Investigating Diverse Parameters for Characterizing Spatial Contrast Transfer in CMOS Event-Based Cameras

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***Abstract*—Event-Based (EB) cameras generate events in response to relative changes in light. The primary characteristics of an EB camera are its sensitivity to light changes and the latency of change detection. These parameters, and consequently the camera's response, are strongly impacted by the lighting conditions. Both temporal and spatial light contrast affect detection capabilities, as spatial contrast translates into temporal contrast for moving objects. When an EB camera fails to resolve objects with high spatial frequency textures, the spatial contrast transfer degrades, impacting temporal contrast and data quality. This preliminary work is an initial step in evaluating the ability of EB cameras to transfer contrast at high spatial frequencies.**

INTRODUCTION

Neuromorphic sensors and cameras are more broadly part of the field known as Neuromorphic Engineering which was initiated in the 1980s by Carver Mead and his students at Caltech [1]. This discipline aims to develop hardware systems inspired by the functioning of biological neural and nervous systems, and the first artificial retina, that is, the first image sensor mimicking the functioning of biological retinal cells, emerged in the late 1980s as part of Misha Mahowald's thesis [2]. Unlike conventional cameras, neuromorphic cameras do not produce on frames but *events*, hence the commonly used term *event-based cameras*. Event-Based (EB) cameras are designed to asynchronously detect relative light changes over time, and generate events every time the temporal contrast reaches a pre-set threshold [3]. This type sensor generates data only when necessary, eliminating temporal redundancies. This enables the design of vision systems with low latency and low power envelope compared to traditional Frame-Based (FB) cameras. These advantages allow event-based cameras to be widely used in application such as object tracking, image motion deblurring, moving obstacle detection, and others that request fast movements capture [4].

EB DETECTTION OPERATION

Figure 1 presents a block diagram of the pixel. The first key component is the logarithmic photoreceptor [5], which outputs a voltage proportional to the logarithm of the illumination. The following two blocks are filters that adjust the signal according to requirements (speed, noise...) and the differential amplifier's output voltage is then compared to the thresholds of the comparators. The combination of the logarithmic photoreceptor and the differential amplifier makes the sensor sensitive to relative light changes. If a threshold is exceeded, an event of the corresponding polarity is generated, and the pixel enters 'reset' mode for an adjustable duration known as the 'refractory period' [6].

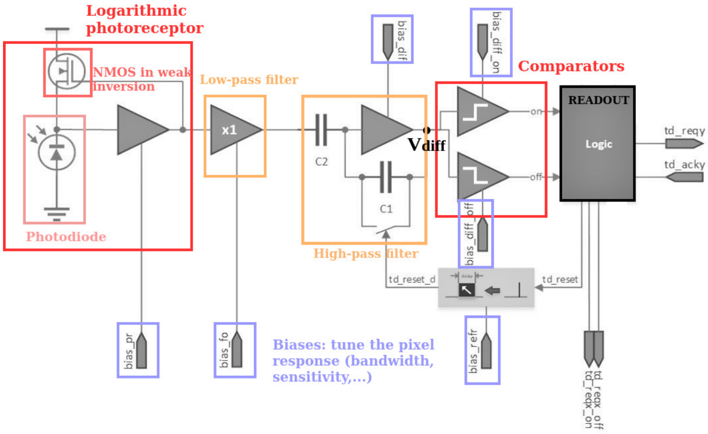

Fig. 1. Main blocks of an EB pixel circuit.

This is illustrated in the time-diagram on Figure 2: as the light level increases, so does V_{diff} until it reaches the ON threshold, generating an ON event and indicating a positive intensity change. Similarly, as the light level decreases, an OFF event is generated, indicating a negative intensity change. More specifically, an event is an array containing several attributes: the position **(x, y)** of the pixel that detected a change in intensity, the polarity **p** of the intensity change (positive or negative), and the timestamp **t** of the intensity change, measured in microseconds.

EB MAIN PARAMETERS

The two main properties of an EB camera are its sensitivity and its latency. Sensitivity is defined as the minimum contrast needed to trigger an event and is quantified in terms of response probability or number of events generated while the latency is defined as the delay between a light change and its corresponding event. Most of the techniques used to assess the image quality of FB cameras cannot be applied to EB cameras, so characterization methods need to be adapted. Characterization test benches are therefore designed for EB cameras and the parameters to be measured, particularly by adding a time-modulated lighting device. The number of events generated by a pixel is directly linked to the light contrast applied to that pixel. This can be measured using a LED modulated with

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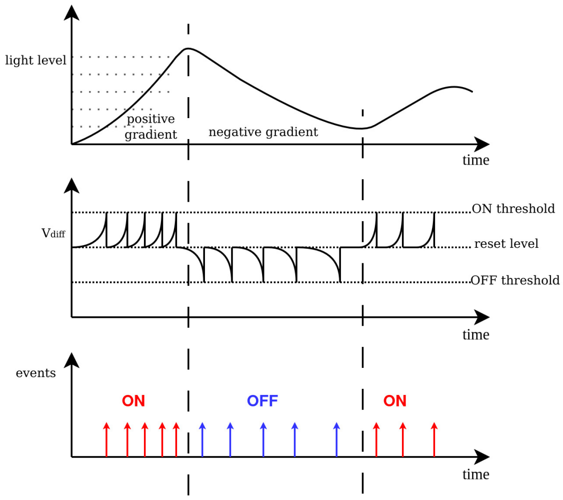

Fig. 2. Time-diagram of a light signal and the corresponding voltage at the output of the differential amplifier, as well as the events generated.

an exponential signal, where the difference between the maximum and minimum light levels of the signal defines the light contrast. The time-diagram in Figure 3 shows the stimulus applied to this LED, the resulting logarithm of photocurrent and the events generated. Increasing the light contrast by following such an exponential signal causes the thresholds of the comparators to be reached multiple times, while allowing enough time for the pixel to reset and thereby generating multiple events.

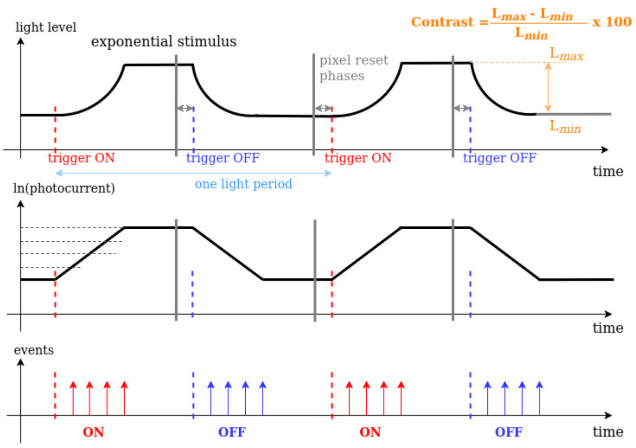

Fig. 3. Time-diagram for counting the number of events over light cycles.

Figure 4 presents a similar time-diagram, but for a latency measurement. In this case, a square light signal is used with external triggers marking the moment of the light change. The time between this trigger and the first event received is measured. For a better estimation of the latency value, this process is repeated over several light cycles, and the mean value is taken as the latency of the pixel. To obtain the latency of the sensor, the mean value of all pixels' latencies is calculated.

These parameters and consequently the camera's response, are strongly impacted by the lighting conditions [7]. As shown on Figure 5, the latency strongly depends on the light level applied to the sensor; the higher the

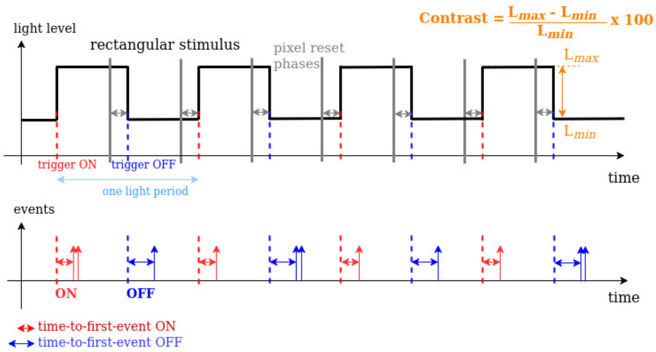

Fig. 4. Time-diagram of latency measurement.

light level, the smaller the latency, i.e the faster the pixel responds. Similarly, as illustrated on Figure 6, the latency also depends on the light contrast of the input light signal; the higher the contrast, the smaller the latency.

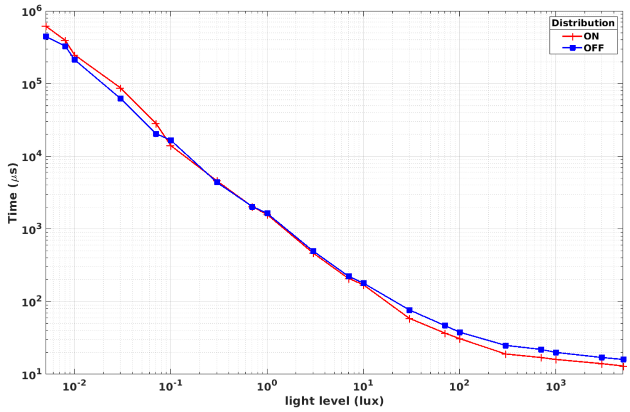

Fig. 5. Latencies ON and OFF as a funtion of the light level, at 100% light contrast. Latencies are calculating on a square of 6400 pixels.

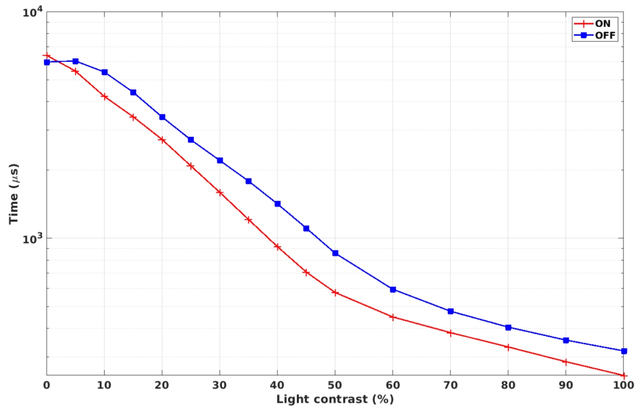

Fig. 6. Latencies ON and OFF as a function of the light contrast, at reference light level ($L_{\max}$) of 10 lux. Latencies are calculating on a square of 6400 pixels.

From this latency data, it is possible to plot the response probability curve of the sensor as a function of the applied contrast, also known as the S-curve (Figure 7). This type of curve characterizes the average sensitivity to light contrast of an EB sensor. The graph emphasizes that the curve shape also depends on the light level: at 10 lux, the sensor's response probability to 50% contrast is nearly

1, while at 0.05 lux and 50% contrast, the response probability is only 0.6.

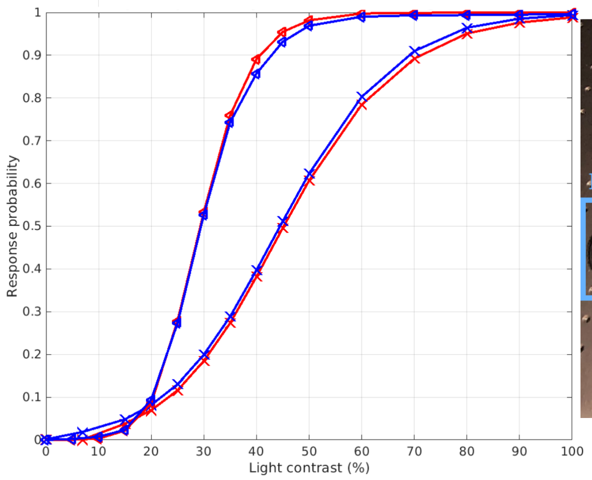

Fig. 7. Example of S-curves, also known as the response probability of the sensor as a function of the light contrast.

Thus, temporal light contrast in particular, affects the sensor's detection capability, but spatial contrast is also important, as it can be transposed temporally in the case of a moving object. When an EB camera fails to resolve an object with high spatial frequency texture, spatial contrast transfer degrades, impacting temporal contrast and sensor response. This preliminary work is therefore motivated by the need to assess EB cameras ability to transfer contrast at high spatial frequencies [8]. Since EB cameras encode relative and not absolute light changes, one of the challenges of this study is to calculate the contrast using a suitable parameter for EB sensors.

Spatial Contrast Characterization

This work adapts resolution measurement techniques from FB cameras [9] to a BSI CMOS EB camera with a 4.86 µm pixel pitch [10]. The test bench presented on Figure 8 includes a 505nm LED modulated in intensity with the light signal presented on Figure 3, and a target consisting of a square-wave Siemens star pattern, typically employed for focus adjustment.

A first attempt was to calculate the spatial contrast using the number of events generated per pixel over a certain number of light cycles. In Figure 9(a), the number of events generated per pixel is plotted over time. Even under identical lighting conditions, the number of events generated per pixel can vary slightly. This is visible in the diagram because there are sometimes multiple symbols (red crosses for ON or blue circles for OFF) following an ON or OFF trigger, whereas one would expect to always have the same number. This variability is partly due to what is known as pixel mismatch in sensitivity, which introduces temporal noise. This noise can be mitigated by counting the number of events over a large number of light cycles (e.g., hundreds). Figure 9(b) presents a 2D visualization of the map obtained through this method. In the selected slice AB, spatial contrast is evident: the light orange parts indicate pixels behind the black branches of the target, which generate no events (corresponding to the

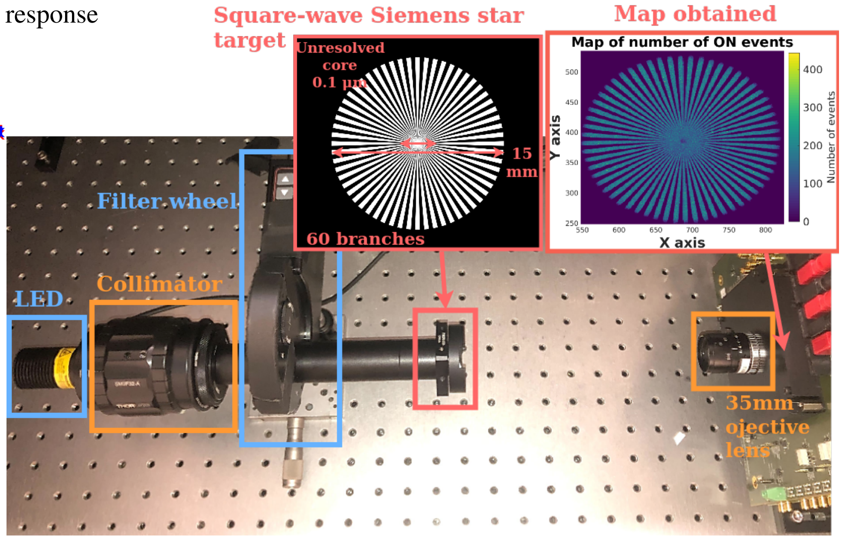

Fig. 8. Test bench used to characterize the spatial contrast transfer.

dark blue bars in the 2D reconstruction). Conversely, the red parts highlight pixels behind the transparent branches, which do generate events (represented by the light blue bars). Concentric circles, such as the black one, are plotted from the center to the outer diameter, each corresponding to a specific spatial frequency. This allows the calculation of contrast in terms of number of events, at each spatial frequency.

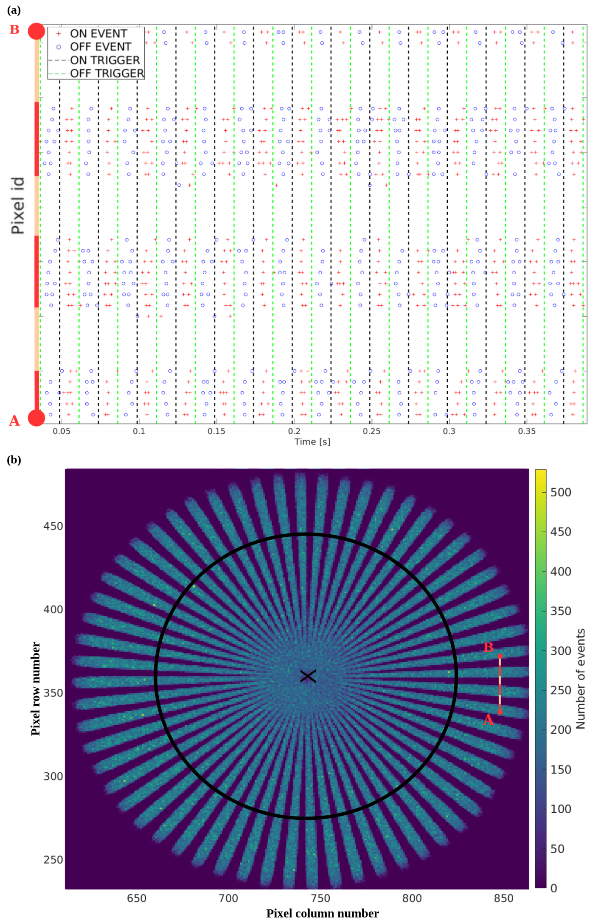

Fig. 9. Events generating by a slice of pixels over time, and their position on a 2D map. The light blue parts are not uniform due to pixel mismatch.

While counting the number of events offers ease of use, it requires integration over time, which is similar to the operating principle of FB cameras. This FB-equivalent approach is highly sensitive to object motion and absolute light levels. Consequently, this method contradicts the benefits of using an event camera, and the results may significantly differ from the sensor's performance in real-life operations.

Hence, the procedure was also performed using latency as the parameter to calculate the spatial contrast. The latency per pixel was measured using the test bench presented in Figure 8, with the LED time-modulated using a square signal at 40 Hz (as shown in Figure 4). The resulting latency measurements are plotted on the 2D map in Figure 10. The color code indicates the fastest (blue) and slowest (yellow) pixels. When there is no color (white/blank), it means the pixel did not respond. It can be understood that the blank branches correspond to the pixels behind the black branches on the target.

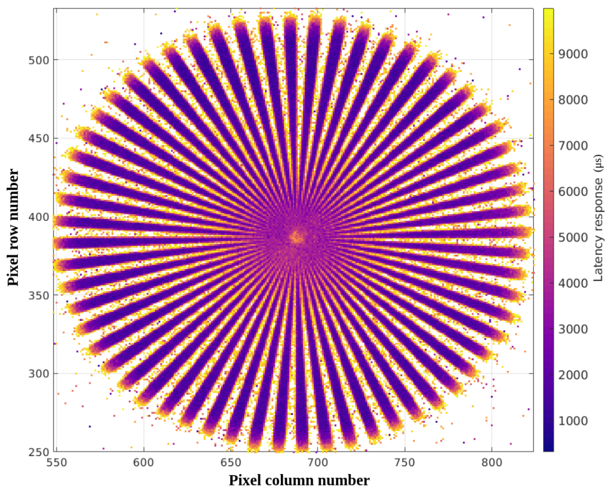

Fig. 10. 2D map representation of the latency data.

The resulting contrast, either in number of events or in latency, is divided by the contrast of the object, i.e. the target. This contrast ratio is plotted as a function of spatial frequency, and the subsequent curves are shown in Figure 11. The purple curve is obtained using the number of events per pixels while the blue curve is obtained using the latency data. The filtered curves are obtained using a mean filter with a 10-point window. The contrast ratio decreases as the spatial frequency increases, and the curves are quite similar to each other but their shapes differ from usual contrast transfer function (CTF) curves measured on FB cameras, particularly the asymptote at high frequencies. A more in-depth study should be conducted to investigate, in particular, the impact of pixel mismatch and sensor background rate on these data.

Conclusion

This study has demonstrated that spatial contrast can be evaluated from EB parameters, such as number of events and latency. Questions remain regarding the shapes of the curves, so investigations are performed to highlight the impact of pixel mismatch and background rate on the results.

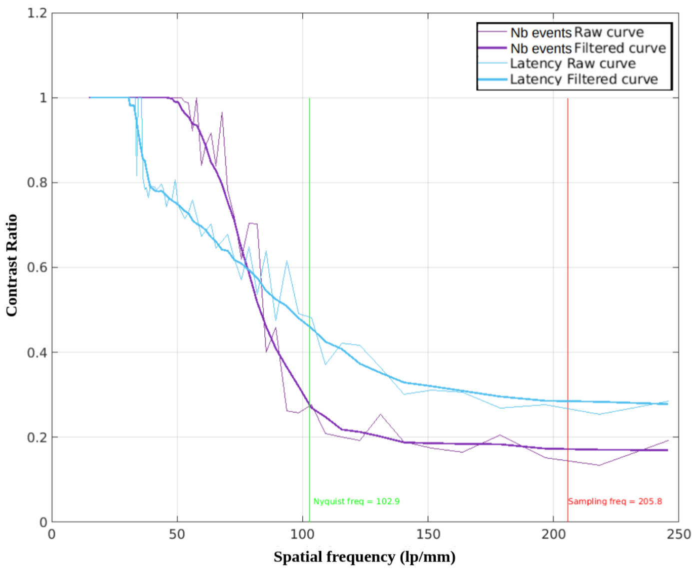

Fig. 11. Contrast transfer curves of an event-based (EB) camera, taken at a reference light level ($L_{\max}$) of 0.01 lux. The purple curve is obtained from the number of events data, while the blue curve is obtained from the latency measurements.

Despite the convenience of the Siemens star pattern, future characterizations will use rectilinear patterns, better suited to rigorous measurements of spatial contrast, especially as they will allow the use of statistics to minimize the effects of pixels with atypical behavior.

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