniently by simply scanning a knife-edge and plotting the digital values obtained across the edge. Most gray-level scanners operate above the minimum sampling rate, so several points are obtained between the "all-black" and "all-white" responses. The approximation is valid to the extent that the scanner characteristics are locally uniform. The horizontal step response of a scanner for opaque (versus transparent) documents is shown in Figure 4.

The displacement between the amplitude values corresponding to the 10-percent and 90-percent points on the curve is called the *spot diameter*. In a well-designed system, the sample spacing is about half the spot diameter. The ratio between the horizontal and vertical spot diameters is the eccentricity of the spot; in most scanners,

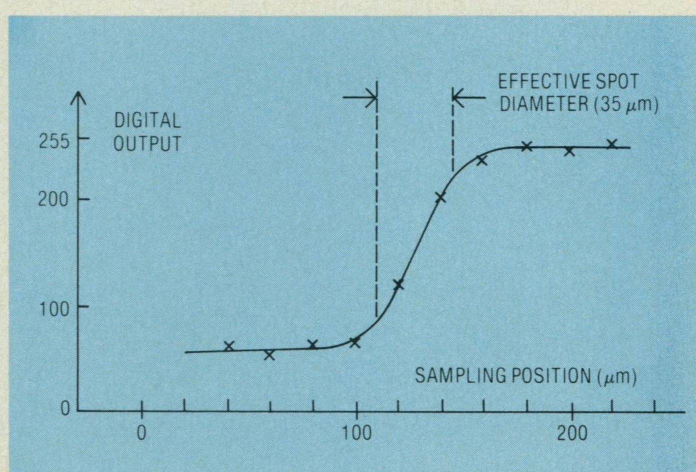


Figure 4. Step response of a document scanner operated at 50 samples per millimeter.

the spot is circular or square, but line segments are more easily detected and symbols are more easily separated with an elongated spot. The amplitude cross sections of the scanning spot can also be obtained using standard optical target patterns with calibrated bar or star charts.

Geometric characteristics. How accurately can we expect to reproduce the positions of the picture elements relative to one another or relative to some external frame of reference? To determine accuracy we must consider geometric linearity, stability, and format.

Geometric linearity is the deviation from the ideal that occurs when a perfect straight line is reproduced. For instance, 0.1 percent geometric linearity means that the digitized version of a 10-cm line segment can deviate from its calculated position at most by the number of pixels needed to make up 0.1 mm. Geometric linearity is most easily measured using an accurately drawn grid and locating the resulting pattern on a printout of the digitized output. The linearity in the two coordinate directions may differ, particularly if a mechanical transport is used for one scan direction. The highest quality microdensitometers typically guarantee a maximum deviation of 1 micron root mean square per centimeter. For precision instruments, the deviation of the sampling spot from its nominal position can be plotted in a form resembling charts of wind direction and velocity. The geometric fidelity can be improved by feedback using fiducial marks recorded either directly on the document or on some component of the optical system. Alternatively, the deviations can be stored in a table and corrected by resampling.

The extent to which the scanner's geometric linearity changes is called its *stability* or repeatability. Short-term stability is the reproducibility of the output in a given experiment without dismounting the document, slide, or film. Long-term stability is the reproducibility from experiment to experiment and is largely a function of the document holder or transport.

The *format* is simply the maximum dimensions of an image that can be scanned with an instrument.

Photometric (radiometric) characteristics. How faithfully are the shades of gray represented in the digitized image? The photometric response curve shows the digital output of the scanner as a function of the reflectance, transmittance, or optical density of the input image (Figure 5). This curve does not depend on the sampling aperture characteristics, but can be a function of position within the frame. It can be measured using a calibrated gray wedge or step-tablet obtainable (but at a suprisingly high cost) from photographic suppliers, and it can be linearized through post-processing.

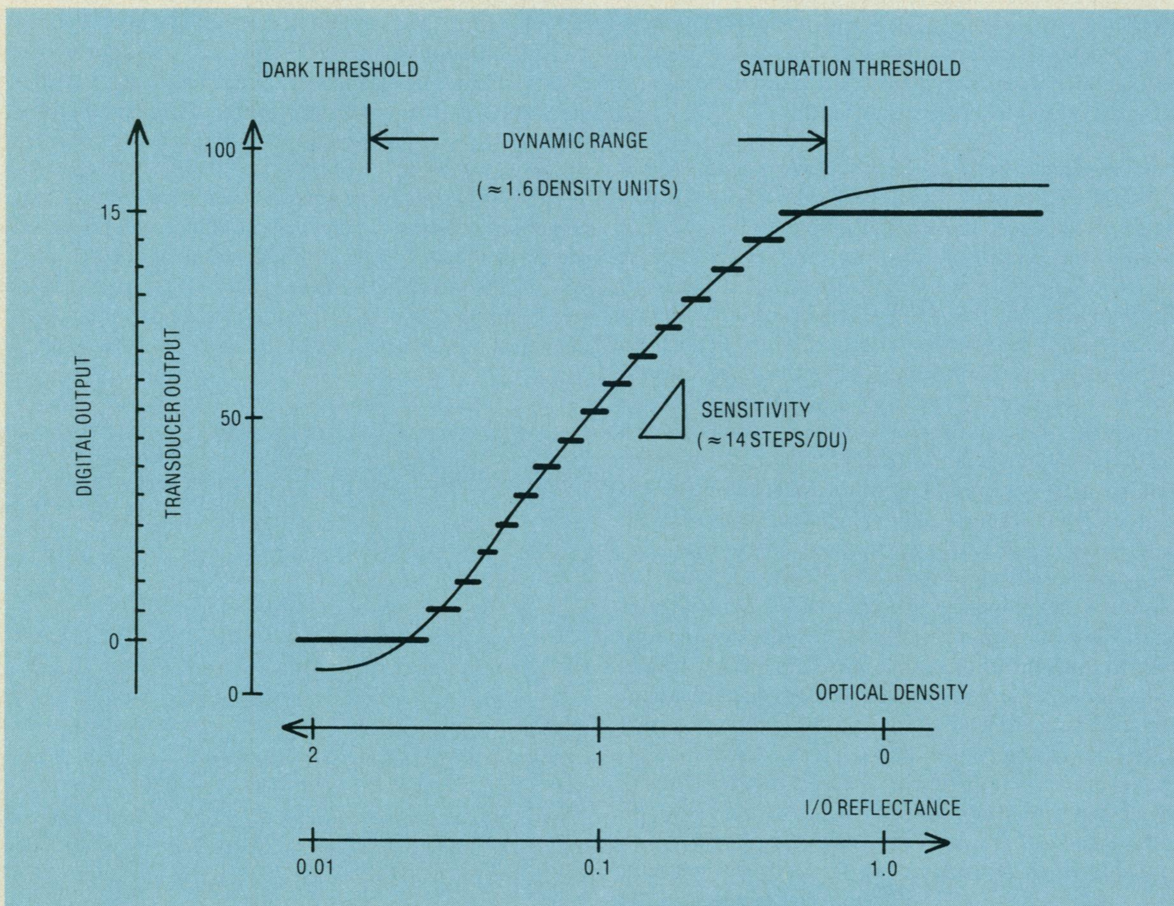


Figure 5. Photometric response curve and digital output of a 16-level scanner adjusted to measure optical density.

A number of factors make up photometric characteristics, including range, sensitivity, uniformity, stability, repeatability, and spectral response.

The *dynamic range* is the difference in optical density corresponding to the saturation and dark thresholds of the device. The dynamic range cannot be extended by post-processing. The range of ordinary photographic prints is just above one optical density unit, while that of negatives can easily reach three units (1000:1 variation in transparency).

The *sensitivity* is the maximum slope of the photometric response curve, and indicates the smallest measurable difference in gray levels. The sensitivity can be adjusted either externally or by feedback depending on the darkest and lightest picture elements encountered in a particular image. Since noise may change the actual response to a given gray level from that indicated by the photometric response curve, the sensitivity indicates only a bound obtainable by repeated measuring. The number of times an image must be scanned to obtain a given photometric accuracy can be estimated from the signal-to-noise ratio or root mean square deviation of the digital output from its average value for a fixed input. The signal-to-noise ratio depends on position, optical density, and integration time.

Photometric uniformity (shading) is a measure of the variation in photometric response from point to point in the image. If, for example, the maximum difference in reflectance between two areas of the image that produce equal output is 5 percent of the dynamic range of the scanner, then the shading is 5 percent. The shading can depend on gray level as well as position; its extreme value is usually found by comparing the center and corner outputs for a uniform image with an optical density just below the knee of the saturation curve. Shading can be corrected by post-processing.

Photometric stability (repeatability) is a measure of the long-term variability of the photometric response function at a specified point. This measure is usually averaged over the entire format to obtain a root mean square value.

The *spectral transfer function* is the amplitude response of the scanner as a function of the wavelength of the reflected or transmitted light. The output depends, of course, on both the spectral composition of the document and on the spectral match between the illumination and the transducer. Some optical scanners produce multiple color representations in a single pass, while others require multiple passes with different filters or source-detector combinations.

Overall system characteristics. What else should we worry about? Many of the system specifications for optical scanners are similar to those for other substantial electronic instrumentation and do not require extensive discussion here. They include quality of documentation, stability, reliability, maintainability, dependence on environmental factors such as temperature, humidity, and building vibration, and ease of interfacing to general-purpose computers and peripherals.

Until recently, optical scanners had innumerable switches, knobs, and dials, but most current products are designed to interface with computers, and the operational parameters can be set and read out with software control. Calibration and monitoring are consequently much easier. All important settings can be recorded with the digitized data. Throughput can also be increased, since areas with dense information can be scanned using high resolution, and information corresponding to blank areas need not be processed at all.

If scanner characteristics are known, photometric and geometric nonlinearities can be corrected, and information can be extracted either automatically or interactively. Examples of useful operations are high-frequency restoration, amplitude linearization, color balance, noise removal (suppressing isolated fragments), line and edge detection, and symbol extraction. Since many of these operations involve neighborhood combinations of picture elements, they tend to be very time consuming and may have to be performed off-line on a large or dedicated computer or on a specialized processor. The total volume of data generated for a given image is proportional to the size of the image, the number of amplitude levels, and the spatial sampling frequency. The data can be streamed directly to a storage device that is accessible to the file-manipulation software required for operational processing of image data. The database system is at this time often the weak link in source-image processing.

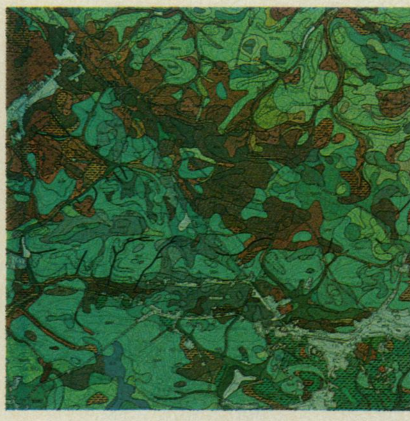
The low-level software provided with many scanners includes routines for scanner control, data formatting and output buffering, communications protocols, photometric compensation, digital filtering (image restoration and enhancement), and geometric distortion removal. The availability of tested software for post-processing is, of course, a definite plus because such software must be written in tight, low-level code. Calibration, diagnostic, and data-compression programs are also handy. High-level software is sometimes available for interactive editing, for image-file management, and for specialized applications.

Peripheral devices commonly used with scanners include storage devices, a slave display for monitoring operations, an independent graphic display for viewing the results of post-processing and for interactive editing, a matrix printer for hard-copy output, low-speed alphanumeric output for the scanner log and program development, and a graphic tablet for scanner control and editing.

Commercial products

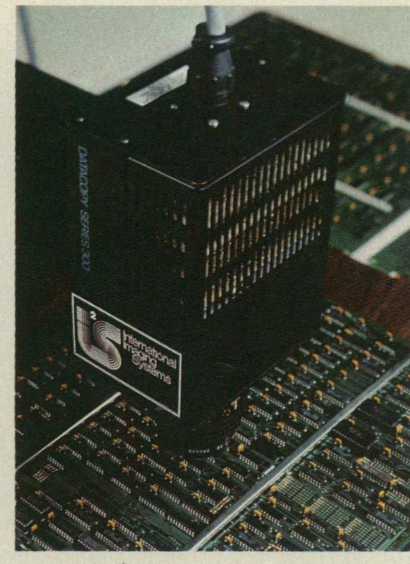
Commercially available scanners can be grouped into electronic, electro-optical, and solid-state devices. The list in the box on p. 22 shows some of the current vendors, but new companies enter and depart the optical scanner market almost every month.

Electronic scanners. Two major types of scanners are based on the deflection, by electromagnetic or electrostatic means, of an electron beam. The first type is the *CRT* scanner. Here a bright spot generated by an electron beam impinging on a phosphor screen is focused on the image, and the light reflected or transmitted is col-

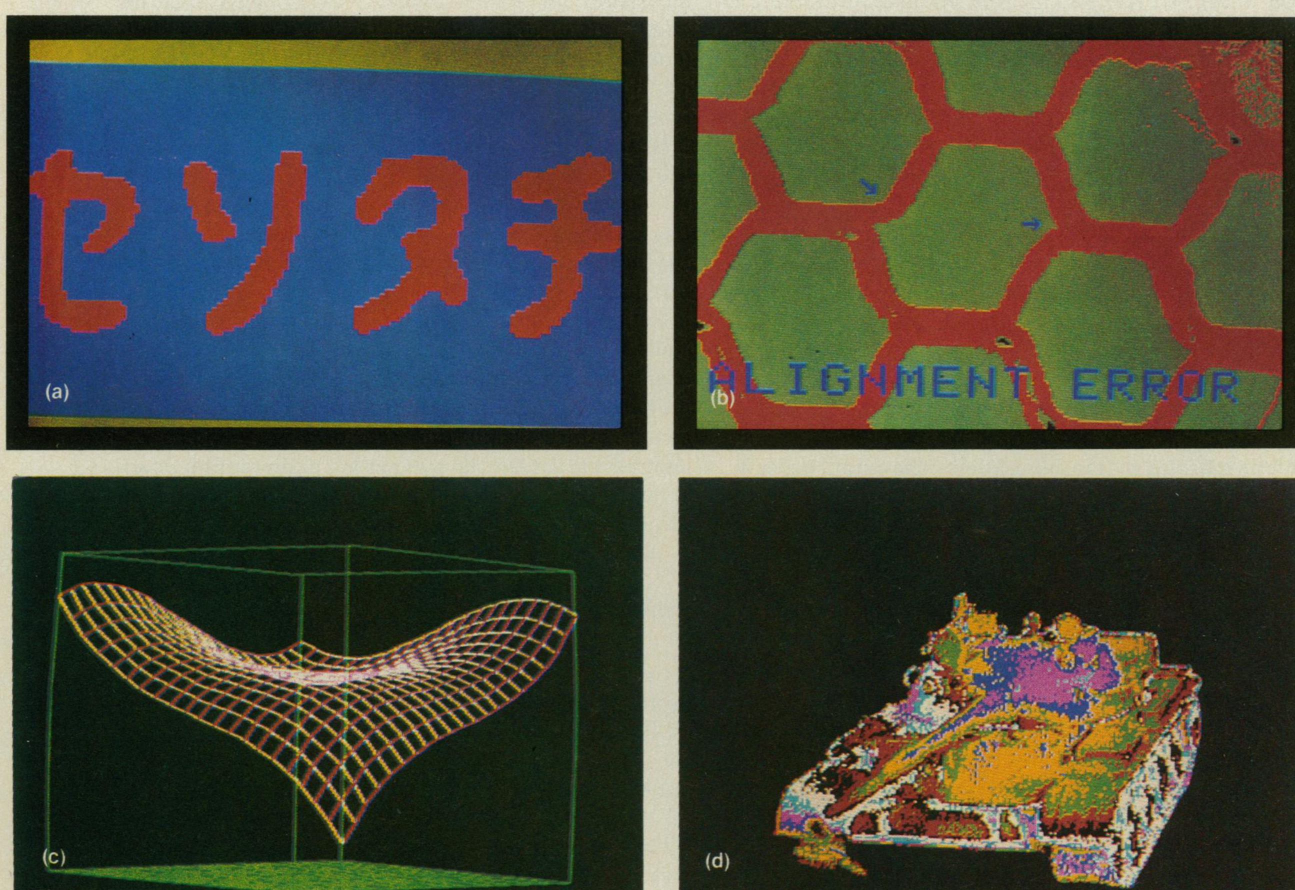


This soils map was produced on a Scitex R-250 system by scanning an existing base map and multicolor polygon overlay manuscript with the system's 12-color recognition scanner. System software converts raster imagery into vector graphics and performs all necessary graphic arts tasks for color printing of the end product. The system user is the Institut Geographique Nationale in Belgium. Photo courtesy of Scitex Corporation.

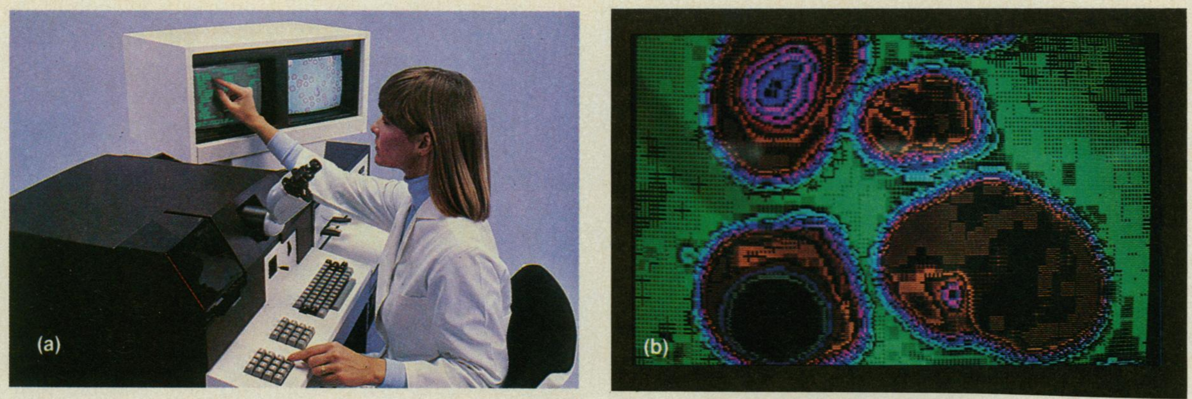
EG&G Reticon's image sensor arrays are used in optical character recognition and point-of-sale applications. The point-of-sale wand shown here is sold by Recognition Equipment. Photo courtesy of EG&G Reticon.



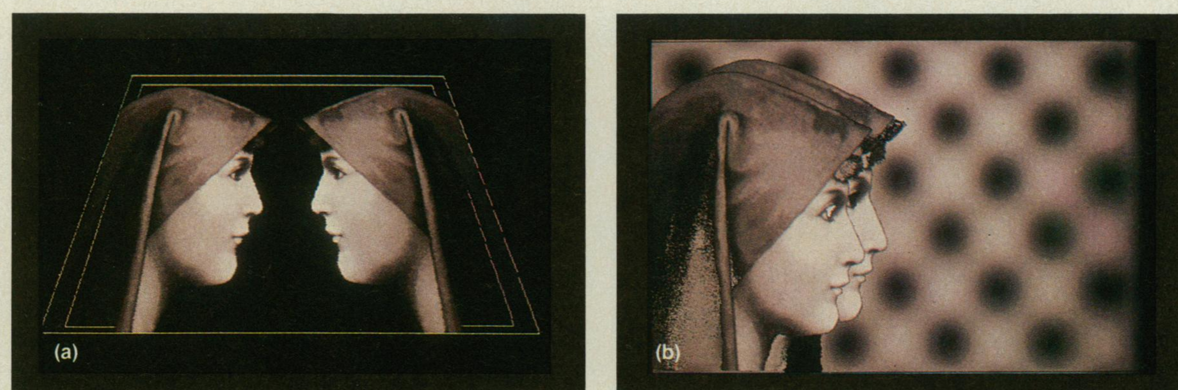
International Imaging Systems uses the Datacopy Model 322 digitizing camera for their image processing system in high-volume, high-precision, noncontact measurement applications. Photo courtesy of Datacopy.



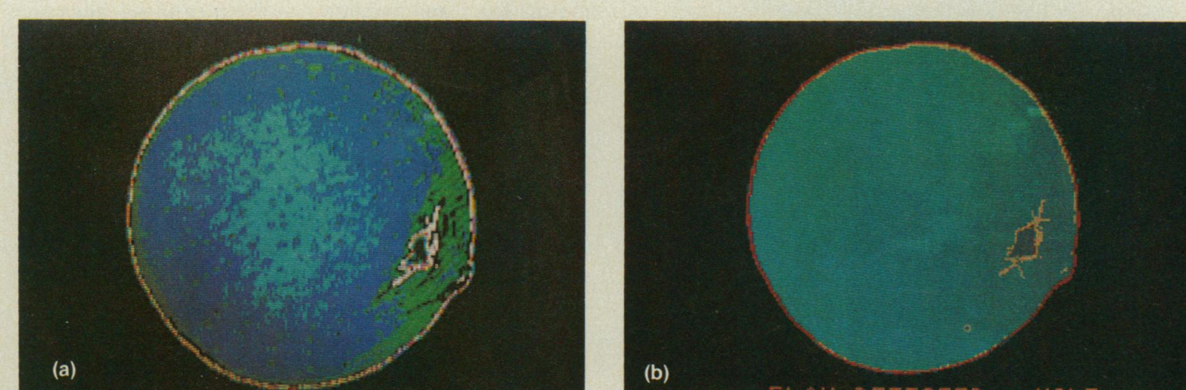
Other applications of inspection system scanners include verifying product labels and logos by comparing letters to known font masks, such as those for Japanese characters (a); controlling a manufacturing process in real time (b); generating graphical data (c); and analyzing thermal imagery (d). Photos courtesy of Electro-Optical Information Systems.



The diff4 cell analyzer (a) from Coulter Biomedical Research is an instrument for automated microscopy. Image data are acquired in two spectral bands simultaneously by solid-state imaging arrays. Cell feature data are extracted by local neighborhood operations, and the feature data permit classification of the various white cell types. The entire analytic process, from loading and oiling of the blood slides through printing of the results is automated; abnormal cells are located and flagged. The above sample of a typical blood slide (b) shows cell images as the processor sees them, digitized into 64 gray levels. Pseudo color was added, by arbitrarily assigning colors to individual gray levels. Photos courtesy of Coulter Biomedical Research.



The above images were digitized using the Via Video System One picture processing system. The video camera used was an RCA TC1005 with a Nikon lens. Kodak Ektachrome (ASA 64) was imaged on the Matrix 3000 color graphics recorder. In the first image (a), a trade card from the 1880's was digitized then duplicated and reflected about its *y*-axis. It was then given perspective. In the second image (b), a background was created by placing two 170-line tint screens together and adjusting them to yield a moire pattern. The background was then placed on a light table and digitized into the original image. Photos courtesy of Via Video.



Pizza anyone? The EOIS 1400 inspection system from Electro-Optical Information Systems can be used to inspect the quality of pizza crusts. An image of the conveyor belt approximately 24 × 20 in. is digitized and can contain up to three crusts. The boundary of each crust is then traced and a curvature metric is evaluated. When a histogram, or intensity distribution, is computed for the region within each boundary, all internal flaws (holes, baking irregularities, grease) will appear as a different intensity from the rest of the crust (normal color). The images above show a flawed pizza crust when it is first digitized (a) and after the flaw has been detected (b). Photos courtesy of Electro-Optical Information Systems.

lected and quantized. The response is thus proportional to the optical density of the portion of the document selected by the deflection circuitry governing the position on the phosphor screen bombarded by the electrons.

CRT scanners are capable of addressing up to 4000 × 4000 nonoverlapping picture elements. Increasing the sampling array beyond about 1000 × 1000 elements requires expensive correction mechanisms, including dynamic focus control and deflection linearization. The photometric linearity of CRT devices is inherently low and nonuniform over the scan field, but can also be improved by carefully designed optics, phosphor compensation, signal integration, and stored linearization tables. The major advantage of CRT scanners is a completely programmable scan pattern.

The second major type of scanner is the television camera. Vidicon and plumbicon cameras offer high speed and relatively high photometric fidelity, but because of the necessity for signal integration, the scan pattern must be fixed, and the lateral charge leakage in the photosensitive surface limits the spatial resolution. Orthicon tubes offer a flexible scan pattern. Image dissectors add to that an arbitrarily small scanning aperture, but their photometric accuracy is inherently low because the signal is not integrated. Television cameras are suitable for applications requiring up to 1000 × 1000 samples, though devices (return-beam vidicons) with up to 4000 × 4000 picture elements have been constructed. The metric accuracy of television cameras is generally far worse than that of mechanical or solid-state instruments, but the price of the cameras is very attractive by comparison. These devices are heavily used for biomedical applications, where the relatively small scanning array and lack of geometric accuracy are acceptable. Several vendors offer a line of vidicon and plumbicon scanners with a 256 × 256 scanning array, 50-micron resolution at 1:1 magnification, and 5-percent gray-level reproducibility for about $10,000.

Electro-optical scanners. Optical microdensitometers, which convert the optical density of a very small area of a transparent object to numerical form, have long been used in quantitative microscopy. A typical application is to determine the concentration of dye in certain tissue or in part of a cell. The optical density range may span three or more optical density units, and three-digit accuracy is obtainable. The necessary spatial resolution, which may be on the order of 5 microns or less, is obtained by means of microscope optics. Such an instrument can be converted to a scanning microdensitometer by providing a precise mechanism (usually a lead screw and stepping motor) for x and y motion of the measuring stage and some means of recording the output. Although these instruments are extremely accurate, they are far too slow for most image-processing applications.

Next in accuracy are *rotating drum* microdensitometers, in which the light source and detector assembly are mounted on a lead screw along the drum. The document to be scanned (opaque or transparent) is mounted on the drum whose rotation provides the other scan axis. The maximum document size is governed by the size of the drum: formats larger than about 100 cm by 100 cm are prohibitively expensive.

Flat-bed and drum densitometers are marketed commercially by several firms. A typical scanner, with a 5- to 100-micron square sampling aperture, a zero to four optical density range, photomultiplier tube detector, three-color simultaneous scan capability, a 50-cm × 50-cm format, 256 (± 3) gray levels, and a 25,000-pixel/second scanning rate is available for about $120,000. Relatively low resolution (100 micron) *mirror, prism,* and *fiber-*

Vendors of Optical Scanning Products

Artek Systems Corporation, Farmingdale, N.Y.; (516) 293-4420
Bausch and Lomb, Analytical Systems Division, Rochester, N.Y.; (716) 338-6000
Broomall Industries, Broomall, Pa.; (215) 328-1040
Burroughs, OEM Corporation, Detroit, Mich.; (313) 972-7000
Caere Corporation, Los Gatos, Calif.; (408) 395-7000
Cognitronics Corporation, Stamford, Conn.; (203) 327-5307
Computer Design and Applications, Waltham, Mass.; (617) 647-1900
Coulter Biomedical Research Corporation, Concord, Mass.; (617) 890-1903
Datacopy, Palo Alto, Calif.; (415) 493-3420
ECRM, Bedford, Mass.; (617) 275-1760
EG&G Reticon, Sunnyvale, Calif.; (408) 738-4266
Eikonix Corporation, Bedford, Mass.; (617) 275-5070
Electro-Optical Information Systems, Santa Monica, Calif.; (213) 451-8566
Geometric Data, Wayne, Pa.; (215) 687-6550
Hamamatsu Systems, Waltham, Mass.; (617) 890-3440
IBM, Armonk, N.Y.; (914) 765-1900
Honeywell, Lexington, Mass.; (617) 862-6222
Joyce-Loebl (Vickers Instruments), Malden, Mass.; (617) 324-0350
E. Leitz, Inc., Northvale, N.J.; (201) 767-1100
LogEtronics, Springfield, Va.; (703) 971-1400
MacDonald Dettwiler, Richmond, BC, Canada; (604) 278-3411
McBain Instruments, Chatsworth, Calif.; (213) 998-2702
Optical Business Machines, Melbourne, Fla.; (800) 327-6429
Optronics International, Chelmsford, Mass.; (617) 256-4511
Perkin-Elmer Applied Optics Division, Garden Grove, Calif.; (714) 895-1667
Recognition Equipment, Inc., Irving, Tex.; (214) 579-6000
Scan-Data Corporation, Norristown, Pa., (215) 277-0500
Scan-Optics, Inc., East Hartford, Conn.; (203) 289-6001
Scitex America Corporation, Bedford, Mass.; (617) 275-5150
Skantek Corporation, Warren, N.J.; (201) 647-7747
Toshiba Corporation, Tokyo, Japan
Via Video, Cupertino, Calif.; (408) 980-8009
VTE Digitalvideo, Herrsching, FRG; 0 81 52 3031
Carl Zeiss, New York, N.Y.; (212) 730-4400

optic scanners are used principally by the OCR industry. Several OCR firms also advertise image processing capabilities.

Good results have been reported with a fiber-optic scanner for engineering drawings using stationary fiber array assemblies, but this product is not yet available commercially. A rotating-mirror laser scanner with a 35-micron scanning aperture is available for legal-size documents. Acousto-optically modulated laser scanners are also emerging from the research laboratories, although deflection is feasible in only one scan direction so far. Lasers provide stable, intense, pin-point illumination, while electro-optical deflection methods are potentially suitable for ultra high speed operation. A laser scanner for document storage has also been advertised.[18-20]

Solid-state scanners. Integrated solid-state array scanners can be either flying spot or flying aperture. Flying-spot scanners use LED arrays, and flying-aperture scanners have self-scanned photodiode, phototransistor, charge-coupled device, or charge injection device sensors. The excellent geometric properties of solid-state array sensors are a direct consequence of this photolithographic method of fabrication. Both one-dimensional (up to 4096 elements) and two-dimensional (256 × 256 elements) arrays are used. With one-dimensional arrays, the other scan direction is provided mechanically. Small linear arrays are used in wands or hand-held scanners.

Arrays can be optically butted together to avoid transition effects. The element-to-element variation in sensitivity is on the order of one percent, hence 64 levels of gray can be reliably obtained. Center-to-center distance between adjacent elements is on the order of 25 microns, but higher resolution can, of course, be obtained by optical magnification. A 2048 × 2048-element device capable of scanning an entire image in 50 seconds is available for about $50,000. Additional features such as backlighting for film scanning, computer-controlled magnification, and a color wheel are obtainable. A relatively low-cost 1728-element line scanner is available for direct interfacing to several small computers. There is little question that this newcomer is rapidly overtaking the more established technologies and that the fabrication of two-dimensional arrays with even more elements will soon render electron-beam devices obsolete for most applications. Special issues of *IEEE Transactions on Electron Devices* that pertain to imaging devices are a good source of up-to-date information on new developments.

The major characteristics of various types of scanners are summarized in Table 1.

Table 1.
Characteristics of commercial scanners.

TYPE	FORMAT	SAMPLING GRID	SPOT SIZE μm	NUMBER OF GRAY LEVELS	PHOTOMETRIC UNIFORMITY (%)	GEOMETRIC ACCURACY (%)	PRICE ($)	APPLICATIONS
TV camera vidicon plumbicon image dissector solid state	variable	256 × 256 to 2000 × 2000	variable	16-256	3-10	2	1000 to 25,000	Biomedical, inspection, robot vision
CRT flying spot	variable	64 × 64 to 4000 × 4000	10 on CRT face	64-256	0.5	0.5	10,000 to 100,000	Film scanners
Integrated linear array	15 mm	4000 × 1	10	2-64	3	0.1	1000	OCR, wands, facsimile
Integrated 2-D array	10 × 10 mm	256 × 256	40	2-64	3	0.1	5000	OCR
Rotating-mirror prism	variable	2000 × 2000 to 10,000 × 10,000	50	16	5	0.1	25,000	OCR, facsimile, drawings
Linear fiber array	100 cm	10,000 × 1	100	2	N/A	0.01	50,000	Engineering drawings
Rotating-drum microdensitometer	100 × 100 cm	50,000 × 50,000	5-100	256	0.1	0.01	50,000 to 250,000	Aerial photos, maps, printing and publishing.
Flat-bed microdensitometer	100 × 100 cm	50,000 × 50,000	1-100	4096	0.01	0.001	25,000 to 100,000	Laboratory instruments, aerial photos, maps
Digital facsimile transmitter	20 × 30 cm	1000 × 1000 2000 × 2000	250 125	2	N/A	0.1	1000	Documents
Thematic mapper		4000 × 4000	50 μrads	256	1%	0.2	millions	Remote sensing

Optical scanners add new dimensions to computer applications. Important developments include relatively low-cost, medium-fidelity page-format scanners and high-precision scanners for large drawings and maps. Hand-held scanners are becoming available for home computers. The most exciting potential development, however, is the high-performance digital camera. It is currently at the Daguerrotype stage of photography: pinhole image formation, glass plates, magnesium flares, and a veritable devil's kitchen for development and printing. In time, however, digital cameras will be as versatile, compact, and easy to use and will have as many optional attachments as today's photographic cameras. Standard mounts, copy stands, color filters, telephoto and wide-angle lenses, provisions for high-contrast or fine-grain scanning, automatic focus and shutter adjustment, repeated exposure contol, arbitrary formats, etc., will be off-the-shelf items. With the Scanamatic of the future, we will be able to plug the camera into a pocket computer, point it towards the desired object, find the image in the viewfinder, press the button, and presto, several million bits will be instantaneously recorded in a digital picture album. ■

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