

Dual-pixel CMOS APS Architecture for Intra-frame Speed Measurement

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Abstract— A dual-pixel APS sensor architecture is proposed in this paper, for vision based speed measurement applications. The proposed sensor integrates two separate imaging element on pixel level, and is designed to generate two separate images: the primary sensor generates a good quality image of the scene for vehicle identification, while the secondary sensor is used for speed measurement, based on the intra-frame displacement of the vehicle. A scaling process is also shown for the sensitivity of the secondary sensor for a specific illuminance value.

Keywords— CMOS Sensor; Global Shutter Efficiency; Multi exposure; Motion Blur; Speed Estimation; Dual-pixel

I. INTRODUCTION

Speed measurement plays an important role in traffic management and control, which enables authorities to manage the traffic flow. The most common devices used for speed measurement, are based on active sensing technologies, like RADAR or LIDAR speed guns. According to US Department of Transportation National Highway Traffic Safety Administration [1], these devices measure the movement speed of the vehicles with high precision, with only a +2, -3 km/h tolerance in the measurement. On the other hand, these tools are expensive, and thus not suitable for example, to monitor the whole road network of a city, which would require a large number of sensing nodes. In addition, a camera is used along with these devices to perform the license plate recognition, to identify the vehicles. In this work, we present an alternative solution, in the form of a vision based speed measurement concept, which has an advantage of using a single sensor for both the speed measurement and the license plate recognition. Vision-based displacement calculation methods can be divided into two categories: inter-, and intra-frame. Inter-frame methods, like optical-flow based algorithms calculate the displacement of certain objects between two frames, or image sequences. On the other hand, intra-frame methods [2-6] measure the displacement during the exposure, thus capable of providing speed estimates based on a single image. For the latter case, there are only a few publications available [2-4]. In these papers, the authors utilize the fast shutter speed and the high resolution of the selected camera, to achieve 2% measurement error, with a deblurring method. Our approach is based on a different measurement principle, using a low-end image sensor, which provide similar accuracy, with better image quality in the region of interest, without the need for deblurring, as described in [5] and [6].

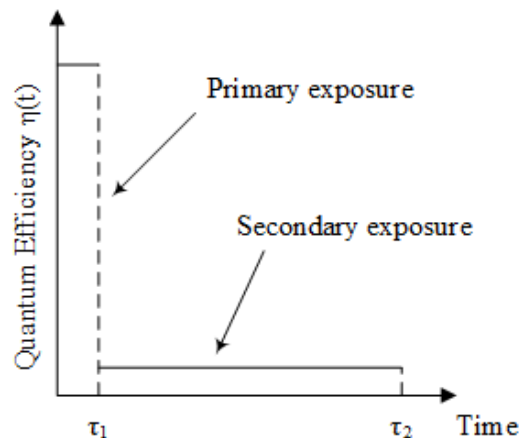


Fig. 1. Exposure-control scheme of the proposed method, with the primary $[0, \tau_1]$ and the secondary $[\tau_1, \tau_2]$ exposure having different QE values

The paper is composed in the following way. The measurement concept and the double-exposure method is described in Section 2, as well as the results of preliminary work using low global shutter efficiency imagers. Section 3 contains the description of the novel dual-pixel architecture, and design considerations related with photodiode scaling based on a given luminous intensity value, and the specifications of the selected technology. Section 4 gives a short summary of the work.

II. INTRA-FRAME SPEED MEASUREMENT CONCEPT

The proposed intra-frame speed measurement concept is based on a modification of the sensor shutter, which ensures sufficient image quality for the license plate recognition, while still holding information describing the intra-frame motion of the vehicles. To achieve such an image, a multi-exposure method has been developed. The modified shutter cycle contains three states of the electronic shutter: open state (primary exposure), semi-open-state (secondary exposure), and the close states. We modeled these integration intervals with different Quantum Efficiency (QE) values, as you can see in Fig. 1. Quantum Efficiency describes the photon to electron conversion efficiency of a sensor in the following way:

$$\eta = \frac{Jh\nu}{\Phi q} \quad (1)$$



Fig. 2. Superimposed image acquired with the low-GSE Aptina MT9M021 CMOS sensor. The saturated trace represents the movement of the headlights during the readout phase.

where J is the incident photon generated current density, q is the elementary charge, Φ is the optical power density, while $h\nu$ represents the energy of one photon. This means, that in the case of the secondary exposure, much more incident light power is required to generate the same signal on the sensor. As a result of this double-exposure method, we get a superimposed image. The short primary exposure generates a sharp image, and the longer secondary exposure with lower QE results in a motion blurred image, where only the brightest regions of the scene will appear (Fig. 2). If we consider a measurement situation, where there is a moving vehicle in front of the camera system with the headlights turned on, light traces will appear on the image, representing the movement of the headlights during the secondary exposure. The length of the traces will be proportional with the movement speed of the vehicle, thus the speed measurement can be interpreted as length measurement on the image plane. If the exact spatial geometry of the measurement setup, and the length of the secondary exposure is known, we can calculate the movement speed of the vehicles. The problem formulation and the calculation of speed estimates can be found in [5] and [6], as well as error analytics and the description of the measurement method itself.

A. Speed measurement with low GSE CMOS sensor

In our previous works [5], and [6], we used a suitable, commercially available sensor for the measurements, featuring low global shutter efficiency. Global shutter efficiency (GSE) is a term, which describes the electrical and optical isolation of the in-pixel memory node, and is defined as a ratio of photodiode (PD) sensitivity to in-pixel store parasitic sensitivity. Global shutter pixel arrays start the integration of incident photons at the same time for all pixels in the array, and the readout is performed in a row-by-row manner. At the end of the integration, the collected charge is transferred to an in-pixel storage node (Fig. 3.). This memory node functions as a parasitic photodiode, incident photons will generate electron-hole pairs in the analog storage also. The PD to storage leakage current and the diffusion current outside of the memory node also contribute to the parasitic current. These effects will modify the stored photocharge until it is read out, so improving optical and electrical isolation (improving GSE) is essential in most CMOS imagers. There are some special applications however, where a sensor with low GSE can be beneficial, for example in the field

of optical speed measurement. The impact of the low GSE on an image is similar to that of the secondary exposure phase of the double-exposure method (described in Section 2), except the length of the light trace depends on its vertical position on the image, and can be controlled through the readout frequency. We developed an FPGA based test framework, capable of controlling multiple imager modules. The cameras use the Aptina MT9M021 CMOS sensor chip, which features the early 3rd generation $3.75\mu\text{m}$ global shutter pixel technology of Aptina [7]. These sensors have relatively low GSE (approx. $1/200$), which enables us to use them for the speed measurement. The proof of concept measurements and the complete description of the measurement method, based on these sensors can be found in [5] and [6]. The fundamental problem with this method is that the length measurement of the traces has an inherent uncertainty. As you can see in Fig. 2, there is a saturated area around the starting point of the trace, which depends on the headlight geometry. In [6], we proposed a method using two synchronized cameras to overcome this problem, but the exact measurement, using a single sensor remained unsolved.

III. SENSOR ARCHITECTURE

CMOS technologies enable the designers to implement various pixel level control and processing innovations, as prototyping of custom ASIC designs with different technologies (including opto technologies, with anti-reflective coating, dedicated to CMOS imager design) are available for universities and research laboratories. We selected a suitable technology for our design, namely the $0.35\mu\text{m}$ AMS C350, which is a dedicated opto technology. Our goal is to develop an imager capable of separating the saturated region of the headlight and the light trace on a hardware level, making the trace length measurement more accurate.

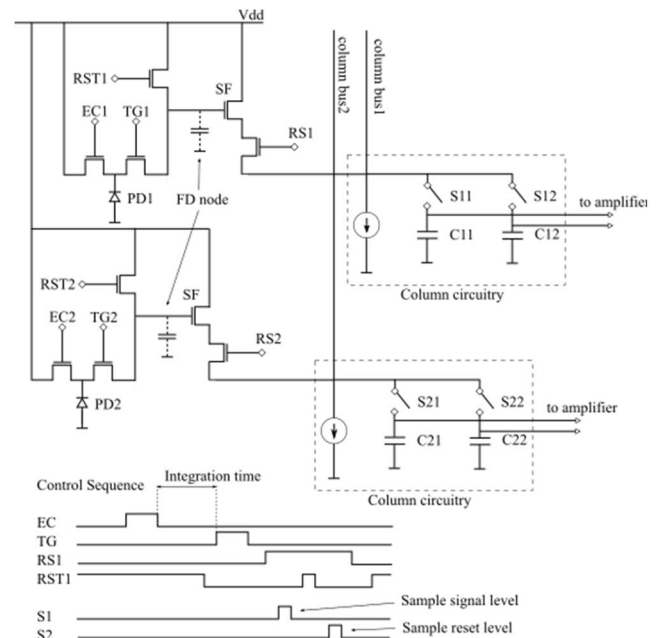


Fig. 3. Pixel architecture is based on a conventional 5T APS pixel. A 5T pixel consists of a photodiode, a floating diffusion (FD - analog storage node) and five transistors. S1X and S2X signals represent the two switches, which perform the double sampling, and sample the signal and reset levels in the analog storage node respectively.

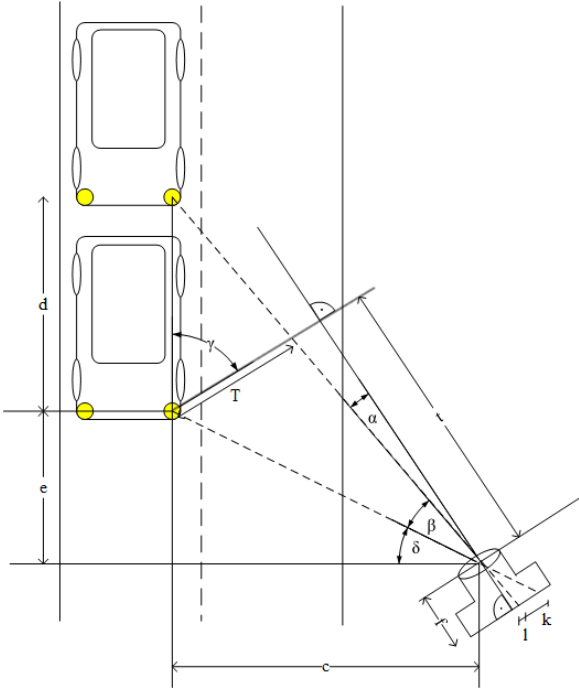


Fig. 4. Geometry of the measurement setup

A. Dual-pixel sensor

The challenge in this design remains the same as in the previous implementations of speed measurement sensors. The requirements are to provide an adequate quality image for license plate recognition, as well as to generate an image, which holds information regarding the intra-frame motion of the vehicle. To satisfy both conditions, we proposed a dual-pixel structure (Fig. 3). Every pixel in the array contains two PD, one of them (the primary sensor) is responsible for the good quality image of the scene, the other one – the secondary sensor, with much less sensitivity (QE) – will be used to measure the intra-frame movement of the vehicle. The pixel structure is based on a conventional 5T active pixel sensor (APS) pixel with double sampling [8]. As both primary and secondary sensors have similar readout circuitry, one pixel contains 10 transistors. This means, that two architecturally similar sensor elements are integrated in a pixel of the proposed dual-pixel sensor. The pixel-level integration is important, because of the integrity of the spatial and temporal features of the scene. The 5T pixel consists of an exposure control (EC) gate, a transfer gate (TG), a reset (Rst), a source follower (SF) and a row select (RS) transistor. The shutter functionality is implemented with EC and TG, while SF act as a buffer amplifier to isolate the sensing node, and RS selects the pixel in the readout phase. Both PDs have separate exposure control, since the exposure has to satisfy different conditions in both cases. In the case of the primary sensor, the exposure control is similar to conventional imagers, the integration time depends on the illuminance of the scene. Our goal is to adapt to the lighting conditions, to generate a sharp image of the scene. The integration time for both sensors is set manually, there is no AEC (automatic exposure control) in the design. However in the case of the secondary sensor, the exposure conditions remain the same for every measurement situation, since only the brightest spots of the scene - often the headlights - will appear on the secondary image, and the

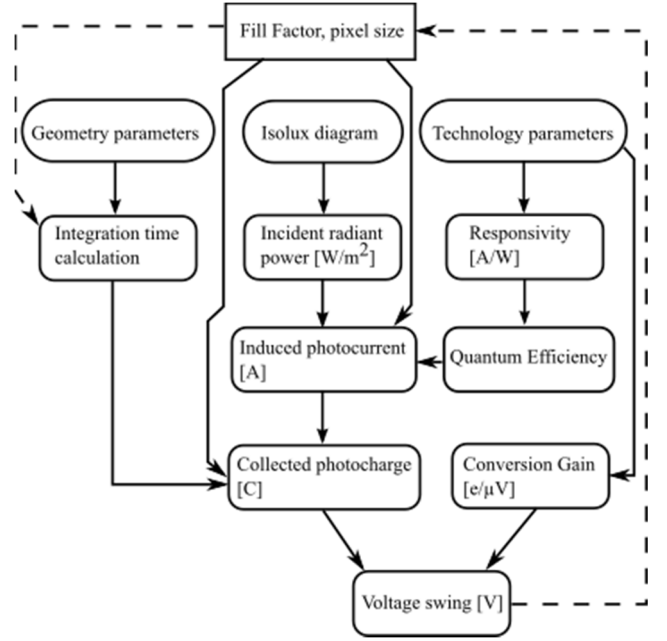


Fig. 5. Flowchart of the PD scaling process based on the geometry parameters, the technology parameters and the isolux diagram of a selected headlight.

illuminance of a headlight can be specified from the isolux diagrams provided by manufacturers. As a result, we can scale the sensitivity of the secondary PD to a specified illuminance level.

B. Integration time calculation for the secondary PD

Based on the parameters of the spatial measurement geometry (Fig. 4.) along with the characteristics of the optical system and the sensor itself, we can calculate the length of the light trace on the image plane in pixels for a given vehicle movement speed. For example, in an urban traffic situation, the speed of the vehicles is typically around 50km/h. Based on the regulations specified in Section 1, in this case, +4, -6% relative error is accepted in the measurements. This specification can be directly transferred to our interpretation of the speed measurement, as the length measurement of the light trace on the image corresponds to the movement speed. As a result, the previously described error range applies to the aliasing error caused by the pixelization also, which affects the accuracy of the length measurement on the image plane, so we can define the required minimum length of the light trace on the image for the given accuracy. After this, based on a pinhole camera model and the geometry setup (Fig. 4), we can specify the integration time for the secondary sensor, based on (2) and (3)

$$v \times t_{int} = d = c(\text{tg}(\gamma - \alpha) - \text{tg}(\gamma - \alpha - \beta)) \quad (2)$$

$$l_{trace} \times s_{pix} = k = f \frac{T}{t} \quad (3)$$

where l_{trace} is the length of the light trace in pixels and s_{pix} is the pixel size. Connection between T and d can be expressed with trigonometric functions from the geometry.

$$\frac{\sin(90^\circ - \alpha)}{d} = \frac{\sin(90^\circ - \alpha - \beta - \gamma)}{T} \quad (4)$$

The calculation of the integration time can be performed iteratively, since the initial pixel size is affected by later stages of the sensor design.

C. Secondary PD scaling based on isolux diagram

The challenge in the secondary sensor design is that we have to ensure that only the brightest regions of the scene have significant impact on the image, so scaling the sensitivity of the sensor is crucial. In the previous subsection, the integration time has been specified based on the spatial geometry. Another starting point of the scaling is the isolux diagram of a headlight. The isolux diagram provides the contours of equal illuminance or luminous intensity in lux or candelas respectively, from a specified position. This diagram can be used to analyze the power distribution characteristics of a headlight and to determine lighting levels in selected directions [9]. The most important steps of the scaling process are highlighted in Fig. 5. Because in many cases, the structure of the PD is pre-defined by the technology, the only features the designers have, to control the sensitivity of the sensor is the fill factor (FF=photoactive area (PD size)/pixel size), and the reverse bias voltage of the PD. In this paper, we focus on the fill factor, the effect of a variable reverse bias voltage on the output through the conversion gain will be discussed in another paper. Based on the luminous intensity provided by the isolux diagram at an angle specified from the geometry, we can calculate the incident radiant power density reaching the surface of the sensor in W/m² after photometric-radiometric conversion. On the other hand, technology parameters define the spectral responsivity function of the PD. After rewriting (1), we obtain the following equation for the QE [10]

$$\eta(\lambda) = R(\lambda) \frac{h\nu}{q} \quad (5)$$

where $R(\lambda) = I_d/P_{pix}$ denotes the responsivity, I_d is the photocurrent, and P_{pix} is the radiant power [W] reaching the surface of the PD. As a result, we can calculate the photocurrent

$$I_d = \frac{q\eta P_{pix}}{h\nu} \quad (6)$$

Taking into consideration the spectral power density distribution of the light source (denoted with $f(\lambda)$), the photocharge cumulated during the previously defined integration time can be obtained as follows

$$Q = A_{eff} t_{int} \int R(\lambda) f(\lambda) d\lambda \quad (7)$$

where A_{eff} denotes the photoactive area of the pixel. The electron to voltage conversion gain can be calculated from the technology parameters,

$$C_{gain} = \frac{q}{C_{jdep}} \quad (8)$$

where C_{jdep} is the area dependent junction capacitance of the PD. After combining (7) and (8), we get an equation for the voltage swing at the pixel output, for the given illuminance.

$$V = \frac{Q}{C_{jdep}} = \frac{A_{eff} t_{int} q}{C_{jdep}} \int \frac{\lambda}{hc} \eta(\lambda) f(\lambda) d\lambda \quad (9)$$

The value of the voltage swing on the pixel output can be controlled with the FF. This method can be performed iteratively, until the voltage swing range meets the specifications, since it is hard to estimate the size of the readout circuitry prior to the actual design process. This will affect the size of the pixels and in the end, the integration time and the fill factor also. The lower fill factor due to extra devices will be compensated by microlens.

IV. CONCLUSIONS

We are developing a novel speed measurement CMOS imager, based on dual-pixel architecture. Some of the most important design considerations are described in this paper. The sensitivity of the secondary, speed measurement sensor is designed for a specific exposure value, based on the luminous intensity of a vehicle headlight. This way, we can ensure that intra-frame motion information will only be extracted from the brightest regions of the scene.

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