

Color Pen-shaped Scanner

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Abstract

A color pen-shaped scanner has been developed. A compact imaging configuration, SOFI (Single Optical Fiber Imaging), enables us to contain a linear image sensor, an array of red, green and blue light emitting diodes (LEDs) and all the other components in a pen-shaped housing. Color imaging is realized by turning on one color LEDs at a time, storing the sensor output as one color information of the input line and repeating this process for the other two color LEDs. The width of the scanner is 13mm and the input width is 110mm. The maximum input speed is 2cm/sec at 200dpi resolution. The average color difference for 21 color patches is 16.0 and 7.4 before and after the matrix correction, respectively.

Introduction

Electronic document input devices have been widely used for some time as facsimiles and also as peripheral devices for personal computers. A facsimile machine and a flatbed scanner are probably the most common and a sheet-fed scanner is gaining its popularity. While these devices are well accepted in a spacious office, a more compact, truly portable device would be desired for some people. A hand-held scanner is an existing compact device but its volume is not small enough to be called “truly portable.” Its almost square body blocks the view of an operator and interferes with objects around a document.

We have studied these features and proposed a pen-shaped scanner [1]. Its housing contains a linear image sensor, a linear array of LEDs, a roller and other mechanical components needed for a hand-held scanner. This pen-shaped housing enables us to place the scanner in a narrow space such as the binding area of a book. It allows us to watch the input area of a document more clearly while scanning. When combined with a touch-sensitive screen of a notebook computer or a personal digital assistant, it also works as a stylus for pen-input. We have already developed a monochrome 200 dpi scanner with 110mm input width and document scanning has been successfully demonstrated [1]. With its 10mm-wide housing and its maximum scanning speed of 12cm/sec, its feel of use is promising. Although this may be adequate for some business purposes, color capability is highly desirable especially for personal use.

Wakabayashi et al. studied the use of LEDs for color scanner applications [2]. Komiya et al. demonstrated color imaging by switching three-color LEDs and detecting the reflected light by a CdS-CdSe photo-conductor image sensor directly in contact with a document [3]. Recently, a relatively compact color image sensor module has been reported by Hamaguchi et al. [4]. Their module contains a linear image sensor, a rod-lens array and a three-color LED array and the height and width of its housing is 11mm and 18mm, respectively. This module does not contain a roller and other mechanical components needed for a hand-held scanner application. Therefore, it is too big to be contained in a pen-shaped housing although it may be compact enough for a sheet-fed scanner.

We have refined the designs of our pen-shaped scanner to incorporate the color capability. In this paper, design considerations are described first. Prototype development and evaluation of color reproduction are described in the following sections.

Design Considerations

Single Optical Fiber Imaging (SOFI)

We have developed a compact imaging configuration which enables us to contain all the components inside a small housing. This is illustrated in Fig.1. Here, an image sensor fabricated on a transparent substrate is coupled to an array of optical fibers. A linear array of LEDs is placed over the image sensor. Each pixel of the image sensor has a photodiode with multiple apertures where the light from the LED array can pass through. This light is transferred inside the fibers and illuminates the document in contact with the fiber array. The reflected light comes back in the same fibers and is detected by the photo-sensitive part of the pixel. An opaque electrode of the photodiode blocks direct illumination. Since a single optical fiber is involved for both illuminating the document and detecting the reflected light, we call this configuration Single Optical Fiber Imaging (SOFI). This optical arrangement and other components such as a roller and front-end electronic circuits are compact enough to be contained in a small pen-shaped housing.

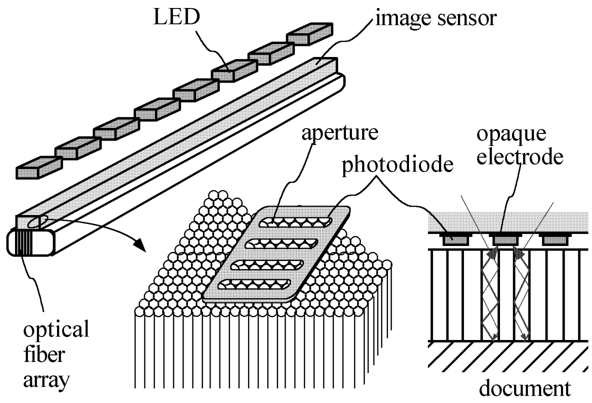

Figure 1. Single Optical Fiber Imaging (SOFI)

Important design parameters include the shape of the aperture, the fiber diameter and numerical aperture, the angular distribution of the light emitted by the LED array, the distance between the LED array and the image sensor, etc. Characteristics to be optimized are the signal yield and the spatial resolution. Choosing the right combination for these design parameters requires lengthy simulation and prototyping. Since the parameter set described in [1] has given adequate characteristics for a monochrome scanner, we have decided to keep these parameters unchanged and focus on two other aspects of the design considerations. These are how efficiently we can use the limited space inside a pen-shaped housing and how color imaging is realized.

Double-Decker Configuration

Following components are to be contained in a housing: a linear image sensor, an array of optical fibers, a linear array of color LEDs, a roller, a rotary encoder which detects the roller rotation, and the associated electronic components. A double-decker structure as shown in Fig.2 helps to use the limited space in the housing efficiently. Here, red, green and blue LEDs are placed on the top printed circuit board. LED selection is important for good color reproduction and this is discussed later in this paper. A linear image sensor, an array of optical fibers and all the mechanical parts such as a roller and gears are placed on the bottom printed circuit board. These two boards are mechanically and electronically connected to each other by the corresponding connectors on each board. This configuration assures good alignment between the image sensor and the LED array. This alignment is especially important for efficient use of the light emitted by LEDs because the light is focused on a narrow line by a small-diameter cylindrical lens. Since the two boards are electronically connected, some electronic components for the image sensor can be placed on the top board. The bottom board can be a part of the scanner housing.

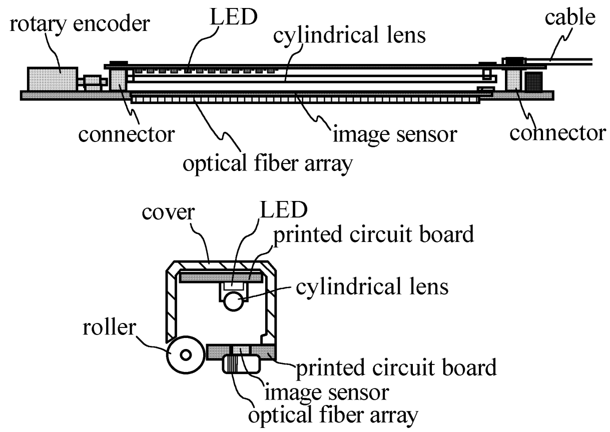

Figure 2. Cross-sections of a pen-shaped hand-held scanner.

Three-Color LED Switching Method

Color imaging is realized by turning on one color LEDs at a time, storing the image sensor output as one color information of the input line and repeating this process for the other two color LEDs. An alternative approach using a white light source and an image sensor with color filters on photo-sensitive elements can read a document faster. However, for our hand-held scanner, we have decided to accept the slow scanning speed of the former approach in exchange for the advantages of using the existing monochrome image sensors and also lowering the power consumption by the LED array. The timing chart for driving the image sensor and the LED array is shown in Fig.3.

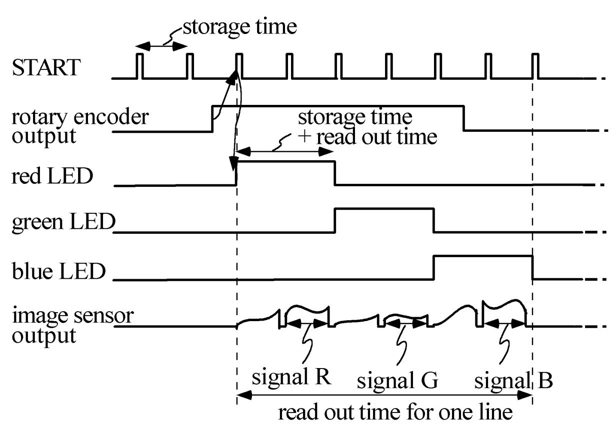

Figure 3. Three-color LED switching method.

The color information on one line of a document is acquired by the following sequence. A driving signal START is given to the image sensor at a constant rate, reading out the bright or dark information of the line all the time. Since each photodiode stores photo-generated charges and are reset to its initial potential at this rate, this interval is called “storage time”. As soon as the scanner is displaced by a predetermined value, the red LEDs are turned on first. This on-time duration must be longer than the sum of the storage time and the read out time required to reset all the photodiodes. During this period, the signal is read out twice from the image sensor. The first sensor output is ignored since the storage time is not constant for all the photodiodes. The second sensor output is acquired as the image data. The same sequence is repeated for the green and blue LEDs.

Color LED Array

Three types of LEDs are to be selected and mounted on a printed circuit board. A chip-type packaging configuration is suited for this purpose. Since its emission angle is designed to be large, a small-diameter cylindrical lens can be used to focus the light on a narrow linear region. For a high signal to noise ratio, it is desired for all of the three LEDs to have a high light intensity. Bright red LEDs have been around for many years and bright blue and green LEDs have become commercially available in the last few years [5,6]. We have acquired several types of LEDs and measured their light intensities. The emission spectra for these LEDs are shown in Fig.4. The curves are indicated by their color-codes and are scaled so that the area under each curve is proportional to its light intensity. There is one bright LED and one less bright LED for each color.

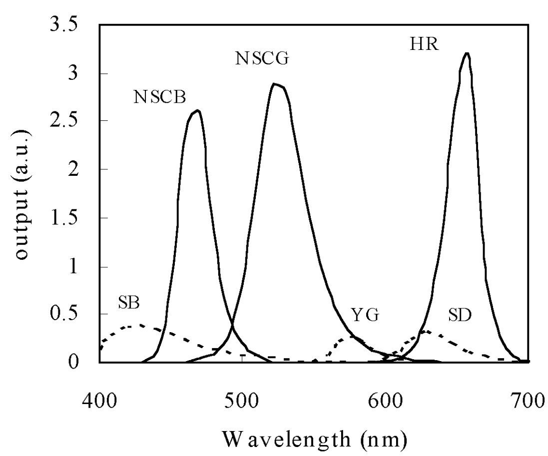

Figure 4. Emission spectra for several LEDs.

Neugebauer's quality factor indicates how well a color sensor can reproduce an original color. It is calculated for each of the three color sensors from its spectral sensitivity, which is determined by the selection of LEDs, the quantum efficiency of the photo-sensitive element, and the transmission characteristics of a color filter, if any. The photo-sensitive element of the image sensor used in our pen-shaped scanner is an amorphous silicon (a-Si) photodiode. It is possible to alter its quantum efficiency by varying fabrication conditions. If color filters are used, it is also possible to vary their transmissions. Although these quantities affect the color sensor outputs, we regard these variables as fixed for a moment and focus on the choice of color LEDs. Neugebauer's quality factors are calculated for some LEDs and the results are summarized in Table 1.

Table 1. Neugebauer's quality factor

Blue	q_B	Green	q_G	Red	q_R
NSCB	0.51	NSCG	0.44	HR	0.05
SB	0.80	YG	0.72	SD	0.32

Among the eight possible combinations of three-color LEDs in Table 1, the best LED combination in terms of the quality factors is SB-YG-SD. The worst combination is NSCB-NSCG-HR. Ironically, the former LED set is the worst in terms of the light intensity and the latter LED set is the best. It is known that scanners with poor quality factors can reproduce original colors well if a 3x3 matrix color correction is employed [7]. Therefore, we have chosen the NSCB-NSCG-HR combination for our color LED array design.

Experiment

Prototype Color Scanner

A linear image sensor has been fabricated on a glass substrate by amorphous silicon (a-Si) and poly-crystalline silicon (poly-Si) technology [8]. A part of this sensor is photographed and is shown in Fig.5.

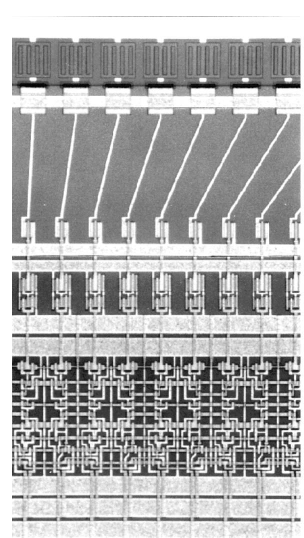

Figure 5. Photograph of the image sensor.

The sensor has 864 pixels and each pixel consists of an a-Si photodiode with multiple apertures and a poly-Si thin film transistor (TFT) as an analog switch. These poly-Si TFTs are turned on and off by a shift-register which is also a poly-Si TFT circuit built on the same substrate. The pixel pitch is 125 mm.

The photograph in Fig.6 shows the pixel area in detail after the image sensor is coupled to an array of optical fibers. Light passing through the apertures in the photodiodes and the optical fibers can be clearly seen in the figure.

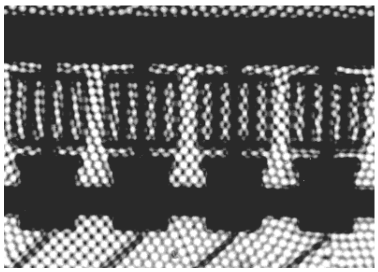

Figure 6. Photograph of the pixel area.

With this image sensor and other components, a prototype scanner has been developed. A photograph in Fig.7 shows the cover, the color LED array and the bottom plate which supports the image sensor coupled to an array of optical fibers, a roller, a rotary encoder, and other mechanical components. The color LED array is placed over the image sensor and is connected to the bottom plate by the connectors. The width and the height of this scanner are both 13mm.

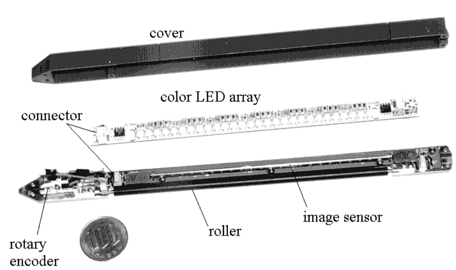

Figure 7. Photographs of the prototype scanner.

At present, the storage time is set to 1msec and the read out rate is 1µsec/pixel. Since the image sensor has 864 pixels, the read out time of 864 µsec and a blanking time of 136 µsec is repeated. Each of the three color LEDs are turned on for 2µsec every time when the scanner is displaced by 125mm. Therefore, it takes at least 6msec to acquire all the color information from a single line and the maximum scanning speed is 2cm/sec.

Imaging characteristics has been evaluated. The signal to noise ratio is 100 for each color and the spatial resolution is the same with our previous monochrome scanner [1]. The average power consumption by the color LED array is less than 300mW.

A color document has been scanned by this prototype successfully. Acquired images are displayed on a liquid crystal display of a notebook computer as shown in Fig.8. Here, a 3x3 matrix color correction is not employed. Even without a color correction, the reproduced images look fine to our naked eyes.

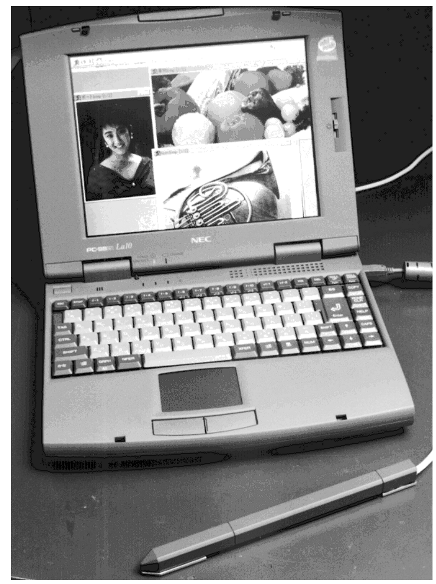

Figure 8. Photographs of the color pen-shaped scanner and a notebook PC displaying the color images acquired by the scanner.

Color Fidelity

The degree of color reproduction was evaluated by the following steps. First, we prepared 21 color patches, measured their spectral reflectances under the standard light source D50, and estimated their tri-stimulus values. Second, these patches were scanned by the pen-shaped scanner and the tri-stimulus values before and after a 3x3 matrix color correction were obtained. Third, these values were compared in the CIELAB space and the color difference ΔE^*ab was estimated. The average color difference for these 21 color patches is 16.0 before the matrix correction and 7.4 after the correction. These numbers are comparable with those in [2,3]. Chromaticity coefficients are plotted for each of these 21 colors in Fig.9.

The solid circles in Fig.9 are the coordinates of the original colors. The empty circles and the triangles are the coordinates of the reproduced colors before and after the matrix correction, respectively. The arrows indicate the changes of coordinates by the color correction. In most cases, the correction reduces the color differences but the differences remain relatively large for the red-purple area. This is consistent with the calculation of the Neugebauer's quality factors, which shows poor color reproduction for the red sensor.

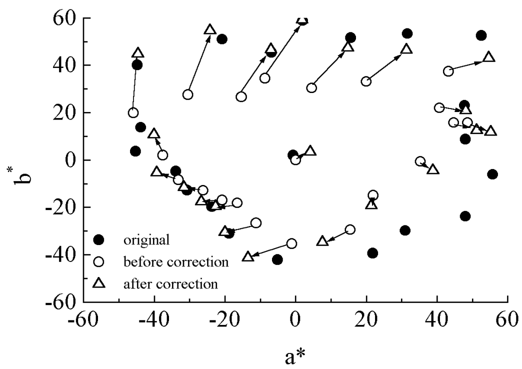

Figure 9. Chromaticity coefficients (a^*,b^*) the 21 colors.

Conclusions

Design of a color pen-shaped scanner has been studied. A compact optical arrangement, Single Optical Fiber Imaging (SOFI), a double-decker configuration and a three-color LED array are the key features of this development. In SOFI configuration, an array of optical fibers is coupled to a linear image sensor whose photo-sensitive elements have multiple apertures. The small space in a pen-shaped housing is efficiently utilized by the double-decker structure of the image sensor and the LED array. As for the selection of LEDs, it is ironic that the best LED combination in terms of color fidelity is the worst in terms of light intensity and vice versa. We have designed the LED array with our emphasis on the light intensity. We have also adopted the three-color LED switching method at the expense of the scanning speed.

With these design considerations, we have developed a prototype pen-shaped color scanner. The width of the scanner is 13mm and the input width is 110mm. The maximum scanning speed is 2cm/sec at 200dpi resolution. Adequate color fidelity has been obtained.

Acknowledgments

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