Optical Scanning System for Recording Large Image*

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An optical scanning system for reading and recording large images with 1 m width has been developed. The laser beam is deflected by an acousto-optical deflector (AOD) and the optical head on which the imaging lens is mounted is moved at high speed in a direction perpendicular to the optical scanning axis. A mechanical feed parallel to the optical scanning axis is added in order to scan the entire surface of the image. To maximize the scanning speed, the laser beam is separated into two beams and two data sets are read and recorded simultaneously. Variations in the optical length caused by the movement of the optical head must be considered in the design of the optics. A cylindrical lens and a ROM for maintaining a constant-frequency sweeping speed are necessary in order to compensate for the cylindrical effect of the AOD. Since the light intensity is too low for use of a CCD to be effective, it is necessary to use a photomultiplier as the scanner.

Key Words: Information Processing Equipment, Optical Instrument, Communication Equipment, Optical Engineering, Laser

1. Introduction

Graphic communication systems, particularly those used in the printing industry, require large plotters and scanners. In this work we describe a feasibility study of a novel scanning technology for these instruments which achieves a scanning length of up to 1 m.

An optical scanning system with a polygonal mirror is widely used in these systems; however, the following problems occur in optical scanning of large images.

(1) First, dynamic accuracy of the polygonal mirror is difficult to maintain due to its large size.

Second, the aperture size of the f θ lens which is used to compensate the proportionality between the deflection angle and the image height on the scanning plane is considerably large.

(2) There is a time loss during scanning due to interference between the beam and the edges of the polygonal mirror parallel to the rotation axis. This does not decrease with increasing scanning length.

Taking the above into account, we have developed a new system combining optical scanning and mechanical reciprocating motion. There is a time loss during reciprocating motion due to deceleration, stopping, and acceleration when changing direction. However, the time loss decreases with increasing scanning length. Moreover, the scanning length can be easily varied and the nonrecording area can be jumped, unlike in a system with rotating motion. However, it is necessary to scan plural lines with one mechanical motion since the speed of linear motion is generally low in comparison to the speed of rotating motion. Hence, two acousto-optical deflectors (AODs) are used together which scan 256 lines each in direction perpendicular to the direction of the reciprocating motion. Thus 512 lines are scanned

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simultaneously and bandwidth is doubled. The lines scanned by the two AODs are combined alternately.

2. System Design

Figure 1 shows the scanning method of the plotter. The first AOD scans 256 lines separated by a distance of two pixels, and the other 256 lines which alternate with the first set of lines are scanned by the second AOD. The high-speed mechanical motion of the optical head on which the lens and the mirror are mounted is perpendicular to the direction of the AOD scan. The motion of the table on which the recording medium is mounted is also perpendicular to the movement of the optical head. The entire surface of the recording medium is scanned due to the combination of the above three movements.

The angle between the optical axis of the AOD which is fabricated from TeO_2 crystal⁽¹⁾ and the first-order diffracted beam is determined by the ultrasonic driving frequency of the AOD. Therefore, optical scanning is performed by continuous sweeping of the driving frequency⁽²⁾.

Figure 2 shows the optical system of the plotter. An argon laser beam is deflected by the AOD and transmitted to the collimator after modulation by the acousto-optical modulator (AOM). The $f\theta$ lens is necessary in order to maintain a constant distance between the deflected lines on the flat recording surface, since the angle of the beam is proportional to the

Fig. 1 Scanning configuration with AOD and high-speed mechanical motion

Fig. 2 Configuration of optical system for the plotter

driving frequency of the AOD.

The scanner is also moved mechanically and utilizes the combination of two optoelectrical scanning operations as in the plotter. Either a photomultiplier (PMT) or a CCD can be used as the detector, but the corresponding optical systems are quite different.

Table 1 shows the specifications of the system. The maximum image density is 1500 lines per inch (LPI). The maximum total deflection angle and the maximum scanning length of the AOD are 44.27 mrad and 10.84 mm respectively, which depend on the image density. The maximum modulation frequency is 10 MHz.

3. Optical System of the Plotter

3.1 Design of the $f\theta$ lens

The distance between the light source and the $f\theta$ lens in this system varies according to the movement of the optical head, in contrast to the case of the conventional $f\theta$ lens. Spherical aberration and curvature of field do not change with the distance; however, coma, astigmatism and distortion change considerably. Concave single lenses with short focal lengths used as the $f\theta$ lens contribute to the change in aberration. It is necessary to avoid such lenses and use single lenses which have long, uniform focal lengths in order to decrease the change in aberration.

The spot size on the recording surface produced by an $f\theta$ lens with focal length f_{θ} is determined by the wavelength λ and the incident beam size D . The distance between the lines recorded by the two beams must also be d . The angle θ_i between the two beams incident on the $f\theta$ lens determines d as follows (Fig. 3).

$$d = f_{\theta} \cdot \theta_i \quad (1)$$

The distance P between the two incident beams is determined as follows using the total focal length f_{col} of the collimator system, which includes the collimator lens and the beam expander.

$$P = f_{\text{col}} \cdot \tan \theta \approx f_{\text{col}} \cdot \theta \quad (2)$$

Table 1 Specifications of the system

Picture size	: Max. 950mm width
Image density	: 600 to 1500 lines per inch
Modulation frequency	: Max. 10MHz
Moving speed of optical head	: Max. 1m/s
Plotter	
Light source	: Argon laser split into two beams
Scanning method	: AOD and mechanical
Scanner	
Detecting method	:
1. Photomultiplier with scanned laser beam	
2. CCD array with halogen lamp illumination

Fig. 3 Ray diagram for $f\theta$ lens, collimator, and beam expander

Fig. 4 Optical path of $f\theta$ lens
Incident beam size : 5.07 mm
Distance between pupil and lens : 944.4 mm

(a) On axis

Optical head position : 482 mm

(b) End of scanning

Optical head position : 950, 20 mm

Fig. 5 Two-dimensional intensity distribution of spots of $f\theta$ lens

Image density : 1 000 LPI

and

$$\frac{P}{d} = \frac{f_{col}}{f_{\theta}} \quad (3)$$

The focal length of the $f\theta$ lens is determined from the above relations. Figure 4 shows an optical path diagram of a designed $f\theta$ lens with a focal length of

244.83 mm at the maximum distance between the light source and the lens.

Figure 5(a) shows the calculated intensity distribution of the spot on the optical axis at the midpoint of the optical head movement. Figure 5(b) shows the result on the end of scanning at the farthest and nearest positions of the optical head movement. Almost identical spots are obtained for the entire scanning area.

3.2 Divergence of the beam

There is a divergence of the scanning AOD beam in the mainscanning direction⁽³⁾. Therefore, the focal points for the mainscanning direction and the subscanning direction with astigmatism are different. This is due to the deviation of the diffraction angle with the ultrasonic frequency sweeping.

The distance F_s between the center of the AOD and the center of divergence is given by,

$$F_s = \frac{V^2 \cdot T}{\lambda \cdot \Delta f} \quad (4)$$

where V is the transmission speed of the ultrasonic wave, T is the sweeping time, λ is the wavelength of the laser, and Δf is the range of driving frequency.

The astigmatism can be compensated by positioning a cylindrical lens at the exit of the AOD. The cylindrical lens must be interchangeable since the focal length of the lens must be varied according to the variation of divergence with the sweeping time, which is determined by the image density.

3.3 Recording experiment

An experimental scanning system is fabricated to verify its feasibility. A pattern consisting of dots separated by a distance equal to the diameter of one dot is recorded by AOD scanning and movement of the optical head. Recording is performed using different curvatures of the cylindrical lens. The driving conditions of AOD are as follows.

Sweeping time (T) : 36.76 μ s

Access time : 11.37 μ s

Frequency (f) : 84.87 MHz to 145.13 MHz

Range of frequency (Δf) : 60.26 MHz

From Fig. 6, it is observed that the new scanning method realizes two-dimensional scanning; however, there are areas where the dots are clearly separated and areas where the dots are defocused and merge. The area with good resolution varies with the curvature of the cylindrical lens. The separation of dots is obtained at the center of the image using a small-radius lens, and the area in which the dots are separated gradually moves into both ends of scanning with increasing lens radius. This shows that continuous variation of divergence occurs with scanning which results in variation of the compensated area as shown in Fig. 7.

Fig. 6 Recording of 1 dot pitch pattern for full scanning length of AOD using cylindrical lenses with various curvatures
Image density : 1 000 LPI

Fig. 7 The estimation of clearly recorded area for cylindrical lenses with various curvatures in relation to angle of divergence and position of scanning

The cylindrical lens is designed assuming that the sweeping speed of the AOD, df/dt , is constant, which ensures a constant divergence. It is found that the frequency sweeping speed is not constant, as shown in Fig. 8, through measurement of the drive circuit. Thus, variation in the divergence of the beam occurs which results in defocusing.

The variation of the divergence is due to the characteristics of the drive circuit of the AOD⁽³⁾. A ROM is used to compensate the sweeping speed and make it constant. Figure 9 shows the improved results obtained with this compensation. Separation of the recorded dots is observed over the entire scanned area, but the dots do not appear to be round. The irregularity in the shape of the dots is probably due to decentering of the optics which can be improved by accurate adjustment.

It is clarified that the proposed scanning system satisfies the target specifications of the plotter.

4. Optical System of the Scanner

4.1 Detection by PMT

Figure 10 shows the configuration of an optical

(a) Designed

(b) Measured

Fig. 8 Error of frequency sweeping speed of AOD

Fig. 9 Recording with the compensation of linearity of frequency scanning speed
Radius of cylindrical lens : 306.5 mm
Laser output : 3.8 mW
Image density : 1 000 LPI

Fig. 10 Configuration of optical system of the scanner with PMT detection

system with a PMT as the detector. The laser beam, scanned using the same optical system as that in the plotter, illuminates the object. The light reflected from the object is detected from two different directions in order to read an object partially obscured. The f_0 lens, the imaging lenses, and the mirrors are mounted on the moving optical head. The light reflected through the imaging lens and the fixed lens is

separated into two beams by the two surfaces of the roof mirror and led to two PMTs in order to read two adjacent lines simultaneously. Therefore, four PMTs are used in the scanner.

The length of the optical path of the reflected light varies with the movement of the optical head. Variation of the focal point is avoided by converting the reflected light a parallel beam using a collimator consisting of the imaging lens and the fixed lens.

A detection experiment is carried out using the two $f\theta$ lenses of the plotter as the imaging lens and the fixed lens. The difference in the signal levels of white and black patterns is 20 mV for illumination without scanning. The quantity of light must be increased since the target value is 1 V and the quantity of light decreases with scanning.

The F number of the $f\theta$ lenses should be small to increase an accepted quantity of light; however, it is 19.3 in the experiment. A second experiment is conducted using an $F:1$ lens as the imaging lens and a single lens as the fixed lens. The difference in the signal levels becomes 0.7 to 1.4 V even at one-quarter of the normal laser output. However, the F number should be large to decrease the size of lens to minimize the inertia of mechanical motion and to obtain the depth of focus necessary to read pasted up object. Figure 11 shows the designed optical system of the scanner. The F number of the imaging lens is 3.5.

The total resolution of the system including the imaging lens and the fixed lens is calculated. The modulation transfer function (MTF) relating the resolution to the spatial frequency is shown in Fig. 12 with respect to the defocus on the image plane. The image density is 1 000 LPI and the distances between the two lenses are 1 000 mm and 20 mm. The resolution at a distance of 1 000 mm is almost aberration-free; on the other hand, the MTF at a distance of 20 mm is lower in the mainscanning direction. However, separation of the reflected light from the two lines is

Fig. 11 Optical system design of the scanner with PMT detection

possible since it is influenced by the resolution in the subscanning direction.

4.2 Detection by CCD

The CCD is a self-scanning device; therefore, illumination is not necessary for scanning. The experimental setup consists of a 300 W halogen lamp and two condenser lenses used to illuminate a target from two directions. The CCD has 256 pixels and a clock frequency of 2.8 MHz. The output of the CCD is saturated if a $F:4$ imaging lens without magnification is used; however, the temperature rise of a 300 W halogen lamp is fairly large.

Therefore, the voltage of a lamp which saturates the CCD output is measured with a 50 W halogen lamp while varying the iris of the imaging lens. The result is shown in Fig. 13. The output is saturated at 60% of the standard voltage with the iris open. On the other hand, the iris should be $F:7$ to 8 in order to maintain the depth of focus necessary for a pasted-up picture. Furthermore, the clock frequency of the scanner is 10 MHz which is 3.6 times that used in the experiment. Thus, it is difficult to decrease the power of the halogen lamp while maintaining the required intensity of light.

Next, the experiment with a He-Ne laser is

(a) Distance between imaging lens and fixed lens: 1 000 mm

(b) Distance between imaging lens and fixed lens: 20 mm

Fig. 12 Calculated total resolution of optical system of the scanner with PMT detection
Image density: 30 lines/mm

Fig. 13 Halogen lamp voltage which saturates CCD signal in relation to F number

(a) He-Ne laser, lighting from oblique direction
Object : white paper

(b) He-Ne laser, lighting from oblique direction
Object : pasted-up paper

(c) Halogen lamp, lighting from two directions
Object : pasted-up paper

Fig. 14 Output voltage of CCD with various objects and illumination conditions

V : 0.5 V/div, H : 20 μ s/div

carried out. A 10 mW laser is used as the light source and the beam is focused into a line using the optics. The driving condition of the CCD is the same as that in the experiment with the halogen lamp. The objects are white paper and a 0.23 mm-thick pasted-up paper. Figure 14 shows the output voltage of the CCD compared to that with illumination using the 300 W

halogen lamp. The shaded area of the pasted-up portion is observed in the signal.

The intensity of light is sufficient since the output is saturated; however, a stable signal cannot be obtained due to the speckle noise of the laser; thus, it is necessary to reduce the coherence of the laser beam by some optical means⁽⁴⁾.

The influence of the pasted-up portion is small for detection by PMT since the signal is obtained using the corrected light intensity. In contrast, it is large for detection by CCD since the reflected light is detected as an image. Furthermore, the magnification of the imaging lens on the recording head must be changed with variation of the image density. This increases the weight of the optical head. It is preferable to use a PMT as the detector in the scanner.

5. Conclusions

Feasibility studies of a plotter and a scanner are carried out by scanning an image surface 1m wide using an AOD and high-speed mechanical motion. The results are as follows.

(1) An $f\theta$ lens with varying location of the incident pupil is designed, and uniform resolution for the full scanning length is obtained. The desired quality of the plotter is obtained for the full scanning length using this lens and compensation of the astigmatism of the beam and the nonlinearity of the frequency sweeping speed of the AOD is achieved using a cylindrical lens and a ROM in the drive circuit, respectively.

(2) The necessary light intensity and resolution of the scanner are obtained for PMT detection and the illumination system using the same laser scanning method as that in the plotter and optimization of the F number of the imaging lens. It is difficult to obtain the necessary light intensity for CCD detection by illumination with a halogen lamp without heating problems. Also, a stable signal cannot be obtained by illumination with a He-Ne laser due to speckle noise.

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