Gain FPN Correction via Optical Flow

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Fixed Pattern Noise (FPN)

- FPN is nonuniformity caused by device mismatches and process parameter variations

Ideal image

FPN corrupted image

- Major source of image quality degradation especially in CMOS image sensors

Offset and Gain FPN

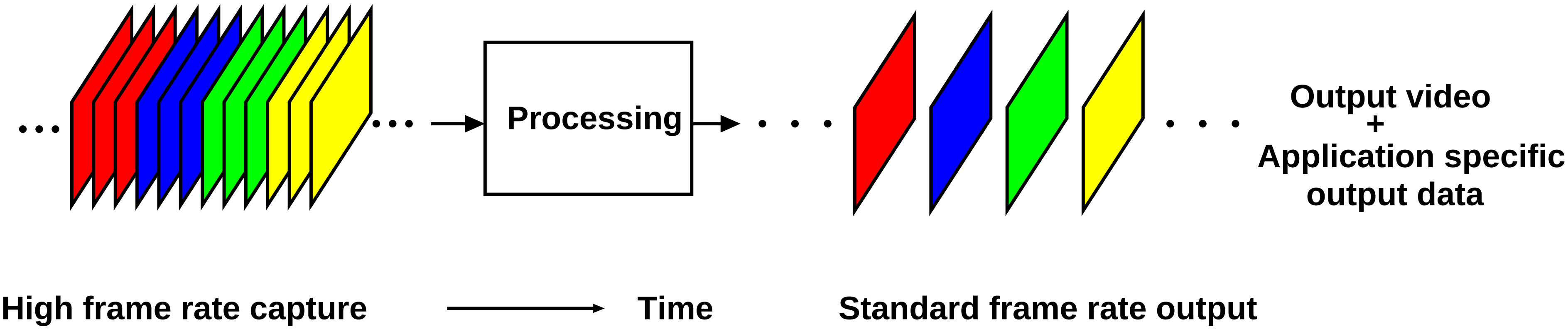
- Assuming linear sensor response, pixel intensity

$$i = hs + i_{os}$$

  - s is input signal (*e.g.*, photocurrent density)
  - h is gain factor
  - i_{os} is offset

- Offset FPN (Δi_{os}) can be canceled by correlated double sampling (CDS)
- Gain FPN (Δh) is difficult to correct
  - use static lookup table (Bloss SPIE'00)
  - characterize gain FPN before each capture

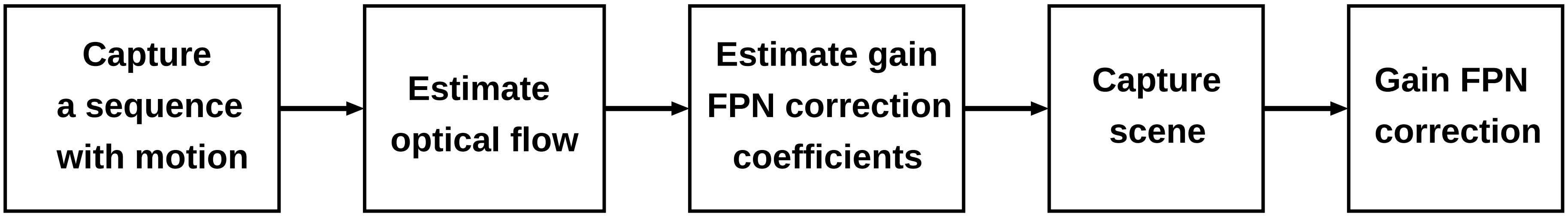
General Approach



- Improve image quality or performance of video processing applications using high speed imager
- Previous applications
  - dynamic range extension (Yang JSSC'99)
  - motion blur prevention (Liu ICASSP'01)
  - optical flow estimation (Lim ICIP'01)

Proposed Gain FPN Correction Method

- The method can be used in a digital video or still camera



- Gain FPN correction coefficients are computed block by block to lower computational requirements

Gain FPN Model

- Assuming offset FPN has been canceled, intensity at pixel (x, y) for frame t is given by

$$
\begin{aligned}
i(x, y, t) &= \left(1 + \frac{\Delta h(x, y)}{h_0}\right) i_0(x, y, t) \\
&= a(x, y) i_0(x, y, t)
\end{aligned}
$$

  - h_0 is nominal gain factor
  - $\Delta h(x, y)$ is gain variation between pixels
  - $i_0(x, y, t)$ is the ideal intensity value

- Gain FPN is the pixel to pixel variation of $a(x, y)$ and its magnitude is σ_H / h_0

Brightness Constancy Assumption

- Intensity value with gain FPN and temporal noise

$$i(x+d_x, y+d_y, t) = a(x+d_x, y+d_y)j(x, y)+N'(x, y, t)$$

  - $j(x, y) = i_0(x, y, 0)$, the ideal pixel intensity at (x, y) for frame 0
  - $d_x(x, y, t)$ and $d_y(x, y, t)$ are displacements between frame 0 and t
  - $N'(x, y, t)$ is temporal noise at $(x + d_x, y + d_y)$ for frame t

- Objective: find $j(x, y)$ from $i(x, y, 0), \ldots, i(x, y, F)$

Problem Formulation

- Let $\hat{j}(x, y, t)$ be the linear estimate of $j(x, y)$ obtained from $i(x, y, t)$ of the form

$$\hat{j}(x, y, t) = k(x + d_x, y + d_y) i(x + d_x, y + d_y, t)$$

  – $k(x, y)$ is the coefficient function to estimate

- For each block B, we estimate $k(x, y)$ that minimizes

$$E_B = \sum_{t=1}^{F} \sum_{(x,y) \in B} (\hat{j}(x, y, 0) - \hat{j}(x, y, t))^2$$

Problem Formulation for Integer Displacements

- To find k^*, we minimize

$$E_B = \sum_{t=1}^{F} \|([I(0)\ 0] - I(t)T(t))\mathrm{k}\|^2$$

subject to: $\mathbf{1}^T \mathrm{k} = n_R$

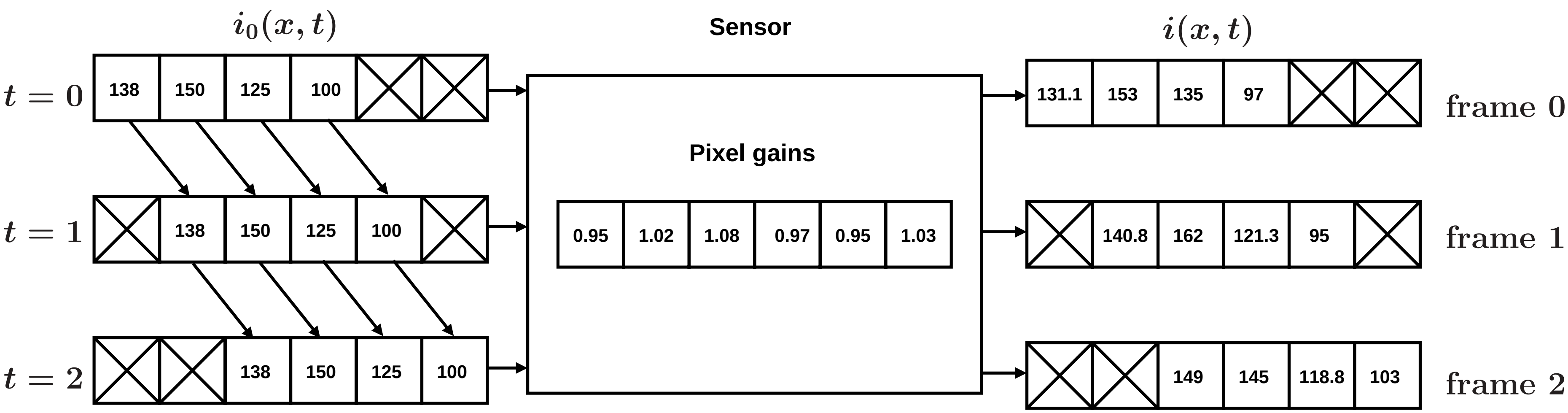
$$\begin{aligned}
\mathrm{k} &= n_R\text{-vector formed by ordering } k(x,y) \\
I(t) &= \text{diagonal matrix whose diagonal elements} \\
&\quad\ \text{are } i(x+d_x, y+d_y, t) \\
T(t)_{ij} &= \begin{cases} 1 & \text{when } i\text{th pixel moves to } j\text{th pixel} \\ 0 & \text{otherwise} \end{cases}
\end{aligned}$$

Problem solution

- Quadratic optimization problem with linear constraint —— has unique global optimum
- Can be solved using standard iterative methods
- After estimating $k(x, y)$ for the entire image, the gain FPN corrected image can be computed as

$$\hat{j}(x, y, 0) = k(x, y)i(x, y, 0)$$

Example: Integer Displacements

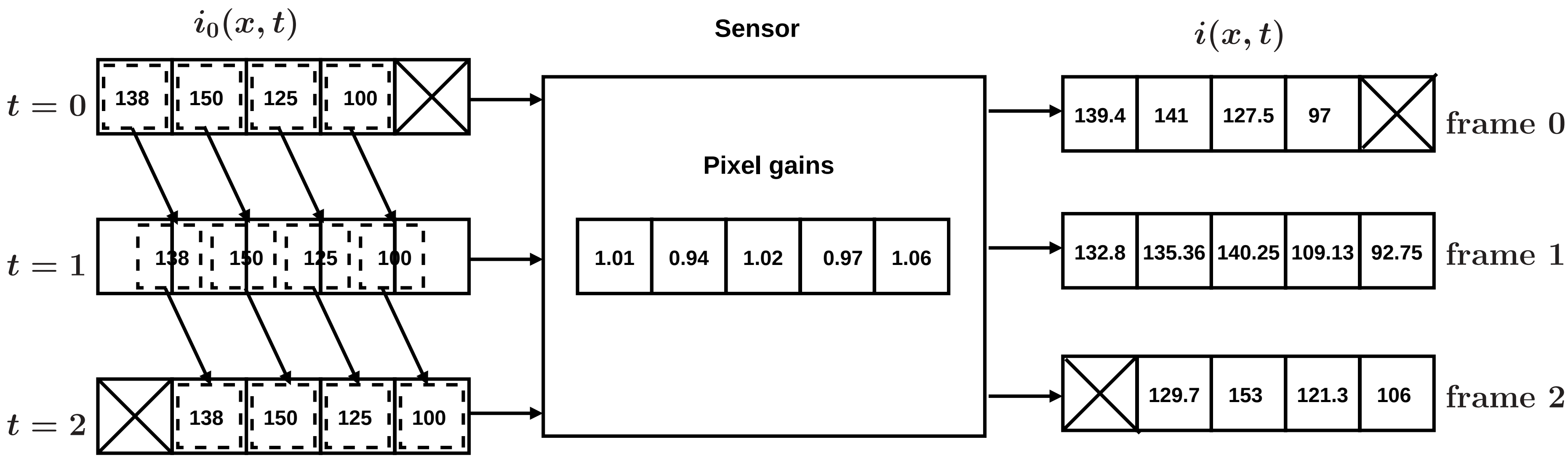


$$T(1) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \quad T(2) = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathrm{k}^* = \begin{bmatrix} 1.0503 & 0.9782 & 0.9239 & 1.0286 & 1.0503 & 0.9687 \end{bmatrix}^T,$$

$$I(0)\mathrm{k}^* = 0.998 \cdot \begin{bmatrix} 138 & 150 & 125 & 100 \end{bmatrix}^T$$

Example: Non-integer Displacements



$$T(1) = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix}, \quad T(2) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathrm{k}^* = \begin{bmatrix} 0.9737 & 1.0465 & 0.9879 & 1.0389 & 0.9530 \end{bmatrix}^T,$$

$$I(0)\mathrm{k}^* = \begin{bmatrix} 135.73 & 147.56 & 125.96 & 100.77 \end{bmatrix}^T$$

Simulation Setup

- **Generated sequences with motion blur, read noise, shot noise, and gain FPN, assuming the following image sensor parameters**
  - **Conversion gain: $32.5\mu V/e^-$**
  - **Voltage swing: $1V$**
  - **Read noise: $50e^-$**
  - **Quantization: 8 bits**
- **Measured performance by comparing the mean square error (MSE) between the ideal image and each of the images before and after gain correction**

Result I

- Pixel gain variations: $\sigma_{H_{pixel}}/h_0 = 0.05$
- 5 frames are used
- Blocksize is 5×5

Before correction

MSE=32.38

After correction

MSE=11.54

Result II

- Pixel gain variation: $\sigma_{H_{pixel}}/h_0 = 0.03$
- Column gain variation: $\sigma_{H_{column}}/h_0 = 0.04$
- 5 frames are used
- Blocksize is 5×5

Before correction

MSE=31.17

After correction

MSE=13.49

Conclusion

- Described a method to correct gain FPN using a video sequence and its optical flow
- The method can be thought of as digital CDS that cancels gain FPN rather than offset FPN
- Demonstrated significant gain FPN reduction using our method
- Another example of how high frame rate imaging can be used to improve still/video image quality