CMOS vision sensor with fully digital image process integrated into low power 1/8-inch chip

Xiangliang Jin (金湘亮)[1,2*], Zhibi Liu (刘志碧)[1], and Jie Chen (陈 杰)[1]

[1] *SuperPix Micro Technology Limited, Beijing 100085, China*

[2] *Mechanical and Materials Engineering Department, University of Western Ontario, London, Canada*

[*] *E-mail: xjin32@uwo.ca*

Received May 22, 2009

A digital still camera image processing system on a chip, different from the video camera system, is presented for mobile phone to reduce the power consumption and size. A new color interpolation algorithm is proposed to enhance the image quality. The system can also process fixed patten noise (FPN) reduction, color correction, gamma correction, RGB/YUV space transfer, etc. The chip is controlled by sensor registers by inter-integrated circuit (I^2C) interface. The voltage for both the front-end analog and the pad circuits is 2.8 V, and the volatge for the image signal processing is 1.8 V. The chip running under the external 13.5-MHz clock has a video data rate of 30 frames/s and the measured power dissipation is about 75 mW.

OCIS codes: 100.0100, 250.3140, 250.5300.

doi: 10.3788/COL20100803.0282.

Charge-coupled device (CCD) is a widely used image sensors in vision systems. Complementary metal-oxide semiconductor (CMOS) imaging technology emerges as an alternative solid state technology for CCD. Because the manufacturing process with standard CMOS technology is easily intergrated with digital signal processing circuit, the main advantages of CMOS over CCD are low power dissipation, low cost, and small size[1,2]. Most commercia available CMOS sensors offer user configuration of color channel gain, integration time, and offset cancellation in analog signal processing like CCD signal processing. It results in large chip size and high power dissipation. Mobile phone camera requires CMOS vision sensor with lower power dissipation, lower photodiode area, and smaller consumed printed circuit board (PCB) size[2,3].

The mobile phone camera also requires slight color errors, random noises, and artifacts[4]. In this letter, we consider a digital mobile phone camera system on a chip. On the vision camera chip, noise reduction, auto-exposure (AE), and auto white balance (AWB) are integrated into the vision chip. The performance of the automatic adjustments of noise reduction, AE, and AWB is improved, which is important for high image quality under various shot conditions. Also, these functions, such as color interpolation, gamma correction, RGB/YUV space transfer, etc., have been integrated into the digital processing. A new color interpolate algorithm is proposed to enhance the image quality. The final image can be output in RGB or YUV format. A compact inter-intergrated circuit (I^2C) data transfer function is designed in the chip for control of the sensor registers. The proposed system consumes low power of 75 mW.

The block diagram of proposed image signal processing system for the mobile phone CMOS vision sensor is shown in Fig. 1. The data from the front-end circuit of CMOS vision sensor is first used after removing the fixed pattern noise (FPN). And then color interpolation must be performed to obtain a full resolution color image and the color correction is used to adjust the gains of RGB to correct color errors. AWB is used to adjust RGB colors to a proper ratio by regulating RGB gains. The gamma correction block is used to adjust the color data to adapt to the computer display. According to the luminance distribution, the AE block regulates the auto gain amplifier in the front-end circuits to keep optical exposure condition. After the space converter and the image processing, the data is output to be displayed or stored in the computer. To meet the demands of various scenes, a lot of programmable factors are stored in the register and the factors can be modified by the I^2C interface to improve the image quality.

The digital data from analog to digital converter (ADC) reduces the FPN noise by the digital FPN scheme as (shown in Fig. 2) before image processing. When the sensor powers grow up, the switch S1 first closes. In the first frame, the values of R, G, and B add accumulatively and then the average values are got and stored in the static random access memory (SRAM) respectively.

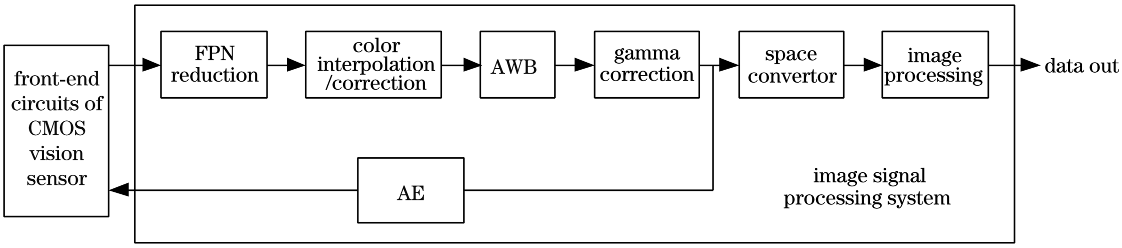

Fig. 1. Block diagram of proposed image signal processing system.

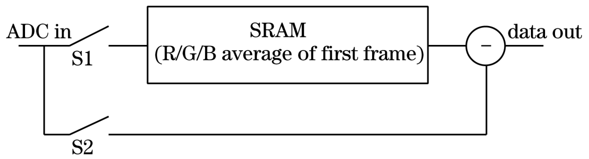

Fig. 2. Digital FPN reduction scheme.

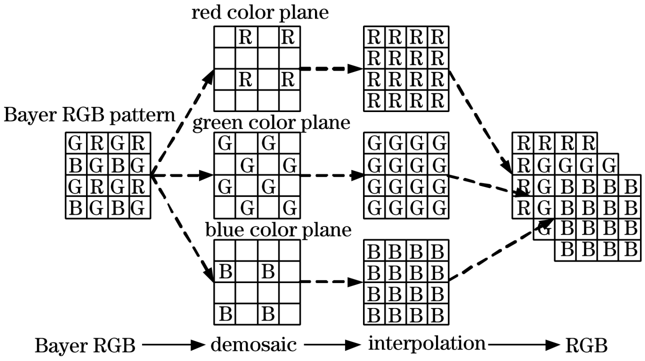

Fig. 3. Color processing.

Then S2 closes and S1 opens in the second frame, the pixel data of R, G, and B subtracts the SRAM value of corresponding R, G, or B. The data difference is the net signal without FPN noise.

The mostly used color filter array (CFA) is the Bayer pattern as shown in Fig. 3. Red and blue are sub-sampled at a rate of 1/2 in both horizontal and vertical directions, while green is sub-sampled at a rate of 1/3 only in the horizontal direction. For implementing the color interpolation and color correction, the Bayer RGB pattern is processed with the demosaic programmer. In general, the bilinear interpolation algorithm[5] is an effective method to perform the color interpolation. In this letter, the new color interpolation algorithm is proposed as shown in Fig. 4. This correlated information among the adjacent pixels is used to improve the image quality. When the green is in the center of window as Fig. 4, the detailed algorithm follows

$$R'_{23}=G_{23}-\sum_{\substack{(g,h)\in\zeta\\(m,n)\in\zeta}} f_1(G_{gh},R_{mn}), \tag{1}$$

$$B'_{23}=G_{23}-\sum_{\substack{(g,h)\in\zeta\\(m,n)\in\zeta}} f_2(G_{gh},B_{mn}), \tag{2}$$

where f_1 and f_2 are the correlated functions. Using similar algorithm, the functions can be obtained if the center is red or blue.

After color interpolation, the image should be corrected[7]. The correction coefficient matrix is

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} +1.2840 & -0.1132 & 0.1197 \\ -0.1164 & +1.3908 & -0.1283 \\ -0.1390 & -0.1487 & +1.3550 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{3}$$

If the RGB value of CMOS vision sensor has been fixed, for a same color scene, the image color will be dependent on the lighting. The AWB is used to adjust RGB colors to a proper ratio through regulating their gains. Owing to the affection of the optical lens, the responses of different regions in the same image are different with the same lighting. The image is divided into five areas as shown in Fig. 5, and there is an accumulator to calculate for each region, and the size can be changed by users.

B_{11}	G_{12}	B_{13}	G_{14}	B_{15}
G_{21}	R_{22}	G_{23}	R_{24}	G_{25}
B_{31}	G_{32}	B_{33}	G_{34}	B_{35}

Fig. 4. New color interpolation digram.

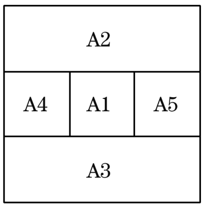

Fig. 5. Diagram of AWB.

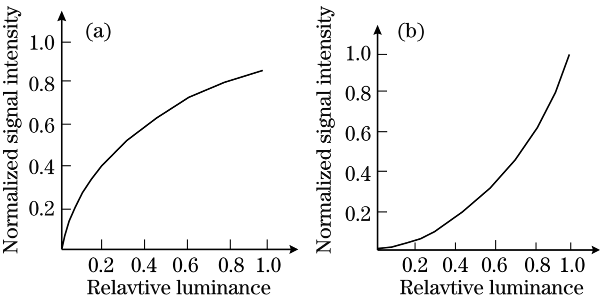

Fig. 6. (a) Cathode ray tube (CRT) display curve and (b) gamma correction curve.

In many digital image displays and printers, the relation between the pixel grayscale values and the luminance of both displays and printers is nonlinear as shown in Fig. 6(a). However, the relation between the incident light luminance and the photo-electric signal is linear. In the image digital processing, the gamma correction should be added and the gamma correction curve is shown in Fig. 6(b). In this letter, the gamma correction function is expressed as

$$R(G,B)_{\mathrm{gc}}=255\times\left(\frac{R}{255}\right)^{\frac{1}{\gamma_{\mathrm{R/G/B}}}}, \tag{4}$$

where $\gamma_{\mathrm{R/G/B}}$ is the gamma coefficient of R, G, and B[8].

Through the I^2C interface the photodiode array can be programmable to be divided into multiple areas up to 16×16. There is an accumulator for each area to accumulate pixel luminance. These accumulation results are stored in the memory for AE. According to the luminance distribution, the AE controller regulates the auto gain amplifier in the front-end circuits to keep optical exposure condition.

Converting an image from RGB to YUV color space is possible to separate the image's luminance and chrominance information of the image. There is a linear relationship between the YUV color space and the RGB color space, and its transfer function is expressed as

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} +0.299 & +0.587 & +0.114 \\ -0.148 & -0.289 & +0.437 \\ +0.615 & -0.515 & -0.100 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \quad (5)$$

It is obvious that green is the biggest contributor to luminance because the human eyes have higher sensitivity to green than to other colors[7,8].

A typical CMOS vision sensor is shown in Fig. 7. In such a sensor, all functions are integrated into the chip, i.e., camera on a chip. The irradiance light energy of the incidences on the pixel array through the optical lens is converted to electrons in the photodiode active pixel array. In color CMOS vision sensor, a red, green, and blue filter array (called the Bayer pattern) is used. The converted electronic signal is red out by the row/column decoder. Analog signal process performs the noise reduction, the signal range expansion, analog to digital conversion, etc. The simple control logic and timing function is also integrated into the front-end block that finally outputs the digital signal to image signal processing. Noise reduction, auto exposure, and AWB are key functions to be integrated in the mobile phone camera with their special know-how. The system also can perform color interplation, gamma correction, space transfer, etc. The functionality is achieved by using dynamic control of sensor registers by I^{2}C interface. Both front-end signal processing and image signal processing constitute the CMOS vision sensor for mobile phone.

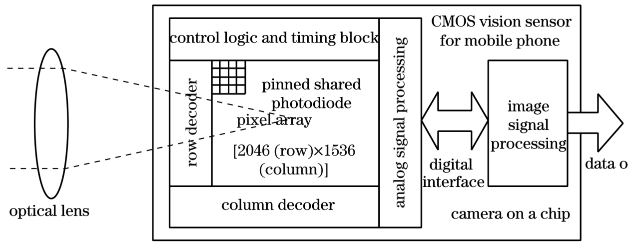

Fig. 7. Proposed system of mobile phone camera.

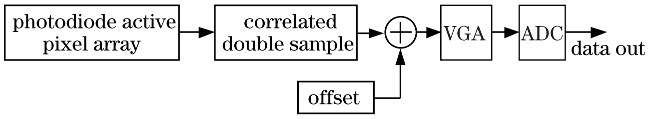

Fig. 8. Front-end analog signal path.

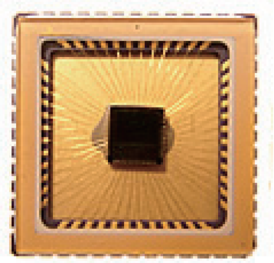

Fig. 9. PLCC packaged chip.

Figure 8 shows the key analog signal path. The photo electronic transformation is corrupted by various sources of noise, including the device noise and operation noise. The signal from pixel array is first input to the noise reduction unit (the correlated double sample). To obtain enough large value for ADC, one variable gain amplifier (VGA) is needed on a chip to enlarge the signal range. Finally, the output signal is digital data. And band-gap circuit is also integrated into the chip to provide the suitable current and voltage to analog block.

For power reduction through architectural design and arithmetic optimization, the power consumption can be further reduced by the layout of the parasitical capacitor and resistor. A prototype ultra-thin 1/8-inch CMOS image sensor has been implemented using 0.18-μm CMOS technology. Figure 9 shows the photo of plastic leaded chip carrier (PLCC) packaged chip.

The noise performance is important for CMOS image sensor to capture the high quality images. The total noise has been tested in the chip with increasing the exposure time as shown in Fig. 10. In general, the chip operates under the normal condition of 30 frames/s at 12-MHz system clock rate clock and its noise level is below 0.8 mV due to the pinned pixel technology, noise reduction circuit, and design optimization. In the long exposure time model, the average and accumulated noise increases to above 2 mV at 200 ms. With the exposure time further increasing to 500 ms, the noise is increasing more than 6 mV, but generally the chip does not work in this mode. And the high quality image is output from this chip, as shown in Fig. 11. In this chip, the voltage for both the front-end analog and the pad circuits is 2.8 V and the voltage for image signal processing is 1.8 V. The power dissipation measured for the chip running under the external 13.5-MHz clock is about 75 mW while the chip has a video date rate of 30 frames/s. The pixel signal-to-noise ratio (SNR) is up to 43 dB and the dynamic range of the signal path is about 68 dB with an 11-bit ADC. Table 1 shows the key characteristics compared with other products.

Table 1. Key Characteristics Compared with Other Products

Vendor	Omnivision	Pixelplus	Samsung	Magnachip	This Work
Product Number	OV7680	PO4030K	S5K83	MC501	–
Pixel Size (μm)	2.2×2.2	2.6×2.6	2.8×2.8	3.0×3.0	2.8×2.8
Lens Size (inch)	1/10	1/8.6	1/8	1/7.4	1/8
Power at 30 Frames/s (mW)	–	123	–	160	75
SNR (dB)	40	–	–	42	43
Dynamic Range (dB)	50	56	–	60	68
Process Feature Size (μm)	0.13	0.15	0.15	0.18	0.18

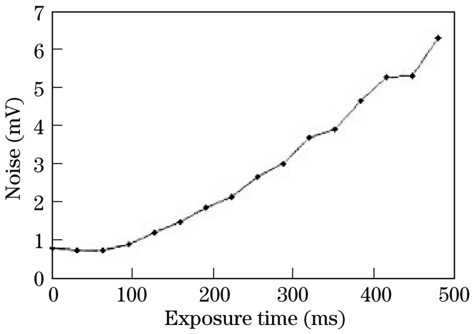

Fig. 10. Dark noise test result.

Fig. 11. High quality image output from the proposed chip.

In conclusion, mobile phone camera requires CMOS vision sensor with low power dissipation, small photodiode area, and small consumed PCB size. A compact front-end system including pixel array, readout circuit, programmable gain amplifier, ADC, row/column decoder, band-gap, etc., is proposed. All of these circuits perform low noise and low power analog signal processing. A digital still camera image processing system on a chip is presented for mobile phone. Noise reduction, AE, and AWB are integrated in the mobile phone camera. The system can also process a color interpolation, gamma correction, color space transfer, etc. The functionality is achieved by using dynamic control of sensor registers by I^{2}C interface.

This work was supported by the National "863" Program of China under Grant No. 2008AA01Z130. The authors would like to thank the people at Tower and SuperPix for their support of this investigation.

References

1. K. Yoon, C. Kim, B. Lee, and D. Lee, IEEE J. Solid-State Circuits **37,** 1839 (2002).
2. S. Yoshihara, Y. Nitta, M. Kikuchi, K. Koseki, Y. Ito, Y. Inada, S. Kuramochi, H. Wakabayashi, M. Okano, H. Kuriyama, J. Inutsuka, A. Tajima, T. Nakajima, Y. Kudoh, F. Koga, Y. Kasagi, S. Watanabe, and T. Nomoto. IEEE J. Solid-State Circuits **41,** 2998 (2006).
3. C. Wang, R. Zhang, and F. Deng, Chin. Opt. Lett. **7,** 483 (2009).
4. Y. Muramatsu, S. Kurosawa, M. Furumiya, H. Ohkubo, and Y. Nakashiba, IEEE J. Solid-State Circuits **38,** 101 (2003).
5. T. Sakamoto, C. Nakanishi, and T. Hase, IEEE Trans. Consumer Electron. **44,** 1342 (1998).
6. I. Kharitonenko, S. Twelves, and C. Weerasinghe, IEEE Trans. Consumer Electron. **48,** 2 (2002).
7. T. Olsen, "An improved image processing chain for mobile terminals" PhD. Thesis (Agder University College, Grimstad, 2002).
8. G. Chen, K. Yang, R. Chen, and Z. Xie, Chin. Opt. Lett. **6,** 468 (2008).