J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

IMAGE SCANNERS

Applications of computers are unlimited. Only a very small part of a computer's capability is usually used. Document preparation is probably the most common use of personal computers (*PC*) in business and home. Personal computers have become a common tool for document processing and communication. All the articles of this encyclopedia have been submitted in electronic form, but this is not the common case in daily official and personal business. Some documents are still created by using typewriters. Even printed from a computer, a document that a person or an organization receives usually is not accompanied by an electronic file. If the document needs to be input into a computer from the keyboard for some reason, the task is time consuming and it is easy to introduce errors. This problem now can be solved easily by using an image scanner and an optical character recognition (*OCR*) program.

Image scanners are devices that scan an image or document and convert it into digital form so that the digitized image can be manipulated electronically (e.g., displayed on a monitor, processed by using an image processing program or a word processor, printed by using a laser printer, and stored in an electronic file). As discussed in this article, image scanning and processing has unlimited applications in offices, industry, schools, and homes, and for research and development (*R&D*) activities.

Desktop Image Scanners

A desktop image scanner has compact size so that it can be placed on a desk beside a PC. It is similar to a photocopier but sends the image to a computer instead of to paper. It scans a photograph or a drawing and changes it into an electronic file. With its scanning software and/or other image processing software, an image scanner not only electronically photocopies the document (picture, drawing, etc.), but can also greatly enhance the scanned image for desktop publishing or document management.

Today's desktop image scanners, like personal computers and printers, are much cheaper and better than earlier models and can reproduce images with very good quality. In addition, memory prices have fallen dramatically and memory capacity is increasing rapidly. Hard disk drives with several gigabytes of memory are available at reasonable prices. The memory capacity of a hard disk in the year 2000 is expected to be around 20 gigabytes or even more. As a result, desktop image scanners have been, and will continue to be, used widely for both business and home with image processing technology.

This article can only cover a very small percentage of the information available publicly regarding desktop scanners. There are many good books that explain desktop scanners in extensive detail. Refer to Refs. 1,2,3,4, 5,6,7 for more detailed information on desktop scanners.

Scanning and Digitization. The basic function of an image scanner is to scan and digitize images. During scanning, a scanner illuminates the original and collects the information. For example, in a flatbed scanner a traveling bar passes under the glass. The bar with a light source illuminates the original. The light reflected from the original is received by a photoreceptor. The photoreceptor creates an analog signal proportional to the intensity and color levels of the reflected light. The analog signal is sampled and digitized

Table 1. Applications of Desktop Image Scanners

Applications	Remarks
Document management	Fast and simple. Usually an OCR package is needed.
Desktop publication	A helpful tool to reproduce photographs, figures, and illustrations for preparing manuscripts, brochures, newsletters, office publications, catalogs, manuals, business forms and reports, company documents, booklets, literature, etc.
Producing graphics for business and visual presentations	Creating signatures and new fonts, producing logos, cartoons drawings, maps, schematics, graphics, diagrams, transparencies for business and visual presentations.
Home usage	Reproducing pictures and attaching them to e-mail messages, season's greeting cards (Christmas cards, New Year cards), birthday cards, home-made calendars, invitation cards, etc.
Copy of documents	Producing copies and improving the quality of the copies, with an image processing program and a quality printer.
Fax of hard copy documents	Giving clearer results than many fax machines offer. A fax modem and/or a PC fax application program is/are needed.

by an analog-to-digital converter (*ADC*). The digitized data are then sent to a computer. A charge-coupled device (*CCD*) array that consists of a fixed number (thousands) of tiny CCD elements that can measure the intensity of light is commonly used as the photoreceptor. The number of the CCD elements determines the resolution of the scanner. The image is displayed on the monitor screen. Users can use the scanning software attached to the image scanner to change the brightness, contrast, and size of the image before storing it in an electronic file. Image files are sometimes compressed for storage to reduce their large sizes (1,3,5,6).

Applications of Desktop Image Scanners. There are many office and home applications of desktop image scanners (1,6,7). Table 1 lists only a small part of desktop scanner applications.

With an image scanner, user-friendly scanning software, and an OCR package, document management (scanning, storage, and retrieval) can be done quickly and simply. We can scan text and pictures and store the scanned items into electronic files for the purposes of data and text entry, desktop publishing, e-mail and network communication, and so on.

We can use image scanners to reproduce photographs, figures, and illustrations for preparing manuscripts, brochures, newsletters, office publications, catalogs, manuals, business forms and reports, company documents, booklets, literature, etc. Many journals and international conferences, including the editor of this encyclopedia, ask for submission of diskettes (electronic files) with the manuscript. Many article contributors may have found an image scanner a helpful tool for preparing manuscripts.

Table 2. Types of Desktop Image Scanners Available on the Market

Types of Scanners	Features
Hand-held scanners	Inexpensive; portable; operated by hand; images can be distorted
Flatbed scanners	Using a glass plate, a plastic lid, a light source, and CCD array; flexible for irregular paper
Sheet-fed scanners	Using a roller mechanism to pull paper and a CCD array to read an image; having an automatic sheet feeder; fast speed; not flexible for irregular paper
Camera-based scanners	Using a CCD camera; relatively expensive
Overhead scanners	With the photoreceptor above the copy board; fast scanning; either expensive or relatively low resolution
Print-head-mounted scanners	With an optical scanning head mounted on the moving head of a plotter or printer; inexpensive; low speed

We can use a desktop image scanner to create signatures and new fonts and produce logos, cartoons, drawings, maps, schematics, graphics, diagrams, and transparencies for business and visual presentations. We can scan pictures of family members, attach them to e-mail messages, and mail them to friends and relatives living in other cities. We can also attach them to season's greeting cards (Christmas cards, New Year cards), birthday cards, home-made calendars, invitation cards, etc.

We can make clean copies with a scanner and printer. The scanning software or an image processing package can improve the quality of the copy so that the final copy may be better than the original. We can fax images and text with better quality. Some image scanners and their scanning software can send hard copy documents through a fax modem with clearer results than many fax machines offer.

Optical Character Recognition. Optical character recognition (5,6,7) is the technology that translates characters from a rastered image into machine-readable characters that can be edited using a word processing program. After an original is scanned by a scanner, the text in the digitized image cannot be edited directly. OCR software changes the imaged text into a text format that can be read and edited with a word processor. OCR can save great time in tedious text entry, large-volume data collection, and database building. However, OCR software cannot always convert all text with 100% accuracy; accuracy also depends on the quality of the original. Spell checking and manual editing are needed.

There are various algorithms to convert images to text. There are some OCR programs using artificial intelligence (*AI*) techniques like fuzzy logic and neural network technology. Some programs require learning (training) and allow users to train them to recognize an unknown character set; others do not. Some packages can recognize multilingual documents.

Types of Desktop Image Scanners. Table 2 lists several types of desktop image scanners available on the market.

Hand-Held Scanners. Hand-held scanners (5,6,7) are operated by manually running a scanning head over an image. Small rollers on the bottom of the head help the scanning. Hand-held scanners are useful for scanning small areas. They are inexpensive and portable. However, the image is distorted if the manual scanning is not consistent. Practice of manual scanning is needed.

Flatbed Scanners. Flatbed scanners (1,2,3,5,6,7) use a method similar to the way a photocopier works. A flatbed scanner has a flat glass plate on which a document is placed face down, and a cover that holds the document. Below the glass, a light-mirror system passes across the document. The light-mirror system is driven by a servomechanism. The image reflected from the light-mirror system is received by a photoreceptor, converted to binary numbers, and sent into a computer. One of the advantages of flatbed scanners is that the original document can be moved on the glass plate freely for precise adjustment.

Sheet-Fed Scanners. Similar to fax machines, in sheet-fed (roller-feed, paper-fed) scanners (2,3,5,6,7), the optical light-sensing (imaging) devices are fixed, and the original document is pulled across them by a roller-feed system during scanning. Possible problems are paper jamming and skewing. The document cannot be adjusted precisely, as it can on a flatbed scanner. It cannot be used for scanning books. However, sheet-fed scanners are useful when large volumes of documents are read. Some sheet-fed scanners can do fully automatic single- and double-sided scanning. They can flexibly handle paper of different thickness and sizes, from business cards up to large size paper B4 (257 mm × 364 mm).

Camera-Based Scanners. In camera-based scanners (3,5), a camera with a CCD array is used. The advantage is in light intensity, resolution, and size. But camera-based scanners are relatively expensive. Recently, digital cameras (6) have become popular. Instead of on film, a digital camera takes an image with a CCD chip and stores it on a reusable floppy disk with large-capacity memory. The image can be edited, stored, transmitted to a PC through a modem, displayed on the screen, and printed. It can also be used in low-light applications. The fast speed with which an electronic image can be produced is one of the reasons why digital cameras are becoming popular.

Other Types. There are other types of desktop image scanners, such as overhead scanners and print-head-mounted scanners. Overhead scanners (6,7) look like overhead projectors. They hold the photoreceptor (a linear or two-dimensional array) above the copy board that holds the original. In print-head-mounted scanners (1,5), a photoreceptor replaces the ribbon or pen cartridge of a printer or a plotter. The head scans across the image, gathering and digitizing the information. Such scanners are inexpensive, but the scanning speed is low.

Unlimited Applications of Scanners

Scanners are also widely used in office automation, *CAD* (computer-aided design), *CAE* (computer-aided engineering), *CAM* (computer-aided manufacturing), *CIM* (computer-integrated manufacturing), reverse engineering, engineering metrology, industrial applications, bar coding applications, medical applications, and so on. Table 3 lists some examples of scanner applications.

Office Automation. In addition to desktop image scanners, fax machines and photocopiers are used in almost every office. Fax machines are scanners. Like a sheet-fed desktop image scanner, a fax machine pulls a document across light-sensing (imaging) elements, digitizes it, and sends the digital signals to another fax machine through a telephone line. Fax machines are widely used for business and personal communication. Sending a text or image by fax in some cases can be cheaper than sending it by mail. Some desktop image scanners support fax machines and send faxes directly with better quality than ordinary fax machines offer.

A photocopier has a light-mirror scanning servomechanism inside that is similar to the one used in a flatbed desktop image scanner and transfers the scanned image through a photosensitive drum to paper instead of to a computer. Some photocopiers are intelligent, computer-based, multiple-functioned copiers. Also, there are inexpensive desktop photocopiers on the market.

CAD, CAE, CAM, and CIM. Most CAD, CAE, CAM, and CIM systems have graphic-input devices. Image scanners are often included in such systems. With them, existing paper drawings are entered into computers, and CAD representations of the images can be obtained in a short time. This saves a lot of time that would be spent redrawing the objects on a CAD system from the very beginning. Image scanners often are part of engineering document management (*EDM*) systems for controlling and tracking drawing, or part of

Table 3. Applications of Scanners

Applications	Types of Scanners
Desktop publishing	Desktop image scanners (see Table 2)
Office automation	Desktop image scanners, fax machines, photocopiers
CAD/CAE/CAM/CIM	Desktop image scanners, 3-D laser scanners
Reverse engineering	3-D laser scanners
Engineering metrology and industrial applications	Infrared thermal scanners, CT scanning systems, ultrasonic scanning systems, 3-D laser scanners, interfacing laser scanners, piezoelectric tube scanners, piezoelectric bimorph scanners, tripod scanners, etc.
Bar coding	Hand-held scanners, flatbed scanners, laser scanners, etc.
Medical diagnostic imaging	EMI scanners, translate-rotate CT scanners, rotate-only CT scanners, multiple-detector-translate-rotate CT scanners, rotate-only stationary detection CT scanners, pencil-beam scanners, thin fan-beam scanners, wide fan-beam scanners, mechanical sector scanners, sector array scanners, line array scanners, etc.

product data management (*PDM*) systems for handling geometric data, design changes, drawing files, analysis results, process plans, and *NC* (numerical control) tool paths (8).

Different from most applications of desktop image scanners discussed in the previous sections, the scanned images (raster data) must be converted to vector information for CAD, CAE, CAM, and CIM usage. There are several methods of converting raster or pixel information to CAD vector data. The use of artificial intelligence, such as fuzzy logic and neural network technology, is required for automation of intelligent database conversion (9).

Automated mapping has been one of the growing uses for computer-aided technology. A map is fed through an image scanner. This produces a raster data set that can be displayed and maneuvered on a computer screen. This technique is acceptable for putting many of the general mapping applications into digital format. The scanned data are processed through a clean-up software program to remove stains and other markings. This is the most inexpensive method to convert existing drawings to electronic forms (10).

Reverse Engineering. Reverse engineering has many applications. One is mold making, which is time consuming, for example for manufacturing plastic products. Another is in the field of medicine (plastic surgery, etc.). Creation of geometric CAD databases is usually one of the most complex parts of CAD/CAM systems. With a 3-D laser scanner and a CAD/CAM software, rapid prototyping can be achieved. This approach includes capturing 3-D data from a complex and free-formed dummy model or real-life object, building a geometric model in a CAD/CAM package, and editing and machining the mold, die, or prototype.

A 3-D laser scanner can be used to capture the raw data of a real-life object or a dummy model. The object is then rebuilt in a CAD/CAM system based on the scanned data. With the CAD/CAM system, the model of the object can be modified, 2-D and 3-D drawings can be generated, and a reverse image of the object can be produced for manufacturing of a mold or die. After definition of the appropriate manufacturing process and the machining parameters, the cutter location (*CL*) data can be obtained. The CL data are used to generate an NC program by a postprocessor. A CNC machining center then reproduces the object or the corresponding mold for injection molding or casting of the object. With the scanner, the time spent from modeling an object to generating the NC code and manufacturing the mold can be reduced enormously (11,12).

Engineering Metrology and Industrial Applications. Scanners consisting of optical scanning devices, detectors, and servomotor controllers are used in infrared thermal cameras. The scanner converts infrared radiation from an object into digital signals and sends them to a PC. The real-time thermal image of the object obtained through the thermal camera is presented on a monitor. Analysis of the thermal image (temperature) data can be carried out for industrial or research and development applications.

Computed tomography (*CT*) and digital radiography scanning systems with X-ray sources, X-ray detectors, object manipulators, and computers are used for nondestructive measurement for research and development and industrial applications. During scanning, an object is moved or rotated continuously between the X-ray source and the detector. After the image data are collected, a 2-D or 3-D image can be displayed, processed, analyzed, and stored electronically by using the computer. An application using such scanning a system is inspection of porosities, cracks, and delaminations inside die-cast Al-alloy products.

Some ultrasonic scanning systems have scanners with three (X, Y, and Z) axes of scanning bridges and rotational servomechanisms driven by stepper motors or servomotors. Some of the main techniques for displaying ultrasonic images are A-scan, B-scan, and C-scan (13). A multiple-section image, 3-D image, or cross-sectional side view of the scanned sample is displayed to show interfaces and defects. Postscanning image processing can be conducted and the images can be printed, loaded, and saved. Examples of applications and potential applications using ultrasonic scanning systems are nondestructive inspection of porosities, cracks, and delaminations in die-cast products, and voids in between an integrated circuit (*IC*) chip and printed circuit board (*PCB*) substrate assembled with an anisotropic conductive film (*ACF*). Ultrasonic imaging is also used for medical applications like diagnostic imaging of the human fetus (13).

3-D laser scanners are used for automatic optical inspection of surface-mounted device (*SMD*) boards. This approach provides reliable inspection. Surface mounting technology (*SMT*) is a key technology for the electronics industry. Surface-mounted devices provide a high packaging density on PCBs. As the number of solder joints per board increases, the yield of the boards becomes a big problem. Automatic optical inspection becomes essential for SMD technology. Such inspection is not used merely to reach an acceptable yield of an SMD production line, but as an indispensable tool for statistical process control (*SPC*) and improvement to achieve a defect level of a few parts per million (14).

Ultraprecision scanners with atomic resolution are used in scanning probe microscope (*SPM*) imaging systems: atomic force microscopes (*AFM*), scanning tunneling microscopes (*STM*), magnetic force microscopes (*MFM*), and electric force microscopes (*EFM*). Since the invention of the STM by Nobel Prize winners G. Binnig and H. Rohrer in 1982, the scanned probe techniques for imaging surfaces with atomic resolution, based on scanning a very sharp tip over a surface, have grown rapidly and are now available commercially (15). Examples of the ultraprecision scanners are piezoelectric (*PZT*) tube scanners, PZT bimorph scanners, and tripod scanners. The vertical resolution of some PZT scanners is $0.01\ \text{Å} = 10^{-11}$ m. With them, three-dimensional images with atomic resolution can be obtained. Scientific and technological applications include wafer analysis; surfaces studies; studies of atomic and crystalline structures; imaging of surface grains, biomolecules, magnetic structures, and nanometer-scale human-made structures like semiconductor devices and microfabricated structures; imaging of atomic scale surface roughness obtained by ultraprecision machining; imaging of the electronic structure of semiconductor surfaces; measuring local magnetic properties; and determining nanometer-scale tribological properties of ultra-precisely machined surfaces like adhesion, lubrication, and the coefficient of friction.

Bar Coding. Bar code scanners (readers) can be seen in libraries and stores (e.g., supermarkets, book shops, grocery stores, convenience stores, and liquor stores). Like desktop image scanners, bar code scanners

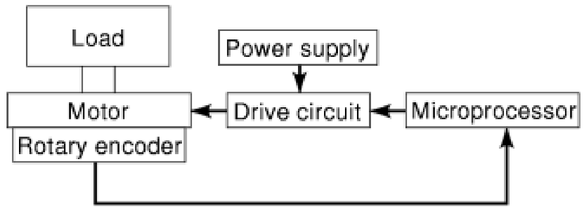

Fig. 1. Block diagram of a simple servo system (servomechanism) that can be used in a scanner. It consists of a microprocessor, a motor, a driving circuit, and a positioning (or velocity) sensor. The load could be any scanning mechanism used in scanners.

(readers) are of many types, but probably the most commonly used are hand-held (wand type) scanners and flatbed (tabletop) scanners. Hand-held scanners are inexpensive and portable, while flatbed scanners are stationary devices typically seen in supermarkets, such as point of sale (*POS*) scanners. In fact, they are also becoming popular in automotive, health care, and retail and wholesale distribution industries. Industrial applications include material tracking, production monitoring, inventory control, scheduling and evaluating work in progress. High speed, high accuracy, and ease of use are the main reasons why bar code scanners are so popular. For details, refer to specialists' books, such as Ref. 16.

As an example of industrial applications, a laser scanner can be integrated with an industrial robot for real-time control of palletization cells (17). The bar coded boxes arriving at the palletization station are decoded, sorted, and palletized by the robots. The bar codes on the boxes include information such as weight of the box, part number, number of pieces, destination, and box sizes. The scanner is used to collect information from various boxes. The robots can be provided with intelligence to operate in an environment requiring complex decision-making capability.

Medical Diagnostic Imaging. Diagnostic imaging scanners are very important tools and are widely used in medical applications, such as ultrasonic imaging; computed tomography, also called computer-assisted tomography or computerized axial tomography (*CAT*); and digital radiography. The images are formed by passing various types of radiation into a body and measuring the output with a suitable detector. There are many types of scanners used for scanning brains, orbits, facial bones, spines, chests, abdomens, extremities, broken bones, beating hearts, the human foetus, etc. Examples include EMI scanners, translate-rotate CT scanners, rotate-only CT scanners, multiple-detector-translate-rotate CT scanners, rotate-only stationary detection CT scanners, pencil-beam scanners, thin fan-beam scanners, wide fan-beam scanners, mechanical sector scanners, sector array scanners, and line array scanners. Refer to specialists' books, such as Refs. 18,19,20,21, for details.

Control of Servomechanisms

Servomechanisms (22) can also be called servo systems. Figure 1 schematically shows a simple servo system that can be used in a scanner. It consists of a microprocessor, a motor, a driving circuit, and a positioning (or velocity) sensor. The load could be any scanning mechanism used in scanners, such as a light-mirror system used in flatbed scanners and photocopiers, or a polygon mirror or a holographic disk used for laser scanning.

Control Methods. In a servomechanism (servo system), the following two basic control purposes (functions) must be achieved (realized): (1) The system is asymptotically stable; (2) the output of the system (for example, the rotational speed or position) tracks the reference input.

To achieve these two basic control purposes, many control methods can be used. Examples include classical control techniques, like PID controllers; modern control techniques, like optimal regulators and eigenvalue

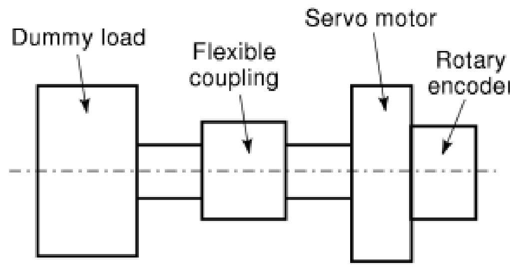

Fig. 2. A dummy load connected to the servo motor with a flexible coupling. This dummy load is used to prevent the actual light-mirror scanning mechanism from breaking in case a test fails at the first stage of the testing.

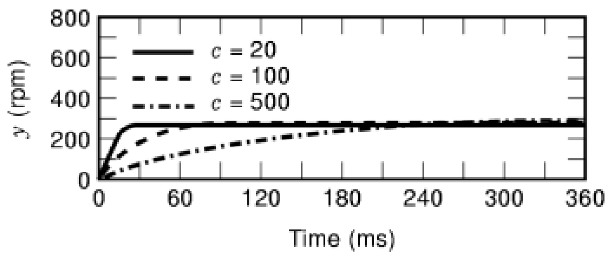

Fig. 3. A testing result of step response using the dummy load. When c is small the rise time, setting time, and overshoot are large, but when c is large enough the rise time and setting time become short and the overshoot is small.

assignment; and new control methods, such as H_∞ control, iterative learning control, and intelligent control (23) (fuzzy logic, neural network technology, and knowledge-based systems).

In this subsection, we briefly discuss the use of eigenvalue assignment and optimal regulator methods, H_∞ control, and iterative learning control.

Modeling of the Servomechanism. In Fig. 1, if a dc servo motor is used and the armature inductance of the servo motor is neglected, $y(t)$, the rotational speed as the output of the system is given by

$$\dot{y}(t) = ay(t) + bu(t) + dT_{\mathrm{L}}(t) \tag{1}$$

where

$$a = -\frac{K_{\mathrm{e}}}{J} \tag{2}$$

$$b = \frac{K_{\mathrm{t}}}{J} \tag{3}$$

$$d = \frac{1}{J} \tag{4}$$

$$K_{\mathrm{e}} = D_{\mathrm{c}} + \frac{K_{\mathrm{T}}^2}{R_{\mathrm{a}}} \tag{5}$$

$$K_{\mathrm{t}} = \frac{K_{\mathrm{T}}A_{\mathrm{i}}}{R_{\mathrm{a}}} \tag{6}$$

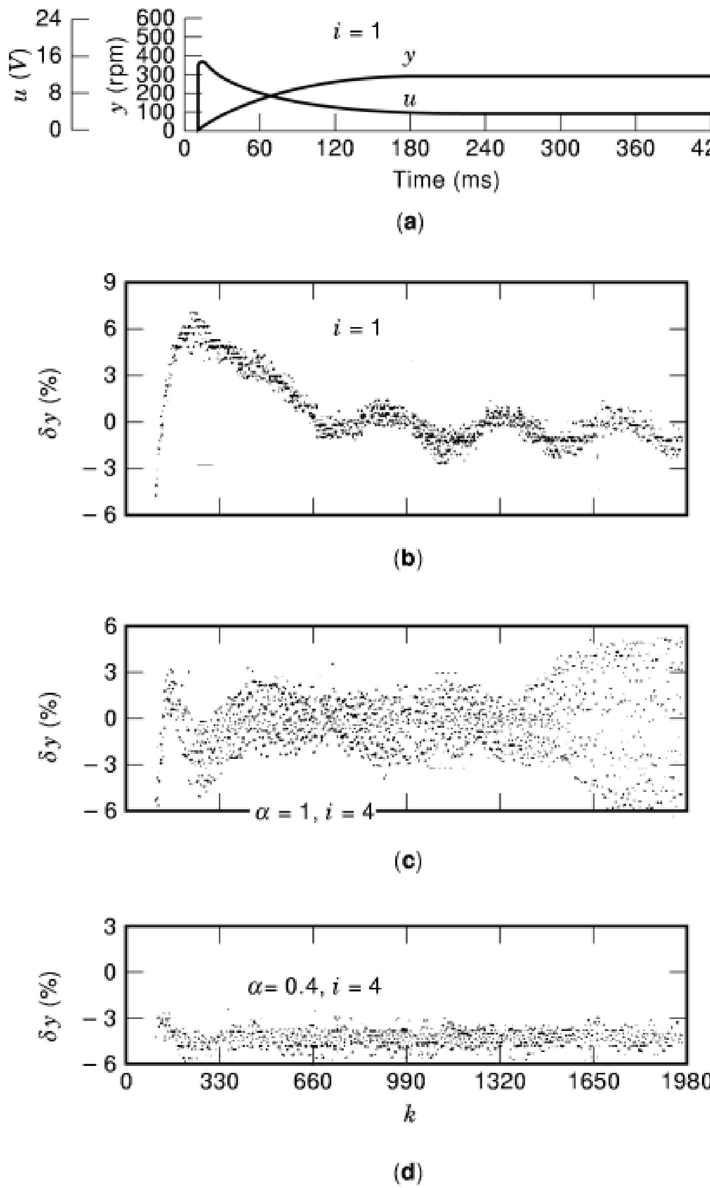

Fig. 4. Effect of the iterative learning control on the step response of the servo system. Part (b) shows that overshoot and rotational fluctuations still exist after redrawing the step response curve in (a) by enlarging the axis of the ordinate. When the iterative learning control is used in which $\alpha = 1$, as shown in (c), the system deteriorates. When $\alpha = 0.4$, as shown in (d), a response almost without overshoot and rotational fluctuation can be obtained.

The symbols represent the following:

J = Equivalent moment of inertia
R_a = Armature resistance
K_T = Torque constant
D_c = Viscous damping coefficient

A_i = Gain of the current power amplifier
T_L = Disturbance
u = Controlling input

The dynamic compensator (controller) realized by using the microprocessor can be expressed as follows:

$$u(k) = x(k) + K_1 e(k) \tag{7}$$

$$x(k+1) = x(k) + K_2 e(k) \tag{8}$$

$$e(k) = r(k) - y(k) \tag{9}$$

Here x is the state variable of the dynamic compensator, and r is the reference input of the system.

In the following three subsections, we will decide the feedback gains K_1 and K_2 based on the eigenvalue assignment method, the optimal regulator, and H_∞ control theories.

Eigenvalue Assignment. When z_1 and z_2, the closed-loop eigenvalues, are assigned, K_1 and K_2 are given as

$$K_1 = \frac{p + 1 - z_1 - z_2}{q} \tag{10}$$

$$K_2 = \frac{1 + z_1 z_2 - z_1 - z_2}{q} \tag{11}$$

where, with the sampling time τ,

$$p = \exp(a\tau) \tag{12}$$

$$q = \frac{b(p-1)}{a} \tag{13}$$

Optimal Regulator. With the following cost function (performance index) where $Q > 0$

$$J = \int_0^\infty (Qe^2 + \dot{u}^2)dt \tag{14}$$

the optimal feedback gains (24) are given by

$$K_1 = \frac{a + \sqrt{a^2 + 2bK_2}}{b} \tag{15}$$

$$K_2 = \tau\sqrt{Q} \tag{16}$$

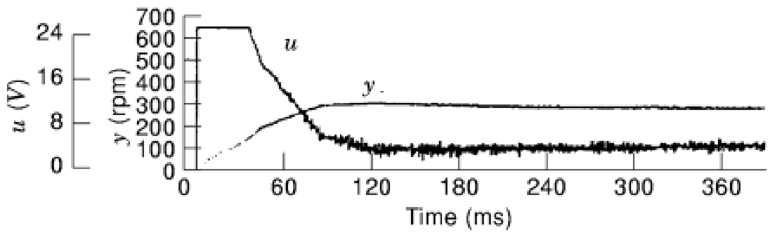

Fig. 5. A step response curve of a real light-mirror scanning servomechanism. The controlling input u is a limited value. The velocity step response seems very good.

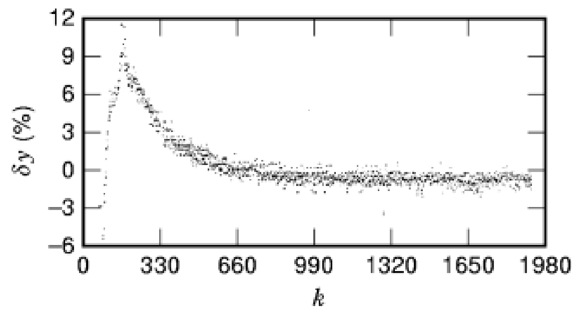

Fig. 6. The same step response of Fig. 5 redrawn by changing the scales of the abscissa and ordinate axes. Overshoot still exists.

H_∞ Control. Usually, some errors occur when a system is modeled and the coefficients of the differential equation are identified. The mathematical model of the controlled object expressed by Eq. (1) is obtained by neglecting the influence of the armature inductance of the servo motor. Furthermore, the same controller must be used for thousands of scanners, not just for a special one. It is desirable to design an identical robust controller without investigating the characteristics of each individual servomechanism and redesigning. Therefore, a controller based on the H_∞ control theory that is prominent in robust control is considered here.

Equation (1) can be rewritten as follows:

$$Y(s) = \frac{n_p}{d_p}\left[U(s) + \frac{d}{b}T_L(s)\right] \tag{17}$$

where $U(s)$ and $T_L(s)$ are the transfer functions of U and T_L respectively, and with a constant $c > 0$,

$$n_p = \frac{b}{s+c} \tag{18}$$

$$d_p = \frac{s-a}{s+c} \tag{19}$$

Choose x_p and y_p as

$$x_p = \frac{a+c}{b}, \qquad y_p = 1 \tag{20}$$

Then the following Bezout identity equation (25) is satisfied:

$$x_p n_p + y_p d_p = \mathbf{1} \qquad (21)$$

Let

$$U(s) = C_1(s)R(s) - C_2(s)Y(s) \qquad (22)$$

From the H_∞ control theory (25), all the stabilizing compensators $C_1(s)$, $C_2(s)$ are given by

$$C_1 = (d_p + C_2 n_p)Q_1 \qquad (23)$$

$$C_2 = \frac{x_p + d_p Q_2}{y_p - n_p Q_2} \qquad (24)$$

where $Q_1, Q_2 \in RH_\infty$, RH_∞ is the subset of H_∞ consisting of real-rational functions, and H_∞ is the Hardy space. The H_∞ norm of a function $F(s)$ is defined as

$$\|F(s)\|_\infty = \sup\{|F(s)| : \operatorname{Re} s > 0\} \qquad (25)$$

Assume

$$R(s) = \frac{r_0}{s} \qquad (26)$$

$$T_L(s) = \frac{T_0}{s} \qquad (27)$$

Here r_0 and T_0 are constants. Since $a < 0$, choose

$$Q_1 = \frac{c}{b} \in RH_\infty \qquad (28)$$

$$Q_2 = -\frac{a(s+c)}{b(s-a)} \in RH_\infty \qquad (29)$$

From Eqs. (23) and (24), we obtain

$$C_1(s) = C_2(s) = \frac{c(s-a)}{bs} \qquad (30)$$

$$\frac{E(s)}{r_0} = \frac{1}{s+c} \in RH_\infty \qquad (31)$$

$$\frac{Y(s)}{T_0} = \frac{d}{(s+c)(s-a)} \in RH_\infty \qquad (32)$$

Therefore, the steady-state error is 0. The larger c is, the better the characteristics of robust regulation are (i.e., stabilization plus tracking and/or disturbance rejection). The feedback gains then can be determined as

$$K_1 = \frac{c}{b} \tag{33}$$

$$K_2 = -\frac{ac\tau}{b} \tag{34}$$

Iterative Learning Control. Iterative learning control is used to generate a reference input by repeatedly using the error information of the foregoing trials (26,27,28). With some differences, the principles of iterative learning control and repetitive control (29,30,31) are the same regarding the use of the error information of the preceding trials or periods. The error convergence condition of the former control system is similar to the stable condition of the latter one.

The iterative learning controller designed for the servomechanism and realized by using the microprocessor shown in Fig. 1, is given by

$$u(k) = x(k) + K_1\bar{e}_i(k) \tag{35}$$

$$x(k+1) = x(k) + K_2\bar{e}_i(k) \tag{36}$$

$$e_i(k) = r(k) - y_i(k) \tag{37}$$

$$\bar{e}_i(k) = \left(1 + \frac{\beta K_u}{\alpha}\right)e_i(k) + \tilde{e}_i(k) + \frac{\beta K_d[e_i(k) - e_i(k-1)]}{\alpha\tau} \tag{38}$$

$$\tilde{e}_{i+1}(k) = \begin{cases} 0 & (k < k_0) \\ \dfrac{K_u}{\alpha}e_i(k) + \tilde{e}_i(k) + \dfrac{K_d[e_i(k+1) - e_i(k)]}{\alpha\tau} & (k \ge k_0) \end{cases} \tag{39}$$

where i is the number of trials,

$$0 < \alpha < 0.5 \tag{40}$$

$$\beta = 1 - \alpha \tag{41}$$

$$\tilde{e}_1(k) = 0 \tag{42}$$

The system is stable if

$$0 < K_u < 2, \qquad 0 < K_d < \frac{2}{c} \tag{43}$$

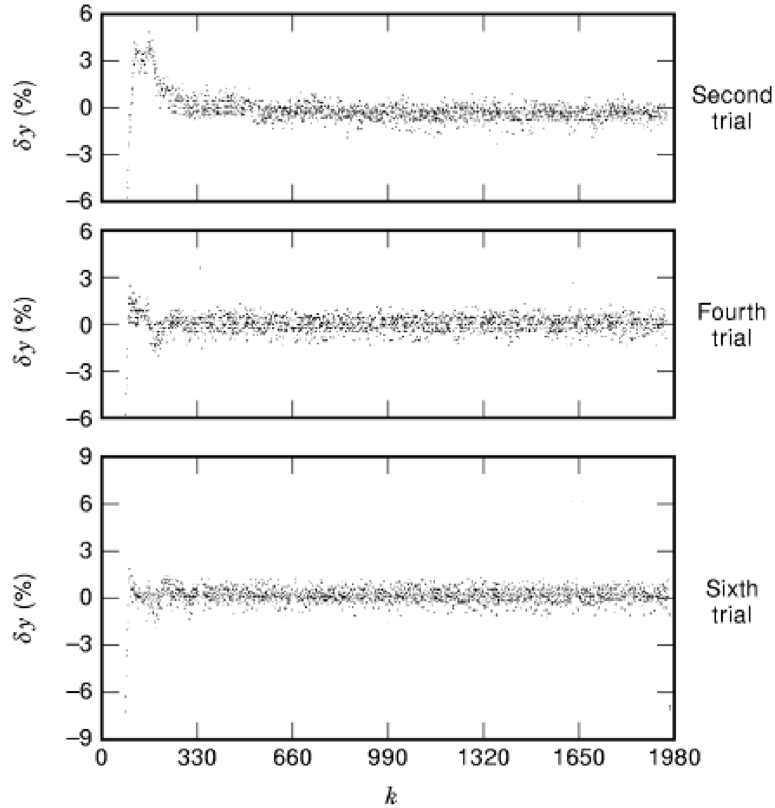

Fig. 7. Effect of the iterative learning control on the step response of the scanning servomechanism ($\alpha = 0.4$). A response without overshoot and undershoot and with very small rise time and setting time can be obtained.

Control Performance. To evaluate the control performance, for example, in a servomechanism, step response tests are usually conducted. The ideal servomechanism used in a scanner has step responses without overshoot and undershoot and with very small rise time and setting time.

In Fig. 1, the controlling input u is calculated by using the microprocessor. The load can be a real light-mirror mechanism used in a scanner system, or a dummy load connected to the servo motor with a flexible coupling, as shown in Fig. 2.

Tests have proved that it is possible but not easy to obtain a step response whose rise time and setting time are very small and with no overshoot, when the feedback gains are designed based on eigenvalue assignment or optimal regulator theory. This could be due to errors in identification of the actual system. However, the design based on the H_∞ control theory is robust, in spite of the existence of the same errors in modeling and identification. As shown in Fig. 3, when c is small the rise time, setting time, and overshoot are large, but when c is large enough the rise time and setting time become short and the overshoot is small.

Figure 4(b) shows that overshoot and rotational fluctuations still exist after redrawing the step response curve in Fig. 4(a) by enlarging the axis of the ordinate. When the iterative learning control is used in which $\alpha = 1$, as shown in Fig. 4(c), the system deteriorates. However, when $\alpha = 0.4$, by three times learning control, as shown in Fig. 4(d), a response almost without overshoot and rotational fluctuation can be obtained. In Fig. 4,

$y(k)$ is the sampling value of y:

$$\delta y = \frac{y(k) - \bar{y}}{\bar{y}} \times 100(\%)$$

$$\bar{y} = \frac{1}{1700} \sum_{k=250}^{1949} y(k)$$

The data shown in Figs. 3 and 4 are from the tests using the dummy load shown in Fig. 2. This is to prevent the light-mirror scanning mechanism from breaking in case a test fails at the first stage of the testing. For instance, the test shown by Fig. 4(c) may damage the servomechanism if the actual light-mirror system is used. Since the parameters of the dummy load system can be designed the same as those in the actual servomechanism, the results obtained using the two systems are almost the same.

Figure 5 shows a testing result of step response using a real light-mirror scanning mechanism. It is not easy to obtain a step response without overshoot, because u is a limited value and a wire and some springs are used in the servomechanism. The velocity step response indicated in Fig. 5 seems very good. However, when it is redrawn by shortening the axis of the abscissa and enlarging the axis of the ordinate, as exhibited in Fig. 6, it is clear that overshoot still exists. Again, when the iterative learning control is used in which $\alpha = 0.4$, by several times learning control, as shown in Fig. 7, a response without overshoot and undershoot and with very small rise time and setting time can be obtained.

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