Postprint of a Digital Camera Crosstalk Image Correction Method Based on Calibration and Image Processing

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Abstract

To address the issue of output image overlap in multi-channel digital cameras caused by signal crosstalk, tracking tests were conducted on crosstalk coefficients based on data from a self-developed four-channel CCD digital camera system, revealing that the crosstalk coefficients exhibit specific patterns with respect to input signal intensity and system readout speed. For this type of system noise-like crosstalk, a crosstalk image correction method based on calibration and image processing is proposed. This method establishes the relationship between crosstalk proportion coefficients and pixel DN (Digital Number, DN) values through calibration, then deduces the interference amount in the disturbed channel from the crosstalk channel, performs system error correction through a restoration algorithm, and ultimately eliminates crosstalk. Test results demonstrate that images corrected by this method exhibit crosstalk levels reduced to the magnitude of background white noise, with image quality significantly improved. This method shows significant effectiveness in eliminating fixed-pattern noise caused by hardware process defects in imaging systems, and also suppresses system noise-like interference. In practical applications, it can serve as a supplementary approach for optimizing image quality in general imaging systems.

Full Text

Method for Crosstalk Image Correction in Digital Cameras Based on Calibration and Image Processing

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Abstract: To address the problem of output image overlap caused by signal crosstalk in multi-channel digital cameras, we conducted tracking tests on crosstalk coefficients using data from a self-developed four-channel CCD digital camera system. The results revealed specific relationships between the crosstalk coefficient, input signal intensity, and system readout speed. For this type of system-noise-like crosstalk, we propose a crosstalk image correction method based on calibration and image processing. This method establishes the relationship between the crosstalk proportion coefficient and pixel DN (Digital Number) values through calibration, then back-calculates the interference amount in the disturbed channel from the crosstalk channel, and finally eliminates crosstalk through a restoration algorithm for systematic error correction. Test results demonstrate that after correction, the crosstalk level can be reduced to the magnitude of baseline white noise, with substantial improvement in image quality. This method shows significant effectiveness in eliminating fixed-pattern noise caused by hardware process defects in imaging systems and also suppresses system-noise-like interference, serving as a valuable supplement for image quality optimization in general imaging systems.

Keywords: signal crosstalk; data fitting; systematic error correction; digital camera

Crosstalk is a common yet challenging problem encountered in the development of various imaging systems. For optical digital cameras, crosstalk manifests as the coupling influence of one pixel on another, essentially interference noise triggered by signal coupling. Numerous factors can cause crosstalk, which can be categorized into two major types based on their formation mechanisms: optical crosstalk and electrical crosstalk. The magnitude of crosstalk is related to optical components in the system, detector structure, backend amplifier signal coupling, and inter-channel coupling factors in signal processing circuits [**?**].

When crosstalk occurs, the interfering channel radiates signals to adjacent channels [**?**]. At this point, the signal in the disturbed channel originates not only from its own channel but also includes coupled signals from neighboring channels. The interference source channel acts as both an interference source for other channels and is simultaneously affected by interference from other channels [**?**]. The more channels operating concurrently, the more complex the effects of inter-channel signal crosstalk become [**?**]. Crosstalk reduces image clarity, affects the resolution performance of the detector focal plane array, and comprehensively impacts the quality of images output by the imaging system.

Currently, extensive research exists on crosstalk, with corresponding control measures adopted for different crosstalk types and problem manifestations. In circuit design, crosstalk in multi-channel signal systems can be actively reduced through methods such as enhancing power supply filtering, reducing ground resistance, using different components for different channels, increasing transmission line spacing, reducing parallel line length, changing transmission line media, expanding transmission bandwidth, and adding shielding lines between transmission lines [?]. After image acquisition, crosstalk can be eliminated through targeted crosstalk modeling and software algorithms, such as linear approximation correction algorithms [?].

The causes of crosstalk are complex, with varying degrees of crosstalk induced by different factors. One particular type exhibits characteristics similar to system noise—its value either remains constant or follows a specific variation pattern, with known or comprehensible causes, and demonstrates regularity, unidirectionality, and repeatability [?]. For this type of crosstalk, we have developed a crosstalk elimination method based on calibration and image data fitting [?]. Verification shows that this method can reduce crosstalk to the magnitude level of baseline white noise without modifying circuit hardware, achieving good correction effects on crosstalk images. This paper primarily introduces the correction basis and elimination algorithm for crosstalk, and verifies the practical effectiveness of the method through experiments.

1. Basis for Crosstalk Correction

1.1 Determination of Crosstalk Degree

Based on a self-developed application-specific integrated circuit, we built a four-channel CCD monochrome digital camera [?]. [Figure 1: see original paper] illustrates the imaging principle of this digital camera [?]. After being illuminated by a light source, objects reflect light that passes through the lens and projects onto the CCD image sensor, generating photoelectrons. Following exposure, photoelectrons are read out from the CCD image sensor, then amplified, denoised, digitized, and data-fused through multi-channel readout circuits to finally form a digital image [?].

The camera’ s readout circuit is a self-developed application-specific integrated circuit containing four identical signal processing circuits that parallel-process the four analog image output signals from the CCD image sensor [?], as shown in [Figure 2: see original paper]. Each signal processing circuit channel corresponds to one output amplifier in the CCD image sensor, with the four signal processing channels operating independently and finally combining into a digital image through data fusion. This digital image is formed by directly combining raw CCD data after baseline subtraction, where specific regions of the image can reflect the conditions of the corresponding signal processing circuits [?].

After completing camera development, we conducted long-term performance monitoring. During monitoring, we discovered inter-channel image crosstalk, with abnormal image overlap appearing in the final digital images, likely caused by insufficient isolation between the four channels due to process defects within the readout circuit chip. To address this, we evaluated the crosstalk degree using the following method.

Select any two readout channels, labeled A and B. Apply a test signal to channel A and zero input to channel B (i.e., short to ground). Under identical conditions, simultaneously read out images from both channels A and B. Since channel B is shorted to ground, its output image should exhibit a flat white noise pattern identical to the baseline background if no crosstalk occurs. If channel A crosstalks into channel B, interference images from channel A will be observable in channel B' s image to some degree. The stronger the crosstalk, the more pronounced the interference image becomes.

[Figure 3: see original paper] shows the output images from channels A and B in our system, with amplitude plots on the left and grayscale legend bars on the right indicating the grayscale range. The crosstalk degree from channel A to channel B in [Figure 3: see original paper] is approximately 4‰. To facilitate visual observation, we increased the display contrast of [FIGURE:3(b)]. Selecting a row with strong channel A signal—row 1416—and reading its pixel amplitude values reveals the crosstalk amount from channel A (blue portion) to channel B (red portion), as shown in [Figure 4: see original paper]. The experimental setup captures images of 2048$×$2248 pixels, where columns 1-1024 belong to channel B, columns 1025-2048 to channel A, columns 2049-2148 to channel B baseline overscan region, and columns 2149-2248 to channel A baseline overscan region.

Let the output signal of channel A be S_A, the system background noise of channel A be N_A; the output signal of channel B be S_B, and the system background noise of channel B be N_B. The crosstalk proportion coefficient from channel A to channel B is c_{AB}, defined as:

$$c_{AB} = \frac{S_B - N_B}{S_A - N_A} \tag{1}$$

The image signal transmitted in channel A will superimpose onto channel B at a certain proportion, causing crosstalk noise. According to equation (1), the crosstalk amount from channel A to channel B is $c_{AB}(S_A - N_A)$. For digital images, each pixel' s current value in channel A will generate a corresponding crosstalk value in channel B.

If c_{AB} remains constant or follows a specific variation pattern, the crosstalk amount corresponding to each pixel point can be precisely calculated and subtracted to achieve crosstalk removal.

1.2 Possible Factors Affecting the Crosstalk Proportion Coefficient

Different environmental factors influence c_{AB} differently, requiring multiple tests to verify whether the relationship curve between c_{AB} and specific factors remains constant. We conducted experimental monitoring on our self-developed system, observing the relationships between c_{AB} and signal intensity, as well as between c_{AB} and readout rate.

1.2.1 Varying Input Signal Strength in Channel A to Observe Changes in c_{AB} While maintaining constant signal readout rate (i.e., unchanged channel operating frequency), we varied the input signal magnitude to channel A and monitored its effect on channel B. The input signal strength in channel A was controlled by adjusting exposure time, which was incrementally increased from 1s, 2s, 3s, ⋯, to 12s. From the 12 images obtained, we selected the mean value of a fixed region in each image as the measurement point and calculated c_{AB}. This test was conducted in two groups, with statistical results showing similar patterns (as shown in [Figure 5: see original paper]), where the crosstalk proportion coefficient c_{AB} exhibits a slightly decreasing relationship with increasing input signal (longer exposure time).

1.2.2 Varying Readout Rate of Input Signal in Channel A to Observe Changes in c_{AB} While maintaining constant input signal magnitude (i.e., same laboratory environment, illumination intensity, and exposure time), we varied the channel readout rate and monitored channel A' s effect on channel B. The readout time for both channels was incrementally increased from 1 s, 2 s, 3 s, ⋯, to 10 s. From the 10 images obtained, we selected the mean value of a fixed region in each image as the measurement point and calculated c_{AB}. This test was conducted in three groups, with statistical results showing similar patterns (as shown in [Figure 6: see original paper]), where the crosstalk proportion coefficient c_{AB} remains almost unchanged with increasing readout rate.

1.3 Distribution Law of Crosstalk Proportion Coefficient vs. Pixel DN Number

Experiments revealed that c_{AB} follows consistent patterns with signal input intensity and operating frequency. We summarized these patterns into a relationship table directly correlated with output image pixel values, i.e., a distribution law table of c_{AB} versus pixel DN number. This relationship table is more convenient for image processing. [Figure 7: see original paper] shows the distribution law of c_{AB} versus pixel DN number obtained through calibration experiment sampling and least-squares interpolation fitting under three gain modes, where the x-axis represents pixel DN number (for 16-bit dynamic range digital images, DN ranges from 0 to 65535), and the y-axis represents the crosstalk proportion coefficient c_{AB} from channel A to channel B (calculated using equation (1)).

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2. Elimination Algorithm

Based on the distribution law statistics from Section 1.3, we can clearly determine how much crosstalk component from channel A is contained in channel B' s output image. According to this distribution law, solving for the crosstalk amount for each pixel point in the disturbed channel based on the corresponding crosstalk coefficient and performing reverse subtraction can effectively eliminate crosstalk effects.

2.1 Distribution Law Calibration

Before algorithmic elimination, the distribution law between c_{AB} and pixel DN number must first be calibrated. After system startup and stabilization, camera gain, readout speed, and other parameters are adjusted to specific values and held constant. Input signal intensity is then varied sequentially, and corresponding images are acquired. From these images, a uniform fixed region is selected, and the crosstalk proportion coefficient c_{AB} is calculated using equation (1). The calculated proportion coefficients are used to plot the c_{AB} versus pixel DN number distribution curve for that parameter mode through interpolation. Then, camera gain or readout speed is changed, and the process is repeated until the distribution laws for c_{AB} versus pixel DN number under all gain modes are obtained.

This step ensures the correctness of the distribution law. After operating for some time, the system may experience slight changes in the distribution law curve due to environmental variations. However, because the procedure is cumbersome and time-consuming, calibration is generally performed only for long-term or currently used shooting modes.

2.2 Crosstalk Elimination Process

After obtaining the distribution law of c_{AB} versus pixel DN number under system operating conditions, this law can be utilized for crosstalk elimination. We qualitatively describe the crosstalk elimination process through the crosstalk calculation model shown in [Figure 8: see original paper].

In [Figure 8: see original paper], channel A's signal point F2 (with value A_2) generates a signal with value A_1 at point F1 in channel B due to channel crosstalk, where A_1 is a value that varies according to A_2. In this system, points F1 and F2 exhibit a mirror-symmetric relationship. Our objective is to obtain the c_{AB} value for point F2 based on the distribution law of c_{AB} versus pixel DN number, then calculate the corrected value for point F1 (denoted as L_1) using equation (3), and replace A_1 with L_1 to achieve crosstalk denoising.

The specific processing steps for crosstalk noise elimination are as follows:

(1) Acquire an image containing both channels A and B, calculate and store the baseline value (system background noise value) for each pixel in channel A. Using point F2 as an example, calculate the system background noise M_{20} at point F2.

The calculation method for M_{20} involves selecting a small fixed-size block BOX_{20} in channel A' s system background noise region, with its center point sharing the same row as F2, and calculating the average value of all points within BOX_{20}, denoted as M_{20}.

(2) According to equation (2), subtract the baseline from pixel point F2 to obtain the "pure pixel," i.e., the pure pixel PP_2 at point F2.

$$PP_2 = A_2 - M_{20} \tag{2}$$

(3) Based on the distribution law of c_{AB} versus pixel DN number, find the c_{AB} value corresponding to PP_2.

(4) According to equation (3), calculate the crosstalk correction value L_1 for point F1 and replace A_1 with L_1:

$$L_1 = A_1 - c_{AB} \times PP_2 \tag{3}$$

where $c_{AB} \times PP_2$ represents the crosstalk amount caused by point F2 on point F1.

(5) Traverse all points F_i in channel A within the image, first calculate L_1, then replace A_1 with L_1, until the entire image crosstalk noise elimination process is completed.

(6) After calculation, the crosstalk-eliminated image is obtained.

3. Effect Verification

The crosstalk elimination method described in this paper was implemented in Python, with the main algorithm flow shown in [Figure 9: see original paper]. Before executing the crosstalk algorithm, the program statistically obtains the crosstalk distribution laws under different operating modes based on calibration data, i.e., the correspondence table between digital DN numbers and crosstalk proportion coefficients. The program then reads the image to be processed and processes the image data according to the elimination steps.

Since pixels in the same row of the CCD image used in the verification experiment share the same background baseline noise, the background baseline noise value data can be shared. Therefore, during algorithm design, the baseline data was pre-calculated and stored for direct table lookup in subsequent operations, which is more efficient than real-time computation.

We used the above program to process two sets of images containing crosstalk and obtained the crosstalk-noise-eliminated images, as shown in [Figure 10: see original paper] and [Figure 12: see original paper]. The left side of each figure shows the original image, while the right side shows the corrected image after crosstalk elimination. For visual comparison convenience, the display range of the images was uniformly mapped to grayscale values between 5000-10000.

We conducted data analysis on channel B (the disturbed channel) before and after crosstalk elimination in [Figure 10: see original paper] and [Figure 12: see original paper], including: the standard deviation S_b of baseline region pixels corresponding to channel B' s crosstalk region, the standard deviation S_B of all channel B image region pixels, and the maximum local CT value in the image crosstalk region. These parameters were compared to evaluate crosstalk elimination effectiveness.

(1) **Standard deviation S_b of baseline region pixels corresponding to channel B' s crosstalk region**

$$S_b = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}} \tag{4}$$

where X_i is the value of a pixel point in the region, $\bar{X}$ is the average value of all pixel points in the region, and n is the total number of pixel points in the region.

S_b reflects the dispersion degree of pixel values in channel B' s camera overscan region.

(2) **Standard deviation S_B of all channel B image region pixels**

S_B reflects the dispersion degree of all pixel values in channel B, calculated using the same method as equation (4).

(3) **Maximum local CT value in channel B' s crosstalk region**

Select a region in the brightest part of channel B' s crosstalk image, then select the corresponding regions in channel A, channel B's baseline region, and channel A' s baseline region, and calculate the CT value for this region.

$$CT = \frac{\bar{X}_B - \bar{X}_{B_{\text{baseline}}}}{\bar{X}_A - \bar{X}_{A_{\text{baseline}}}} \tag{5}$$

where n is the total number of pixel points in the region and $\bar{X}$ is the regional average value. The maximum CT can reflect the maximum influence coefficient of channel crosstalk.

[Figure 10: see original paper] shows the comparison before and after processing for Test Case 1. The calculated parameter values before and after crosstalk elimination are presented in :

TABLE:1 Test Case 1 Parameter Table

Parameter	Before	After
Local maximum CT	2.95$×10^{-3}$	7.61$×10^{-6}$

Selecting row 1000 at the middle of the crosstalk region, we read the pixel values of this row to compare changes before and after crosstalk elimination, as shown in [Figure 11: see original paper].

[Figure 12: see original paper] shows the comparison before and after processing for Test Case 2. The calculated parameter values before and after crosstalk elimination are presented in :

TABLE:2 Test Case 2 Parameter Table

Parameter	Before	After
Local maximum CT	3.65$×10^{-3}$	1.19$×10^{-6}$

Selecting row 1250 at the middle of the crosstalk region, we read the pixel values of this row to compare changes before and after crosstalk elimination, as shown in [Figure 13: see original paper].

The test case results demonstrate that crosstalk occurs significantly in the image region of the CCD image sensor, while the baseline overscan region is almost unaffected. Before crosstalk elimination, the local maximum CT value constituting crosstalk to channel B was at the 10^{-3} magnitude; after crosstalk elimination, the overall S_B for channel B dropped to the level of the baseline overscan region, with the local maximum CT value suppressed to the 10^{-6} magnitude. Reading the pixel values of a row in the crosstalk occurrence region ([Figure 11: see original paper], [Figure 13: see original paper]) clearly shows that after crosstalk processing, the crosstalk pixel values in channel B are restored and return to baseline level.

The test results indicate that the method proposed in this paper has a significant effect on eliminating channel crosstalk noise.

Conclusion

For the crosstalk problem in multi-channel digital imaging systems, this paper proposes a crosstalk elimination method based on calibration and image processing. This method establishes the correspondence between the crosstalk proportion coefficient c_{AB} and pixel DN numbers, back-calculates the interference amount for each pixel point in the disturbed channel through the crosstalk channel, and then corrects the crosstalk amount through algorithms to achieve crosstalk elimination. Verification demonstrates that the crosstalk level can be reduced to the magnitude of baseline white noise, with substantial improvement in image quality.

This method shows significant effectiveness in eliminating fixed-pattern noise caused by hardware process defects in imaging systems and also suppresses system-noise-like interference, serving as a valuable supplement for image quality optimization in general imaging systems in practical applications.

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Note: Figure translations are in progress. See original paper for figures.