CCD Array Scanning Servomechanism for a High Resolution Camera-Type Color Image Scanner*

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The need for a high-resolution camera-type color image scanner has become much keener, because such a scanner would make good man-machine interaction and high-quality image acquisition possible. This type of scanner, however, needs a highly accurate servomechanism to scan a CCD array. We have developed a compact and highly accurate CCD array scanning servomechanism with the following features. 1) A compact scanning mechanism having magnetic circuits of the CCD array scanning linear motor in common with those of a color filter changing linear motor. 2) A color filter changing servomechanism having a color filter carriage which closely follows the CCD array scanning carriage. 3) A highly accurate (1/4 000) position-sensing system employing another CCD array. By using this mechanism, a high-resolution (240 dots/inch for B 4-size document) camera-type image scanner has been attained.

Key Words: Servomechanism, Positioning, Mechatronics, Electronic Equipment, Automatic Control, Image Scanner, CCD, Color, Camera

1. Introduction

The need for high-resolution color images has been increasing as the processing capability of personal computers grows. Although various image scanners have been developed so far, most of them⁽¹⁾ are of the flat bed type. They have the problem of ineffective handling in man-machine interactive applications such as image filing systems and video conferences. When an operator tries to designate the specific region to be input, he cannot see the original document, because the document must be set face down, hidden from the operator during scanning. The camera-type image scanner has recently gained favorable attention in comparison with flat-bed-type image scanners. By using this type of scanner, the operator can see the original documents during scanning. He can also input the image of a solid body.

Some camera-type image scanners have been developed by using a two-dimensional CCD image

sensor. These scanners, however, cannot input a high-resolution image, because the image sensor has only 500×500 picture elements. Even with recent semiconductor technology, it is difficult to manufacture two-dimensional image sensors having more than $2\,000 \times 2\,000$ picture elements. Therefore, moving a one-dimensional CCD array in the direction perpendicular to itself for two-dimensional scanning is the most suitable way to obtain a high-resolution image. This kind of scanner needs a highly accurate scanning servomechanism to move the CCD array, because the image of the document is reduced by the optical lens. A color filter changing mechanism is also necessary for inputting color images.

In this paper, a compact and unique scanning servomechanism for a camera-type image scanner with a high resolution of 240 dots/inch is newly presented. In the beginning of this paper, an outline of the camera-type image scanner attained using this scanning servomechanism is described. The following sections describe the components of the developed mechanism: the scanning mechanism with a color filter changing mechanism, the high-resolution position sensing system employing a CCD array, the CCD

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array scanning servo system and the color filter changing servo system. Finally, experimental results of the manufactured mechanism are discussed to prove the performance of this mechanism.

Nomenclature

- r_i = command signal
 y_i = position
 d_i = disturbance
 M_i = moving mass of the linear motor
 KF_i = force constant
 KA_i = amplifier gain
 KS_i = sensor gain
 T = holding time of the position detector
 M = mutual inductance between two voice coils
 L_i = inductance of the voice coil
 R_i = reactance of the voice coil
 A_i = open gain of the driving amplifier
 Rf_i = detecting reactance of the driving current

Subscripts

$i=1$ and $i=2$ correspond to the scanning servo and the color filter changing servo, respectively.

2. Camera-Type Color Image Scanner

Figure 1 shows a block diagram of the developed camera-type color image scanner⁽²⁾. In this scanner, the original document is set face up on the flat base, over which the camera head containing the optical lens and the scanning servomechanism is mounted. The lens projects the image of the document on the focal plane, where a CCD image sensor array (4 000 picture elements) is moved perpendicularly for two-dimensional scanning by the scanning servomechanism. The scanning servomechanism also has three color filters (red, green, blue) and a transparent filter between the lens and the CCD array.

This servomechanism moves the CCD array with $7\ \mu\text{m}$ accuracy, equivalent to the picture element size when the image is input with high resolution ($4\ 000 \times 4\ 000$ dots). When the designated region of the document is input with the desired resolution, this servo-

Fig. 1 Block diagram of the scanner

mechanism moves the CCD array to the designated region quickly and scans with the step size proportional to the desired resolution.

In order to input a color image, the scanning servomechanism changes the color filters sequentially and scans for each filter to obtain each color component of the image. By using the transparent filter, the scanner also inputs black and white images speedily.

The output signal from the CCD array is fed into the signal correction circuits where shading distortion, uniformity of the sensor array, and gamma characteristics are corrected. The stored image is immediately observable via a high-resolution CRT monitor, which is of great help to an operator in deciding the desired resolution and region of the document.

3. Scanning Mechanism

Figure 2 shows the structure of the scanning mechanism. The scanning carriage on which the CCD array for image scanning is mounted, is supported by two guide bars and three ball bearings on the focal plane. The two voice-coil linear motors are attached, one on each side of the scanning carriage. The scanning carriage is smoothly driven in the scanning direction by the linear motors. The position of the scanning carriage is detected by another CCD array which is mounted on the camera base.

The carriage for changing the color filters is supported by three sliding bearing bushes and two guide bars which are mounted on the magnetic circuits of the linear motor. Four filters are set on this carriage at about 4 mm intervals. The two voice coils are attached on each side of the carriage as in the scanning carriage. It should be noted that the color filter carriage and the scanning carriage use the same magnetic circuit.

The four photointerrupters are set on the scanning carriage corresponding to each color filter, and the fin for the photointerrupters is attached to the color filter carriage. The relative position between the scanning carriage and the color filter carriage is detected by the fin interrupting the light from the

Fig. 2 Structure of the scanning mechanism

photointerrupters. Therefore, the relative position between the two carriages is kept at zero by feeding the detected position into the linear motor for the color filter carriage.

The color filter carriage and the scanning carriage are very light and small because the color filter carriage is not mounted on the scanning carriage. Thus, by using this structure, the entire mechanism is kept quite small.

4. High-Resolution Position-Sensing System

When a B4-size document is input with a resolution of 240 dots/inch, the positioning accuracy of the scanning carriage must be $1/2\ 500$ at least. Therefore, the resolution of the position sensing for the scanning carriage must be less than $1/2\ 500$. Conventionally, an optical encoder or a magnetic encoder has been used for the high-resolution position sensor. These are, however, very expensive and too large for this mechanism. Here, a new position-sensing system employing a CCD array has been developed to achieve highly accurate detection of the scanning position. The accuracy of this position-sensing system is equivalent to the pixel-to-pixel interval ($7\ \mu\text{m}$) of the CCD array, and the resolution of this system is $1/4\ 000$.

Figure 3 shows the block diagram of the position-sensing system and scanning servo system. The position-sensing system consists of an LED (light emitting diode), a mirror, a lens, a CCD array fixed on the camera base and a position-detecting circuit. The mirror and the lens, which are built to the scanning carriage, focuses a light of the LED on the fixed CCD array. The light corresponds to the scanning carriage position. The position-detecting circuit derives the position signal from the CCD array video signal.

Figure 4 shows the block diagram of the position-detecting circuit. This circuit consists of a CCD array driving circuit, two counter circuits, a D/A converter and a peak-detecting circuit. The CCD array is repeatedly driven by the driving circuit to obtain the video signal of the photospot image. In order to make the counter clock coincide with the driving clock of

Fig. 3 Block diagram of the scanning mechanism

the video signal, the pixelwise charge reset clock, ϕR , for the CCD array is input to the counters. Similarly, the counters begin position counting by the transport clock, ϕSG , which starts the CCD array scanning cycle. The counter is latched once in a cycle by the peak-detection pulse from the peak-detection circuit. The latched value corresponding to the photospot position is converted to the carriage position signal by the D/A converter.

Figure 5 shows the signal waveforms of the peak-detecting circuit. The video signal is fed to an LPF (low pass filter) to cut out the high-frequency component. The output signal from the LPF is fed to an HPF (high pass filter) to obtain the differential signal, and the differential signal is fed to a zero cross comparator to obtain the peak-detection pulse signal. These processes avoid the influence of peak amplitude fluctuations in the video signal.

5. Servo System

The scanning servo system consists of a CCD array scanning servo system and a color filter changing servo system as shown in Fig. 3.

In the scanning servo system, the scanning signal from the MPU (microprocessing unit) is fed into the controller of the system. The signal is a ramp signal, and its slope is variable according to the desired resolution of the inputting image. The controller feeds the error signal between the scanning signal and the detected position signal into the linear motors for the scanning carriage.

Fig. 4 Block diagram of the position sensing system

Fig. 5 Signal waveform of the peak detecting circuit

The controller of the filter changing servo system feeds the relative position signal detected by the photointerrupter into the linear motors for the color filter carriage to follow up the scanning carriage. By selecting one photointerrupter from the four, the desired color filter is selected to obtain the color component of the image.

Figure 6 shows a detailed block diagram of the entire servo system, and Table 1 shows the transfer functions of the servo system. In this block diagram, the two linear motors are modeled as a second-order integral element. The position-detecting circuit is modeled as a time lag and zero-order holding element, because it contains the counter circuit and the D/A converter. $G_{11}(s)$ and $G_{22}(s)$ are the transfer functions of the scanning carriage driving amplifier and the color filter carriage driving amplifier, respectively. $G_{12}(s)$ and $G_{21}(s)$ are the transfer functions modeled on the electromagnetic interaction between the two linear motors. The interaction occurs because the two linear motors use common magnetic circuits. In this servo system, however, it was confirmed by computer simulation and experiments that the interaction did not affect the responses of the servo system at all. This is because the bandwidth of the servo system is much lower than this interaction frequency band. Therefore, the interaction can be ignored when the servo system is designed.

The transfer function, $C_i(s)$ [$i=1$ to 5], shows the compensators of the servo system. The servo

Table 1 Transfer function of the servo system

$C_1(s) = \frac{a_1 s + a_0}{s^2 + a_1 s + a_0}$	$G_{11}(s) = \frac{Z_1 A_1}{Z_1 Z_2 - M^2 S^2}$
$C_3(s) = \frac{g_0}{s^2 + b_1 s + b_0}$	$G_{12}(s) = \frac{M A_2 S}{Z_1 Z_2 - M^2 S^2}$
$C_4(s) = \frac{b_1 s + b_0}{s^2 + b_1 s + b_0}$	$G_{21}(s) = \frac{M A_1 S}{Z_1 Z_2 - M^2 S^2}$
*) $Z_i = L_i S + R_i + (1 + A_i) R_{fi}$	
	$G_{22}(s) = \frac{Z_1 A_2}{Z_1 Z_2 - M^2 S^2}$

*) $i=1$ and $i=2$ correspond to the scanning servo and the color filter changing servo respectively.

Fig. 6 Detailed block diagram of the servo system

system must be designed robustly to disturbance forces for high-resolution scanning. The compensators have been designed by the polynomial algebraic method^{(3),(4)} based on the robust control theory. By using this method, the stabilizing compensator, $C_2(s)$, has been designed systematically. The compensator is constructed of a phase lag-lead element and a phase lead-lag element. The former is for high stiffness of the system in the low-frequency region, and the latter is for stabilizing the system. The precompensator, $C_1(s)$, is an LPF for smoothing the scanning signal from the MPU, because the D/A converter produced a step-shaped signal.

$C_3(s)$ and $C_4(s)$ construct the observer to estimate a more accurate position of the scanning carriage from the output signal of the position sensing system and the driving current of the scanning linear motor.

Figure 7 shows the signal waveforms of the observer which are simulated by a computer. In this figure, Y_1 is the real position of the scanning carriage, and Y_{s1} and Y'_{s1} are the output signals of the position-sensing system and the output signal from the observer, respectively. From the figure, it should be noted that the position-detecting error, caused by the time lag and the zero-order holding element in the D/A converter, is compensated for by the observer. The bandwidth of the observer is chosen similar to the scanning servo system.

$C_5(s)$ in the color filter changing servo system is designed as a simple phase lead-lag element. This is because less accurate positioning is required for the color filter carriage than for the scanning carriage.

6. Experimental Results

The scanning servomechanism described in the preceding sections was manufactured so that its performance could be tested.

Figure 8 shows the detected scanning signal for the scanning carriage, the detected position signal of the scanning carriage, the detected error signal between the scanning signal and the position signal,

y_l : Real position of the scanning carriage
 y_{sl} : Output signal from the position sensing system
 $y'sl$: Output signal from the observer circuit

Fig. 7 Simulation of the observer circuit

and the detected relative position signal between the two carriages. Those are the signals when the mechanism is scanned with $7\text{ }\mu\text{m}$ accuracy. From this figure, it is confirmed that the scanning position error is less than $7\text{ }\mu\text{m}$. On the other hand, the relative-position needs less than 1 mm , because the width of each color filter is 2 mm . It is also confirmed that the relative position is less than $200\text{ }\mu\text{m}$ from Fig. 8. This mechanism also proves that random access to any position within 400 ms is possible.

Figure 9 shows the camera-type image scanner developed using this scanning mechanism. By using this scanner, it is confirmed that the color image of the document is input with 240 dots/inch resolution.

7. Conclusions

For a high-resolution (240 dots/inch for B4-size document) camera-type image scanner, a compact and highly accurate CCD array scanning servomechanism has been developed. This servo-mechanism has the following features.

(1) Compact linear motors drive the color filter carriage and the scanning carriage, using a common magnetic circuit.

(2) A unique color filter changing mechanism using a servo system in which the color filter carriage follows closely the scanning carriage of the CCD array.

(3) A highly accurate ($1/4\text{ }000$) position-sensing system employing the CCD array.

Scanners using this scanning servomechanism are expected to make it very easy to improve man-machine interaction in such computer systems as image filing systems and video conferences.

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Fig. 8 Signal waveform of the servo system

Fig. 9 Scanner using the scanning mechanism

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