Adaptive Exposure Control for Mitigating Rolling Shutter Effects in CMOS Image Sensors

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ABSTRACT

CMOS image sensors are prevalent in modern digital cameras due to their efficiency and cost-effectiveness, but they suffer from rolling shutter effects caused by line-by-line image readout. These effects manifest as geometric distortions, especially in scenes with fast motion, due to misaligned exposure moments across sensor rows. This paper introduces an adaptive exposure control method that aligns the mid-exposure moments of all rows through dynamic, row-level exposure adjustment. By varying the start and end capture times for each row, the proposed method ensures uniform mid-exposure timing, thus preserving geometric accuracy in dynamic scenes. Real-time motion analysis is incorporated to allocate shorter exposure times to rows with significant motion to reduce motion blur, while allowing longer exposures in stationary rows to enhance image quality and signal-to-noise ratio. Post-processing compensates for exposure duration variations, ensuring consistent brightness across the image. The approach offers a low-cost and computationally efficient alternative to global shutter sensors, is compatible with existing CMOS architectures, and requires minimal hardware modification. Simulation results demonstrate that this technique effectively mitigates rolling shutter artifacts while maintaining high image quality, making it suitable for consumer devices and other applications requiring robust motion capture.

Keywords: Rolling Shutter, CMOS Image Sensor, Adaptive Exposure Control, Mid-Exposure Alignment, Motion Analysis, Image Distortion Correction

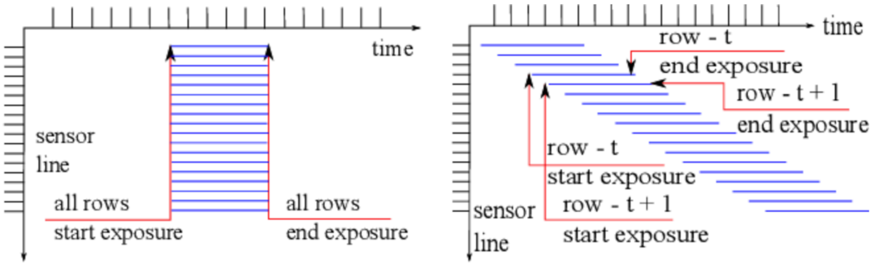
1. INTRODUCTION

CMOS image sensors used in most cameras and phones have a rolling shutter where image data is read line by line, while a CCD image sensor (used in high-end Cameras) with a global shutter where all data is read simultaneously. Because of the time delay in exposure with line-by-line data transfer, image distortions occur when objects in the captured image are moving. The images below show a typical rolling-shutter effect with objects in the image moving horizontally.

(a) (b)

Figure 1a and 1b: Rolling-Shutter Effect on Horizontal Motion

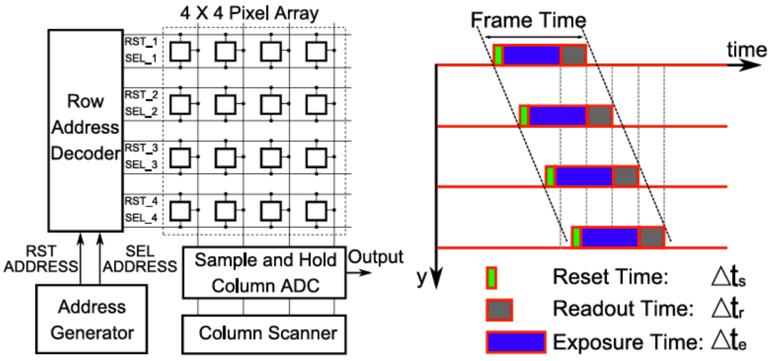
Figure 1a shows the typical rolling-shutter effect where the object is moving horizontally. The camera position is landscape. The train is moving from right to left, and the image data is scanned line by line from top to bottom. Figure 1b is an example of taking a picture from a moving train. Here, the train is moving from left to right. Note that the closer the object is to the camera, the more distorted the image.



(a) Global shutter exposure (b) Rolling shutter exposure

Figure 2. Global shutter exposure vs Rolling shutter exposure.

Figure 2 shows the difference between global shutter exposure and rolling shutter exposure. The global shutter will have all rows of pixels exposed for the same time period, while the rolling shutter will expose the rows one by one with a time delay. Usually, the constraint of the time delay in rolling shutter is that the readout time of each row cannot be overlapped as the sensor only has one line buffer to hold the samples for output, as we can see in Figure 3, in order to save space and cost.



(a) CMOS image sensor architecture (b) Timing for rolling shutter

Figure 3. The CMOS image sensor architecture and the timing for the rolling shutter.

Rolling shutter effects have been a well-documented limitation of CMOS sensors, impacting a wide range of applications from consumer electronics to professional cinematography. Traditional solutions have focused on minimizing these effects through faster readout speeds [1] or employing global shutter technologies [2], which capture the entire image simultaneously. Since readout time is the limiting factor that causes the rolling shutter effects, reducing the readout time will increase the slope in Figure 3b and mitigate the rolling shutter effects. However, faster readout speeds can lead to increased power consumption and heat generation, while global shutter technologies typically come with compromises in sensor sensitivity or complexity in manufacturing, resulting in higher costs.

Another way to correct the rolling shutter effects is through computational methods in post-processing. It primarily involves analyzing the captured images or videos to detect and correct distortions due to the sensor's sequential exposure of rows or columns. These methods can be broadly categorized into geometric corrections, where distortions are corrected by warping the image [3][4], and machine learning approaches that train an ML model to recognize and correct rolling shutter artifacts [5][6]. These models require extensive training data but can potentially offer more generalized solutions to various distortion types.

In this paper, we propose a method to mitigate the rolling shutter effects by dynamically adjusting row-level exposure durations to align mid-exposure moments across all rows. High-motion regions are assigned shorter exposure times to reduce blur, while stationary areas receive longer exposures to enhance detail. The proposed approach introduces minimal cost and computational overhead, making it a practical and energy-efficient alternative to global shutters.

2. ADAPTIVE EXPOSURE CONTROL

The proposed method aims to maintain the geometric integrity of images captured by CMOS sensors in the presence of moving objects by adjusting the exposure time across different rows. This objective is to ensure each row's mid-exposure time aligns, so straight lines remain straight, addressing the distortion characteristic of rolling shutter effects. The approach also varies the exposure time dynamically, with shorter exposures for areas containing fast-moving subjects to minimize motion blur, and longer exposures for stationary or slow-moving areas to maintain image brightness and quality. Below we will describe the notation used in this approach.

Notation

- N: Total number of rows in the sensor.
- δt: Time interval required to read out a single row.
- T_{min}: Minimum allowable exposure duration.
- t_{mid} : Common mid-exposure time for all rows.
- M_i: Motion metric for row i, representing the magnitude of motion (e.g., derived from optical flow analysis).
- T_i: Assigned exposure duration for row i.
- t_i^{start} : Exposure start time for row i.
- t_i^{end} : Exposure end time (readout time) for row i.

Mid-Exposure Time Alignment

In this method, we adjust the exposure starting time of each row so that every row will have the same mid-exposure time. In other words, for rolling shutter imaging, each row i starts its exposure at time t_i^{start} and ends at t_i^{end}, resulting in a mid-exposure time $t_i^{\text{mid}} = \frac{t_i^{\text{start}} + t_i^{\text{end}}}{2}$. To eliminate geometric distortions, we enforce:

$$t_i^{\text{mid}} = t_{\text{mid}}, \quad \forall i$$

where t_{ref} is a constant reference time for the entire frame. This constraint implies that:

$$t_i^{\text{start}} = t_{\text{mid}} - \frac{T_i}{2}, \quad t_i^{\text{end}} = t_{\text{mid}} + \frac{T_i}{2}$$

Here, T_i denotes the exposure duration for row i. By varying T_i while keeping t_i^{mid} constant, we maintain geometric consistency across the rows of the captured image while the readout time of each row is non-overlapped so that a single line buffer can hold the samples for output. This way, a straight line is still straight, and the tradeoff is that different lines have different amount of exposure time needed to be compensated, and at the same time, different rows will have different amount of motion blur.

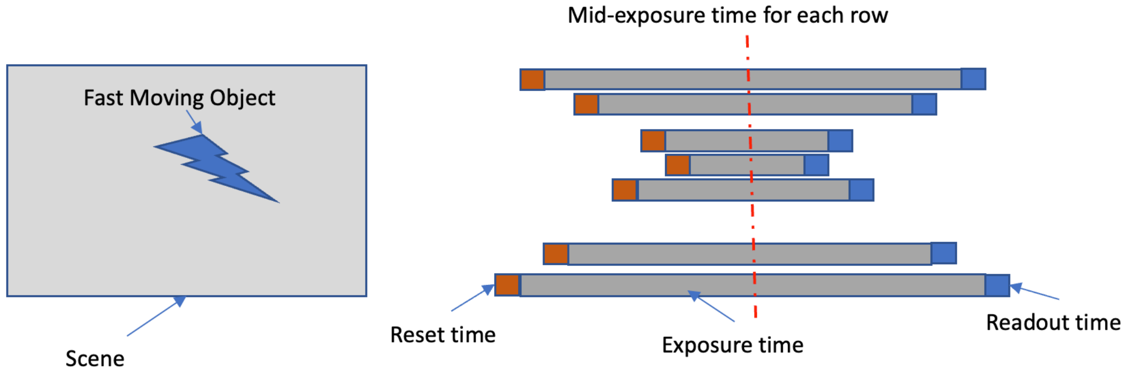


Figure 4. An example of a fast-moving object is identified and the corresponding reset, exposure, and readout time for each row.

Motion-Adaptive Exposure Allocation

For motion blurs, if we identify the moving object area, we can use the smallest possible exposure times on those rows with higher motion, which could effectively reduce the motion blur. At the same time, as the slowly moving area will be resilient to the motion blurs, we can have longer exposure time on those slowly moving rows.

Figure 4 shows one example where a fast-moving object is identified, and the corresponding rows are now having the smallest exposure time, while all rows have the same mid-exposure time. Therefore the captured image will have no rolling shutter effects, and at the same time, the fast-moving object will have minimum motion blur.

Below are the algorithm steps we used to determine the exposure time for each row and the start and end scheduling.

Algorithm Steps

1. **Motion Analysis**:
    - Compute the motion metric M_i for each row i, representing the magnitude of motion within that row. This can be achieved through optical flow estimation or other motion detection algorithms.
2. **Exposure Duration Assignment**:
    - Sort the rows based on their motion metrics M_i in descending order, resulting in a sequence $\{i_1, i_2, \dots, i_N\}$ where $M_{i_1} \geq M_{i_2} \geq \cdots \geq M_{i_N}$.
    - Initialize the exposure duration for the first row in the sorted list:

    $$T_{i_1} = T_{min}$$

    - For each subsequent row i_k (where $k = 2$ to N), assign the exposure duration incrementally:

    $$T_{i_k} = T_{min} + 2 \cdot (k-1) \cdot \delta t$$

    - This ensures that each row's exposure duration increases by $2 \cdot \delta t$ compared to the previous, accommodating the sequential readout constraint.
3. **Exposure Timing Calculation**:
    - For each row i_k, compute the exposure start and end times to align the mid-exposure time:

    $$t_{i_k}^{\text{start}} = t_{\text{mid}} - \frac{T_{i_k}}{2}$$

    $$t_{i_k}^{\text{end}} = t_{\text{mid}} + \frac{T_{i_k}}{2}$$

    - These calculations ensure that all rows share the same mid-exposure time t_{mid}, effectively mitigating geometric distortions.
4. **Readout Scheduling**:
    - Schedule the readout of each row i_k at its exposure end time $t_{i_k}^{\text{end}}$.
    - Ensure that the readout times are spaced by δt to prevent overlap:

    $$t_{i_{k+1}}^{\text{end}} = t_{i_k}^{\text{end}} + \delta t$$

    - This sequential scheduling respects the sensor's hardware constraints and ensures efficient utilization of the readout mechanism.

Exposure Compensation

With the above exposure timing and readout scheduling, each row has a distinct exposure duration T_i. This variation leads to inconsistencies in pixel brightness across the image, as longer exposures accumulate more light, resulting in brighter pixels. To ensure uniform brightness and maintain image quality, each pixel's intensity should be scaled inversely proportional to its row's exposure duration. Let I_i^{raw} denote the raw pixel intensity for row i, and T_i the corresponding exposure time. The compensated intensity I_i^{comp} can be calculated as:

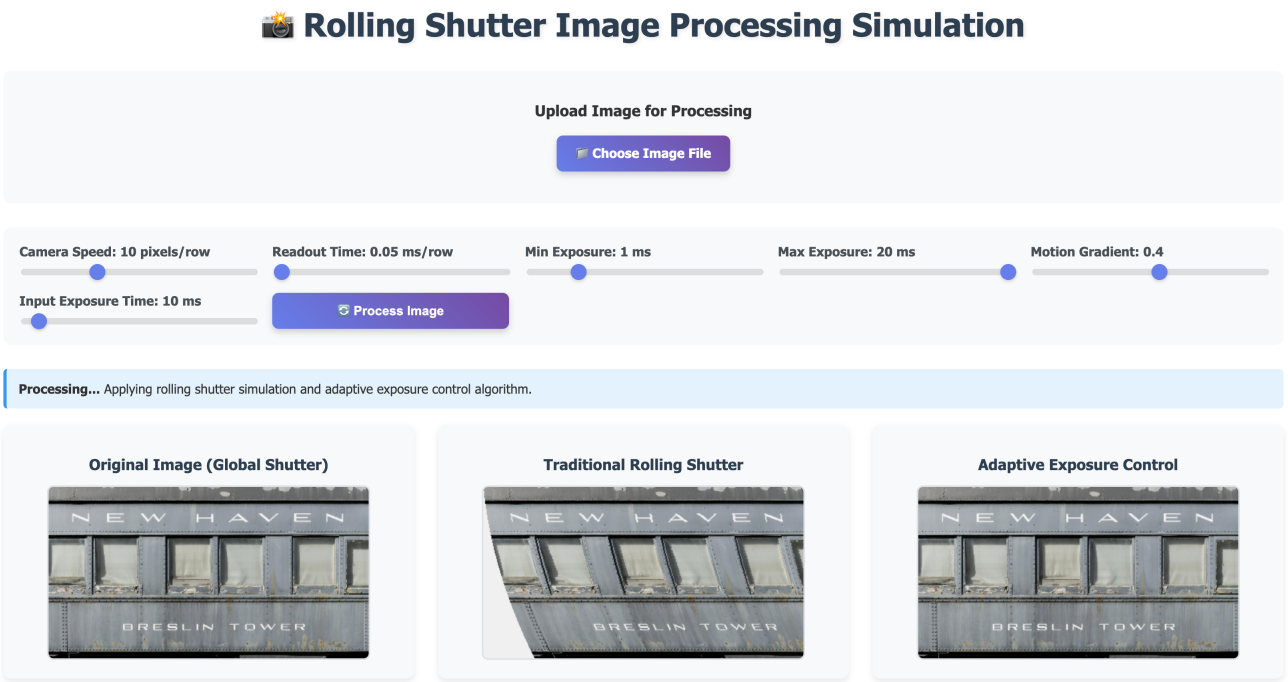
$$I_i^{\text{comp}} = I_i^{\text{raw}} \times \frac{T_{\text{ref}}}{T_i}$$

Here, T_{ref} is a chosen reference exposure duration, such as the minimum exposure time T_{min} or the average exposure time across all rows. This scaling ensures that all rows contribute equally to the final image brightness, compensating for the differences in exposure durations.

3. EXPERIMENTAL RESULTS

To evaluate the efficacy of our adaptive exposure control algorithm in mitigating rolling shutter artifacts, we developed a comprehensive simulation tool that emulates the behavior of CMOS image sensors under various motion scenarios. This simulator models the sequential row-wise exposure and readout processes inherent to rolling shutter mechanisms, allowing for precise evaluation of our method's performance. Figure 5 shows the user interface of the simulation tool, as well as one set of input and output images.

Simulation demonstrated a significant reduction in geometric distortions and motion blur compared to traditional fixed exposure methods. Visual assessments confirmed the preservation of straight lines and overall scene integrity, validating the efficacy of our adaptive exposure strategy in rolling shutter scenarios.



📸 Rolling Shutter Image Processing Simulation

Upload Image for Processing

Camera Speed: 10 pixels/row

Readout Time: 0.05 ms/row

Min Exposure: 1 ms

Max Exposure: 20 ms

Motion Gradient: 0.4

Input Exposure Time: 10 ms

Processing... Applying rolling shutter simulation and adaptive exposure control algorithm.

Figure 5. The UI for rolling shutter simulation, with comparison between the traditional rolling shutter effects and the output fromour adaptive exposure control.

4. CONCLUSION

This paper presents an adaptive exposure control approach designed to mitigate rolling shutter artifacts in CMOS image sensors. By aligning the mid-exposure times across all sensor rows and dynamically adjusting exposure durations based on scene motion, the proposed method effectively reduces geometric distortions and motion blur. A simulation tool was developed to validate the approach, demonstrating its efficacy in various dynamic scenarios. Future work may explore real-time implementation and further optimization of exposure allocation algorithms to enhance performance in diverse imaging conditions.

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