High-Precision Representation of High-Speed Scene Dynamics with a Neuromorphic Imaging System

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***Abstract*—This paper presents and evaluates an ultra high-speed synchronous arbitration process for transient pixels' data of a neuromorphic temporal contrast imaging sensor. Enabling a high-precision timestamping, this system demonstrates its uniqueness for handling high peak rates and preserving the main advantage of the neuromorphic electronic systems, that is high and accurate temporal resolution. Based on synchronous arbitration concept, the timestamping has accuracy better than 1 µs. Both synchronous and (state-of-the-art) asynchronous arbiters have been implemented in the neuromorphic dual-line vision sensor chip in a standard 0.35 µm standard CMOS process. The performance analysis of both arbiters and the advantages of the synchronous arbitration over asynchronous arbitration in capturing high-speed objects are discussed in details.**

I. Introduction

Biologically-inspired vision aims to duplicate the effect of human vision by electronically capturing, perceiving and understanding images. Introduced in the late 80's, neuromorphic engineering is tremendously evolving with the enduring motivation in rebuilding part of the human vision mechanism in low-cost and low power electronics. The main concern of these systems is the representation of information by the relative values of analogue signals, rather than by the absolute values of digital signals as argued by Carver Mead in the invited paper [7]. Temporal contrast vision sensors, focused in this paper, consist of pixels, which autonomously operate and respond with low latency to relative illumination changes by generating asynchronous events [8]. They generate two types of events, which represent a fractional increase (ON-event) or decrease (OFF-event) in light intensity that exceeds a tunable threshold. Combined with the pixel address, these events are referred to as 'Address-Events' (AE) [5]. Unlike frame-based imagers, neuromorphic imagers require an arbiter to organize the access of multiple asynchronous data sources (pixels) to a common communication bus. As the pixels are autonomous, they can generate AE instantaneously, hence, the AE interface (arbiter) is needed for the arbitration.

K.A. Boahen [3][4] has developed AE asynchronous communication circuits for the transmission and handling temporally coincident pixels' events. However, the digital timing information is not allocated on-chip and has to be attached in an external unit (e.g. DSP). Furthermore, the arbitration process is not deterministic because of the unfettered design of this AE communication circuit.

For this reason, we have developed a synchronous AE interface [6] for deterministically arbitrating between multiple asynchronous sensor elements and adding a timestamp to the AE at the generation time, for preserving ultra-high precision temporal information. Both arbiters [3] and [6] have been implemented in the temporal contrast vision dual-line (2×256 pixels) sensor chip [8] where only one of them can be activated at a time for data acquisition.

This paper presents the evaluation results for high-speed scene capturing and representation using the asynchronous and synchronous AE interfaces. We show the advantage of the synchronous arbitration [6] over the asynchronous arbitration [3] in representing high-speed moving shapes as well as preserving the high temporal resolution of the temporal contrast pixels.

The paper is structured as follows. In Section II, the detailed description of the AE communication interfaces (asynchronous and synchronous) is given. Section III provides data examples from the temporal contrast vision dual-line sensor using the synchronous arbitration. A performance analysis of the dual-line sensor using both arbiters (asynchronous and synchronous) in provided in Section IV. The experimental results using both AE communication interfaces in capturing high-speed moving objects are presented in Section V. A summary is given in Section VI.

II. Address-Events Communication Interface

To keep this paper self-contained, the description of both

AE communication interfaces, asynchronous and synchronous, are provided in this section. This description is schematically reported in [1].

A. *Asynchrnous Arbiter*

The pixels handshake asynchronously with the peripheral circuits and communicate their address and the type of event (ON: for intensity increase and OFF: for intensity decrease). The pixels' data are transferred via a shared communication bus. Therefore, an AE communication interface [3] aims to lossless transmit all AE in arbitrating between temporally coincident events. The AE circuits of the dual-line sensor are based on the ones described in [3] but have been modified to be non-greedy like the one described in [4].

The time information is allocated to the events off-chip, in the processing unit. Therefore, the timing accuracy of AE strongly depends on the performance of the arbitration and on the stimulus-driven spatiotemporal activity; a fast stimulus may yield a bulk of events from coincident pixels saturating the arbiter.

The data are encoded into AE and arbitrated for coincident pixel activities at the pixel interface. The time information assignment occurs in the processing unit that lead to data consisting of **T**imed **AE** (TAE). These data consisting of timestamps and AE are stored in the memory and are ready for further processing.

B. *Synchronous Arbiter*

In addition to arbitrating between coincident pixels events, the synchronous arbiter [6] performs the timestamp assignment with respect to the occurrence of an event at the arbiter input. They are generated using a continuous counting device while assigning the current counter value to the events. The timestamps are combined with the corresponding AE to compose a stream of data packets, which are called TAE at the output of the arbiter. Events with the same timestamp value are interpreted as concurrent and they are arbitrated according to descending addresses.

A timestamp is attached on-chip to the AE data with a temporal resolution of 100ns at the input stage of the arbiter. Therefore, the output of the sensor consists of TAE with the AE and their accurate occurrence time. In order to avoid data loss, an event FIFO is build at the output of every pixel in order to handle peak data rates and allow storage of the pixels' data whenever the synchronous arbiter is temporary computationally saturated.

Both arbiters have been implemented in a standard 0.35 µm standard CMOS process on the dual-line sensor.

III. DATA EXAMPLE FOR THE NEUROMORPHIC DUAL-LINE VISION SENSOR

Fig.1 (top) depicts data examples of shapes crossing the sensor's field-of-view at velocity of 10 m/s using the dual-line sensor with activated synchronous arbitration. Only the edges trigger events. The bottom figure shows the corresponding Timed AEs (TAE) delivered by one sensor pixel line in response to the visual stimulus, using the synchronous arbiter. The vertical axis is the pixel address (0-255), the horizontal axis shows the event generation time. The time has been converted to isogonal spatial information on the basis of the known object speed measured by correlating the data from the two pixel lines. The white dots consist of ON events while the black dots correspond to the OFF-events.

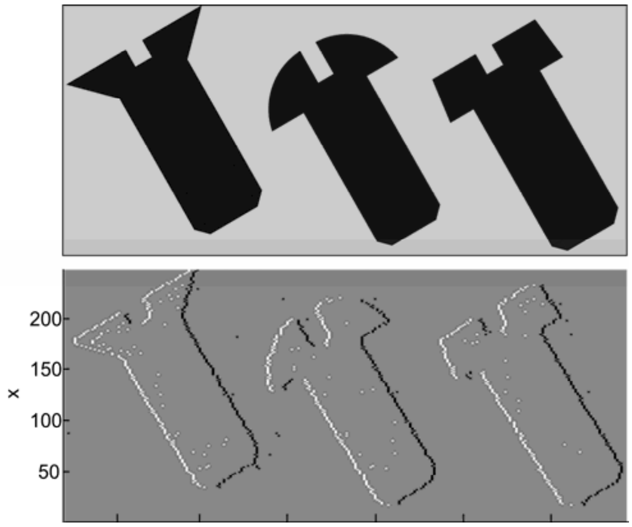


Fig.1. Original shapes depicted on the top figure. Their correspondent data representation using the dual-line sensor are given on the bottom figure

IV. PERFROMANCE ANAYLSIS

The dual-line sensor chip [8] has implemented the arbitration concepts: asynchronous arbiter and synchronous arbiter as digital circuits, to handle temporally coincident pixels' events. Only one arbitration concept can be active at a time. The dual-line sensor consists of two lines of 256 autonomous pixels, which asynchronously respond to relative illumination changes. The sensor performance using the asynchronous and synchronous arbiter as summarized in TABLE I.

From the analysis of the theoretical characteristics of the asynchronous and the synchronous arbiters, it can be noticed that the asynchronous arbiter arbitration behavior is not deterministic and the temporal information is not preserved within the AE interface. However, the synchronous arbiter includes the time information to the AE and thus preserves the high temporal resolution aspect of the pixels. This advantage has a consequent influence on the dual-line sensor performance in capturing high-speed moving objects by preserving the object shape. The experimental evaluation of both arbiters is provided in the next section.

TABLE I. DUAL-LINE SENSOR PERFROMANCE ANALYSIS USING THE ASYNCHRNOUS AND THE SYNCHRNOUS ARBITER

Characteristics	*Asynchronous Arbiter*	*Synchronous Arbiter*
Arbitration behavior	Not deterministic	Deterministic (pixel address in a descending order per timestamp)
Data organization	Random	Timestamp + pixel addresses in decreasing order
On-chip temporal resolution	No time quantization	≥ 100ns
Peak input data rate	10^6 Event/s	2.56 10^9 Event/s @20 MHz system clock frequency
Peak output data rate	10^6 Event/s	10^7Event/s @20 MHz system clock frequency
Handling of Peak data rate	None	Event FIFOs included to minimize data loss and to maintain the temporal information
Possibility for pixel masking	No	Yes
Clock frequency	No clock	10 – 40 MHz

V. EXPERIMENTAL RESULTS

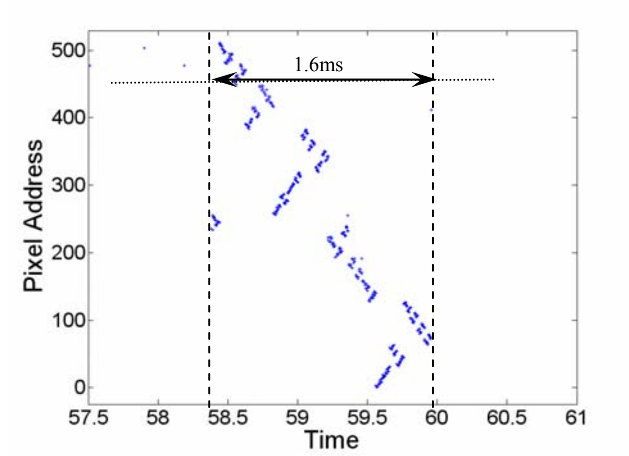
Both communication interfaces are implemented in the dual-line sensor chip and only one interface can be activated at a time for scene capturing. For evaluating the arbitration performance, we activate the synchronous arbiter and capture a scene, then we activate the asynchronous arbiter and capture the same scene and we compare afterwards both object representations between both acquisitions.

As a first step, both arbitration processes have been evaluated using the dual-line sensor stimulated by a pulsed laser source light, instantaneously flashing on all pixels to generate coincident events. Afterwards, the arbitration processes have been evaluated on capturing high-speed moving objects.

A. Evaluation using Laser Source Light

In this test, a laser light flashing instantaneously on all pixels has been used in order to evaluate the arbitration performance between the coincident events. The latency of the laser light flashing is less than 30 ns and thus far below the pixel latency (~ 1µs) such that it does not affect the evaluation credibility. In order to achieve the same contrast change for all pixels, a light diffuser is used between the laser source and the dual-line sensor chip. Five milliseconds time segments are depicted in Fig.3 from the data resulting from the dual-line sensor test using the asynchronous and synchronous arbiter. The absolute time values are not equivalent as both tests have not been synchronized.

a.) Results using the asynchronous arbiter



b.) Results using the synchronous arbiter

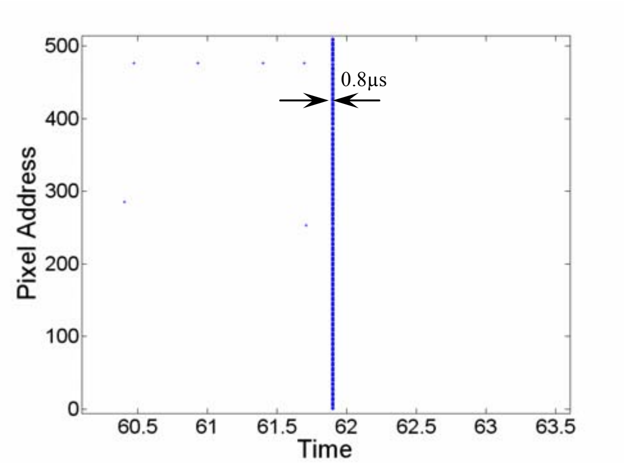


Fig. 2. Dual-line sensor data for the laser light flash using a.) the asynchronous arbiter and b.) the synchronous arbiter

All 512 pixels (2×256) have to instantaneously send an event as a reaction to the laser light flash. As all pixels events are temporally coincident, this test is adequate for evaluating the efficiency of both arbiter to route all the events to the shared communication bus. The x-axis in the figures of (Fig. 2) represents the time in milliseconds resolution while the y-axis represents the pixel index from 0 to 255 for the top and bottom lines of dual-line sensor. Fig.2 .a) shows that the asynchronous arbiter requires 1.6 ms to handle the 512 concurrent pixel events, which seems to degrade the expected laser signal (vertical line). Indeed, the arbiter greedy behaviour, as mentioned in [3], handles the coinciding events in queue, which is reflected in representing high-speed stimulus. In contrast, the synchronous arbiter (Fig. 2.b)) is able to handle the 512 concurrent events within a time period of 0.8 µs and to transmit the data in a duration of 52 µs to the processing unit. The time used for data transmission only affects the overall latency but it has no impact on the temporal information within the events due to the separative aspect of the data transfer from the processing.

These results show that the synchronous arbiter is at least 1000 faster than the asnychronous arbiter in handling 512 coincident pixels' events. Fig. 3 depicts the results statistical evaluation of the arbitration duration for several measurements with both arbiters. The x-axis (the arbitration duration) is represented in a logaritmic scale in order to plot both histograms (from the synchronous and asynchronous arbiters in one figure). The synchronous arbiter shows a systematic arbitration duration of of 0.8 µs while the asynchronous arbiter lies between 1.6 ms and 3.5 ms in handlinging all 512 coincident events.

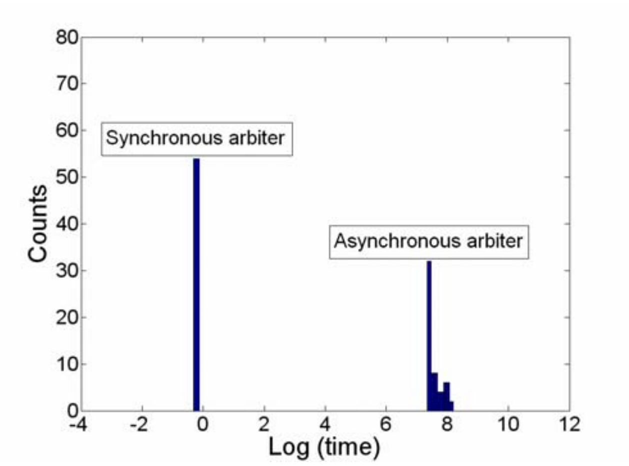
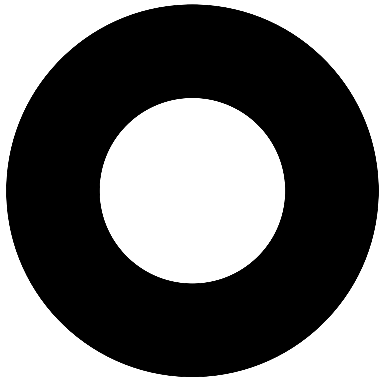


Fig.3. Histogram of the arbitration duration with the synchronous (left) and asynchronous for several measurements

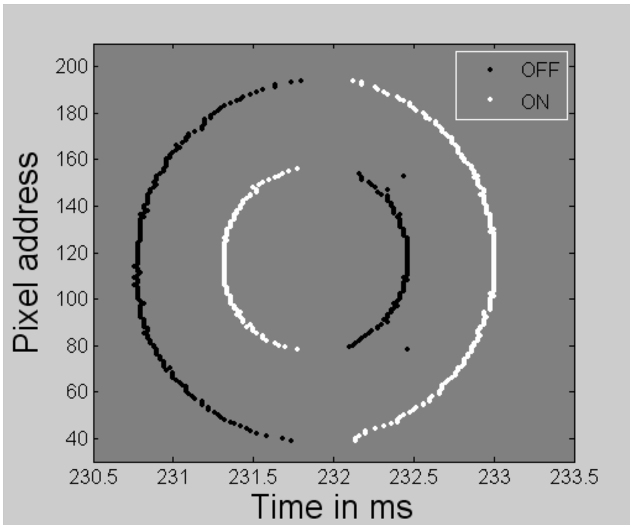
B. Evaluation on Capturing of High-Speed Moving Objects

In this test, objects crossing the sensor field of view at ultra high-speed are used for evaluating the arbitration processes. Several 2-D objects have been fixed on a rotating drum with velocity greater than 15 m/s, and the corresponding AE data have been generated with either activated asynchronous arbiter or activated synchronous arbiter. The main evaluation criterion is the capturing and high-speed object representation performance of the dual-line sensor using both arbitration processes. The figures Fig.4 – Fig.7 show original objects (a) and their AE representation using the dual-line sensor with activated synchronous arbiter (b) or activated asynchronous arbiter (c). It can clearly be noticed the distortion caused by the asynchronous arbitration for representing the object shapes due to the off-chip time-stamping and to the structural and non-deterministic behavior of the asynchronous arbitration. The synchronous arbitration allows the preservation of the temporal information, and thus the object shape representation using the on-chip timestamp assignment at the arbitration level. In this context, the synchronous arbiter support the temporal contrast sensor in preserving its main advantage "the high-temporal resolution" in efficiently handling concurrent AE and thus supporting ultra high-speed applications.

a.) Original object



b.) Dual-line sensor data using the synchronous arbiter



c.) Dual-line sensor data using the asynchronous arbiter

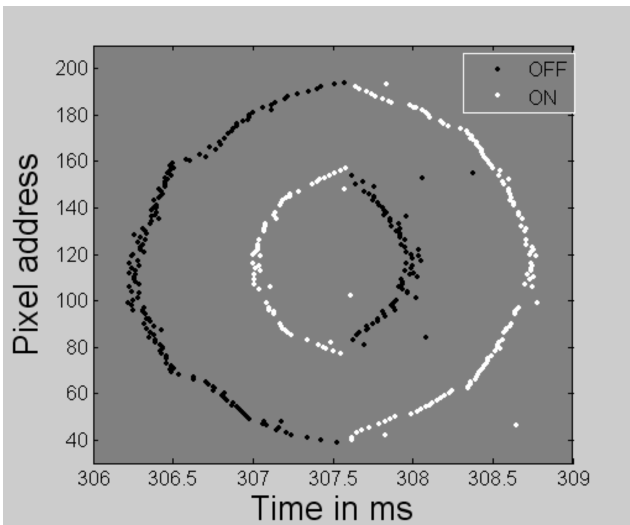
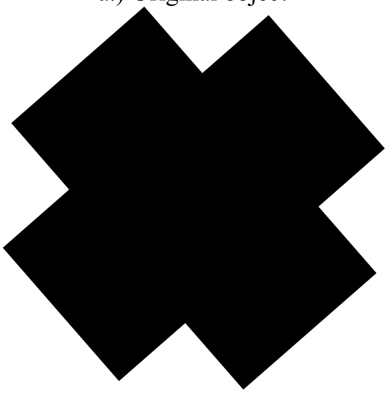
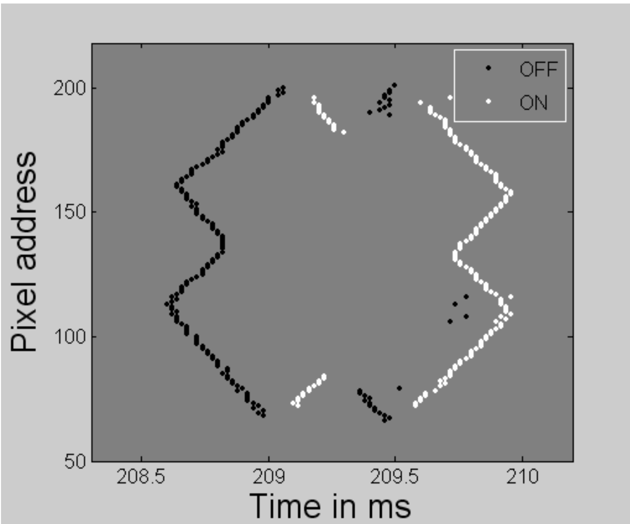


Fig.4. Original object (a) and its AE representation using the dual-line sensor with synchronous (b) and asynchronous (c) arbitration

a.) Original object



b.) Dual-line sensor data using the synchronous arbiter



c.) Dual-line sensor data using the asynchronous arbiter

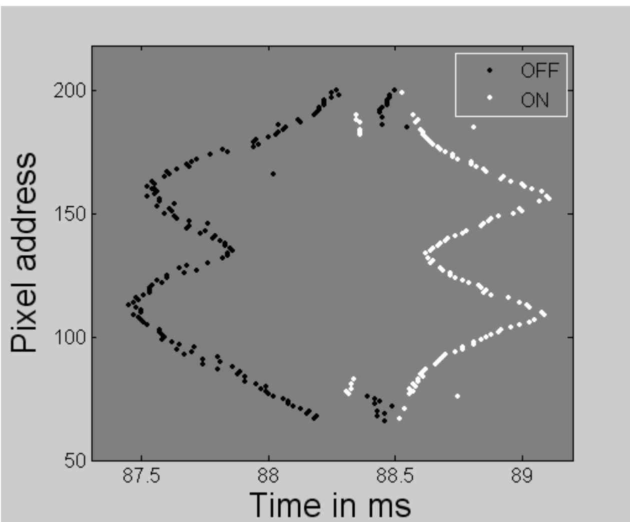
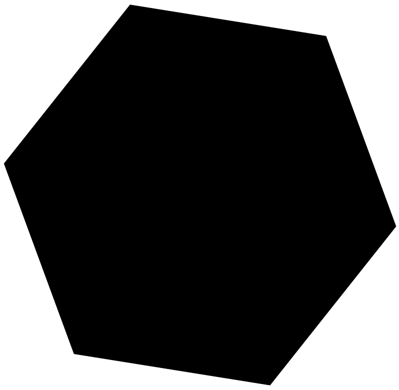
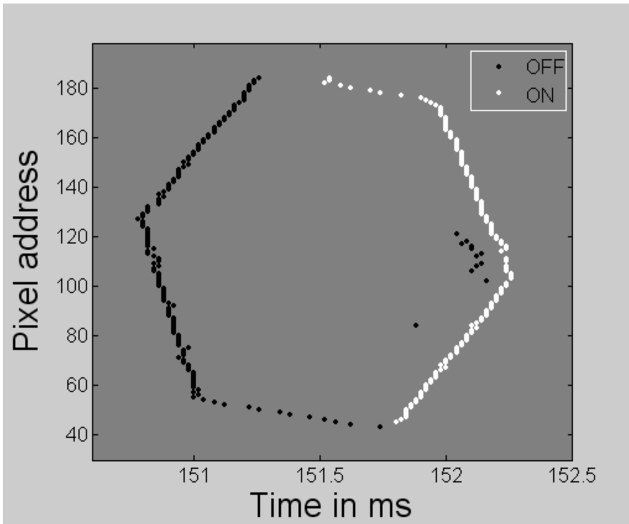


Fig.5. Original object (a) and its AE representation using the dual-line sensor with synchronous (b) and asynchronous (c) arbitration

a.) Original object



b.) Dual-line sensor data using the synchronous arbiter



c.) Dual-line sensor data using the asynchronous arbiter

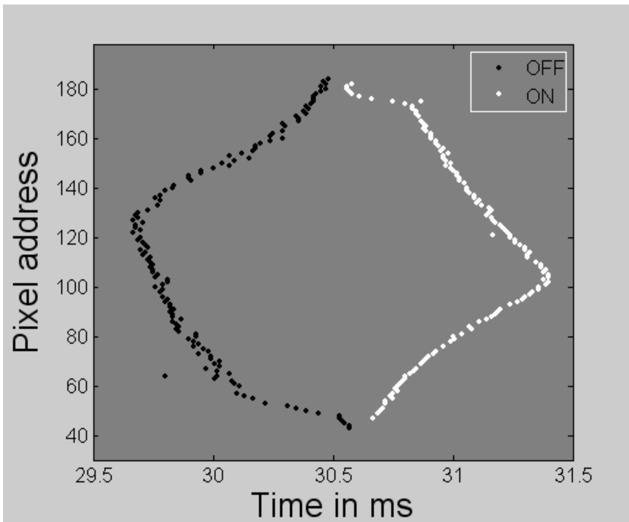
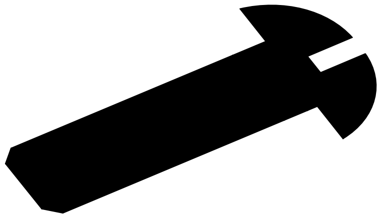
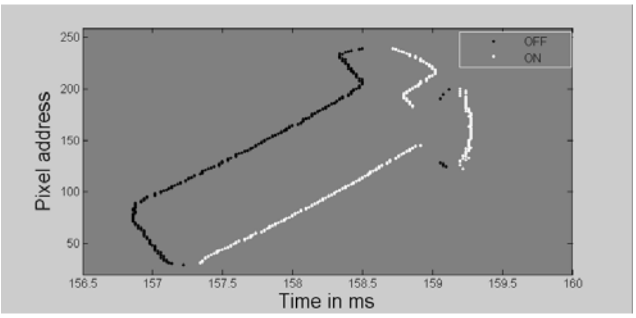


Fig.6. Original object (a) and its AE representation using the dual-line sensor with synchronous (b) and asynchronous (c) arbitration

a.) Original object



b.) Dual-line sensor data using the synchronous arbiter



c.) Dual-line sensor data using the asynchronous arbiter

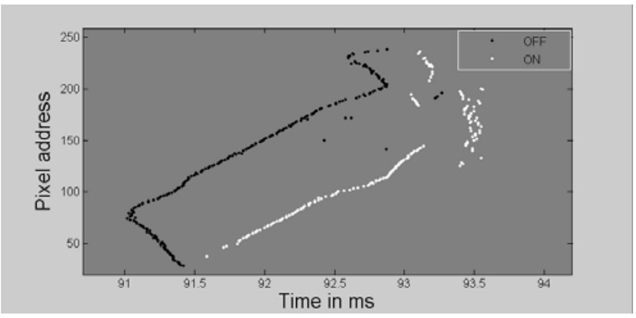


Fig.7. Original object (a) and its AE representation using the dual-line sensor with synchronous (b) and asynchronous (c) arbitration

The synchronous arbitration efficiently handles coincident pixels events with high accuracy as well as the object shape is maintained. Moreover, due to the deterministic behavior of the synchronous arbitration, the AE data stream is advantageous for vision applications in terms of algorithmic efficiency.

VI. Conclusions

The representation of high-speed moving objects is evaluated in this paper using the neuromorphic temporal contrast dual line sensor. This sensor implements two arbiters (synchronous and asynchronous), where only one can be activated at a time. A comparison between the synchronous and the asynchronous arbitration of temporal concurrent pixels events for preserving the object shape at high-speed is provided. Including an on-chip timestamp assignment, the synchronous arbiter preserves the neuromorphic systems advantages in ultra-high temporal resolution as well as the temporal accuracy of the pixel activities, to make the system attractive for ultra-high speed vision applications. Furthermore, the synchronous arbiter offers possibility to handle higher peak rates than those for the asynchronous arbiter and thus yield to minimal data loss by exploiting the individual Event FIFO set at the output of every pixel. Moreover, this synchronous arbiter and its digital integration allow masking and unmasking pixels in the array to adapt the sensor to different applications.

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