

On Threshold Comparing Biomorphing Image Sensors

Waqas Mughal¹, Luiz Carlos Gouveia¹, and Bhaskar Choubey²

¹ University of Glasgow, Glasgow, U.K.

w.mughal.1@research.gla.ac.uk Luiz.Gouveia@glasgow.ac.uk

² University of Oxford, Oxford, U.K., bhaskar.choubey@eng.ox.ac.uk

Abstract

CMOS image sensors have become the principal image sensors for the vast majority of digital cameras currently in market. The market popular sensor is a typical linear sensor which can capture 3-4 decades of illumination intensity, compared to 6-7 decades captured by the human eye. This has inspired research into biomorphing image sensors for over two decades by various groups leading to a number of adaptive pixels, threshold comparing pixel with neurons like firing mechanism as well as logarithmic pixels utilizing sub-threshold transistors. However, these have met little commercial success, often due to higher temporal and fixed pattern noise as well as limited dynamic range. In the paper, we will present a different approach to threshold comparison pixels, wherein a monotonically increasing reference signal is compared to the photo generated charge. The value at which the two signals intersect is recorded as the pixel's response. The monotonically increasing reference signal can be changed at the pixel's operation to produce any transduction function from the pixel. The tone mapped reference signal can be used to produce tone mapped responses.

Keywords: CMOS Image Sensor, Neuromorphic pixels, tone mapping

1 Introduction

Digital cameras have experienced an explosion in their application and have led to a sea-change in computing and communication devices. With the ability to manufacture the image sensor in the same CMOS process used for most integrated circuits, low cost and yet good imaging quality devices are being increasingly found in standalone camera as well as embedded in other devices [5]. In addition to the lower cost, CMOS sensors provide an opportunity to design pixel circuits for image processing as well. This has naturally led to investigations into design of silicon retinas and focal plane processing arrays. However, these have met with limited success. In the second section of this paper, we analyse the reasons for their failure and propose an alternative route for design of threshold comparing pixels. Section 3 presents a different direction of neuromorphic inspired threshold comparing pixel which utilises a continuously varying reference signal to capture high dynamic range of images as well as undertake on-the-fly tone mapping for direct display of these images on low dynamic range displays.

2 Biomorphic pixels and their failure

The human retina has inspired image sensors designers from its early days. The first image sensors were indeed designed to be focal plane arrays which performed retina like simple processing while acquiring an image ([3, 15]). Focal plane processing as well as potential for silicon retinas have led to a significant amount of research ([12, 7, 14]). We will discuss only a few of these as representatives of a vast field. A typical approach to design neuromorphic pixels is to design a pixel, which produces spikes as its response similar to biological neurons. The simplest design is to compare the photogenerated charge in a diode with a threshold and produce a spike, whenever the charge exceeds that of this predetermined threshold ([7]). The pixel can then be reset and allowed to discharge again till the same threshold, generating another spike. The interspike interval between the two instances can be used as a measure of the input intensity. However, they can be very large when imaging low intensities. This limits the speed and hence the frame rate of the sensors. To overcome these shortcomings, time-to-first spike architectures have been proposed ([14]).

Inspired by neuromorphic approaches, pixels have also been designed which integrate the photocurrent till the output reaches a known threshold value([10]), without generating spikes. For example, Hynecek's pixel provides a provision for resetting the pixel only when the accumulated charge exceeds a certain threshold voltage and ignoring the reset at all other instances ([10]). Yet another pixel which resets mid-frame after comparing to a threshold is from Ikebe and Saito([11]) which they utilise a columnar circuit to compare the pixel output to a threshold value followed by a reset of the pixel. Counters have also been implemented inside each pixel to count the number of times a pixel integrated within a frame [1, 13]. However, these schemes require a large number of transistors inside each pixel, which increases the pixel area and/or reduces the diode area leading to poor the optical efficiency.

Yet another inspiration from the human visual system has been to produce a response function similar to that of the human visual system that is logarithmically compress the input intensity [6]). This has been made possible by the subthreshold response of a transistor. However, limited sub-threshold gain reduces the signal to noise ratio in such pixels and despite several attempts to improve their noise performance, they have not been able to produce good imaging results. Another approach to design human eye like sensor has been to design foveated image sensors ([16]). These imagers arrange pixels in high resolution central region and low resolution peripheral region similar to the arrangement of rods and cones in the human eye. However, there has been limited development of algorithms which can process such images, which limits their usability. Finally, any display medium requires two dimensional scanning, thereby further limiting the usability of such image sensors.

All of these approaches; however, have generally failed to capture the market's attention. Their principal limiting factor has been the additional circuitry required inside each per pixel. This reduces the photosensitive part of the pixel leading to low optical sensitivity. For example, Andoh's pixel utilises 214 transistor with a fill factor of only 13.7% in $50 \times 50 \mu\text{m}$ pixel ([1]) and Stopa's pixel has fill factor of 11 % in a pixel as large as $24.65 \times 24.65 \mu\text{m}$ ([18]). This is in contrast to an active pixel sensor or a logarithmic pixel with 3 or less transistor per pixel and fill factor above 50%. Use of several devices per pixel also degrades the uniformity of pixel responses. Pixel designs generally require the use of smallest geometry transistors to increase the fill-factor. However, these transistors suffer from high mismatch. This means that pixels designed using these transistors have a non-uniform response to uniform stimulus. This appears as fixed pattern noise (or salt and pepper noise) in the images produced by such image sensors. This is the principal reason for failure of the logarithmic pixels despite their small transistor

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