Dual-pixel CMOS APS architecture for intra-frame movement detection and speed measurement

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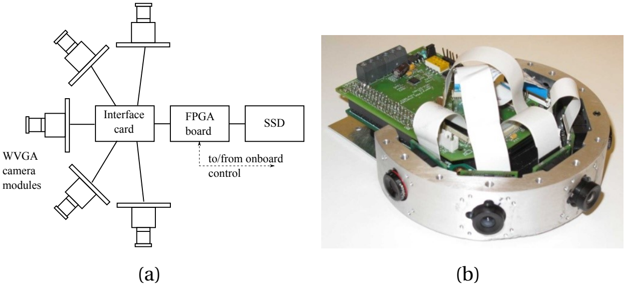
1 Introduction

Nowadays one of the most emerging fields of sensor technology are image sensors. An important part of this evolution is machine vision, and the research related to the vision systems and vision based decision making systems of various autonomous vehicles. I had the opportunity in the Computational Optical Sensing and Processing Laboratory of Hungarian Academy of Sciences Institute for Computer Science and Control (SZTAKI), to take part in a project, aiming at the development of a compact UAV, capable of autonomous maneuvering, even in highly utilized airspace, due to its onboard non-cooperative collision warning and avoidance system. The collision warning is based on a multi camera vision system, and the related image processing hardware [J1]. The research and development work related to the WVGA cameras of the vision system (shown in Figure 1.) was a good motivation for my research in the field of the pixel structures used in CMOS image sensors.

There are two types of image sensors used in imagers: Charge Coupled Devices and CMOS cameras. In general, the sensitivity of CCD devices is superior to that of the CMOS cameras, because of the higher fill factor, and the smaller sensitivity to noise sources. On the other hand, the most important advantage of CMOS sensors over CCDs is the fact that these are manufactured with CMOS compatible technologies, hence the integration of image sensors to conventional VLSI circuitry is much easier and cheaper. Because of this, many focal plane image processing functions and custom pixel structures can be integrated and implemented on CMOS sensor chips.



(a) (b)

Figure 1: (a) The block diagram of the vision system; (b) The assembled camera holder frame and its components.

1.1 The structure of CMOS image sensors

In the case of CMOS based image sensors, multiple different devices (photodiode, phototransistor, photogate) can be used for the photon-electron conversion in the pixels. The most widespread of these structures are photodiodes. During an exposure cycle, a photodiode is first reverse biased, then the incident light induces a photocurrent, which discharges the parasitic capacitance of the pn junction. The wavelength dependent photocurrent can be calculated in the following way:

$$\mathrm{I}_{ph} = \frac{q\eta\mathrm{P}_{ph}}{\hbar\omega} \tag{1}$$

where I_{ph} is the photocurrent, q represents the elementary charge, η is the quantum efficiency, P_{ph} is the incident radiant power, $\hbar$ is the reduced Planck constant and ω is the angular frequency of the incident light. After the exposure, the output voltage of the pixel carries the visual information from the scene. Based on the structure and functionality, pixels can be divided into two groups: passive and active. The passive pixel sensors (PPS) include only a MOS switch – besides the photodiode – for the readout. Active pixel sensors (APS) on the other hand consists of many other components, for example a source follower stage, and the exposure control switches. The exposure in APS sensors is implemented with shutter control transistors. These shutter mechanisms can be divided into two groups. The first is the so called rolling shutter, where the exposure starts in a slightly delayed manner for every row of the sensor. This causes geometrically incoherent images when capturing objects moving at high speed. This fact calls for the other type of CMOS sensors featuring global shutter pixels (Figure 2.). In this case, every pixel is equipped with a pixel-level memory element, which allows simultaneous integration of the pixel array.

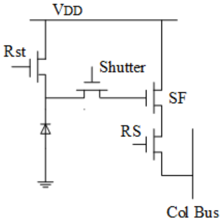


Figure 2: Transistor scheme of a common global shutter pixel, with four transistors (4T APS).

2 Methods

Scientific studies in the field of vision based speed measurement can be divided into two major research directions: optical flow (inter-frame) and motion-blur (intra-frame) based displacement calculation methods; however, there are only a few papers related with the latter case. Inter-frame solutions calculate the movement speed of the object of interest based on the displacement of the object between frames or frame sequences. In order for this to work, the moving objects has to be identified in each frame and tracked throughout the frame sequence. This requires a large processing power of the hardware platform.

On the other hand, the input of the inter-frame methods is only a single image, where the intra-frame motion information is coded by the motion blur effect. In most applications, motion blur is an unwanted image degradation effect, but in our case, it is a fundamental part of the measurement. The most important drawback of the motion blur based methods is that the measurement concept itself is based on the degradation of the image, which is – in most cases – controversial with other image processing algortihms (object identification, classification etc.), hence the whole image is affected.

In Chapter 2, I show a method, which ensures that motion blur applies only on specific regions of the image, while the rest of the frame is not affected, hence different image processing algorithms can be carried out. I have also shown that using a specific sensor structure, the motion blur (which holds the motion information), can be separated from the rest of the image in the sensor, making the post processing much less complicated. In my theses, I analyze the theoretical and practical aspects of intra-frame movement detection and speed measurement.

3 New Scientific Results

The new scientific results of my research are separated into two Thesis Groups. Thesis Group 1 contains the theoretic results and mathematic background of intra-frame speed measurement, while Thesis Group 2 contains the research results related to the pixel structure, optimized for the measurements. The results have been published in journals (denoted with [J]) and conference papers (denoted with [C]).

Thesis Group 1: Intra-frame movement detection and speed measurement on superimposed images

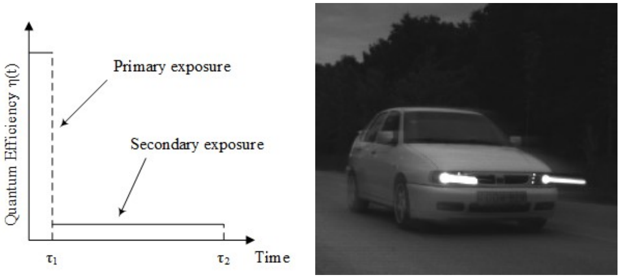
The amount of incident light reaching the imager sensor is determined by the cameras shutter speed (t), the lens relative aperture (N), and the luminance of the scene (L_v). Considering a measurement situation where N, L_v are given, the intra-frame behavior of fast moving objects on the image plane can be controlled through shutter speed. The appearing motion blur on an image is proportional to the speed of the object and the shutter speed. The accuracy of the displacement calculation is most importantly defined by the exposure time (because of the pixelization). The longer t gets, the better the accuracy will be, but the image degradation increases also in the moving areas, creating a tradeoff between image quality and measurement accuracy. In this Thesis Group, I have given an intra-frame speed estimation method for moving objects with light sources.

Corresponding publications: [J2], [C1]

Thesis 1.1 *I created a double exposure image acquisition model, which results in superimposed output images. I showed that cameras with low global shutter efficiency can be used to emulate this exposure sequence.*

The captured superimposed image consists of two component images. The primary image contains the visual information of the scene, while on the secondary image, only the high intensity regions appear. The motion blur affects only this secondary image, thus it can be used for the intra-frame speed measurement, while maintaining adequate image quality because of the primary image. To capture such an image, I extended the classical shutter cycle (open, close) with an intermediate, semiopen state. I modeled the exposure phases with different quantum efficiency values. The first phase of the double exposure is a short interval, when the electronic shutter is fully open. During this time, the dominant component of the integrated image is collected. Since the time interval is small, even the moving objects will not be blurred. Then, in the semiopen phase, the process continues with significantly longer exposure, but with a lower QE (Figure 3.). This means that much less portion of the incident light will generate charge carriers in the photodiode in a time unit, reducing the responsivity of the sensor. This implies that in the case of a high intensity light source, a light trace appears on the image plane according to the movement path of the light source during the secondary exposure, and the length of the trace is proportional to the speed of the object.

The global shutter efficiency (GSE) is defined as a ratio of photodiode sensitivity during open state to pixel storage parasitic sensitivity during closed state. Or in other words, it is the ratio of the QE in the open state to the QE in the closed state of the shutter. In the case of low GSE sensors, the charge accumulation during the closed state of the shutter can significantly modify the pixel values, even drive them into saturation. This effect makes these sensors suitable for intra-frame speed measurement (Figure 3.)



(a) (b)

Figure 3: (a) The exposure scheme with the primary $[0,\tau_1]$ and the secondary $[\tau_1,\tau_2]$ exposure phases; (b) Superimposed image, captured with a low GSE sensor

Thesis 1.2 *I showed a method for calculating the intra-frame displacement of high intensity regions on a superimposed image, assuming the measurement geometry and sensor parameters are known. I analyzed the theoretical measurement error, and the effect of parameter changes to the result of the calculation and the achievable accuracy.*

Assuming the measurement geometry (Figure 4.) and the exposure sequence parameters are known, the movement speed of the light source can

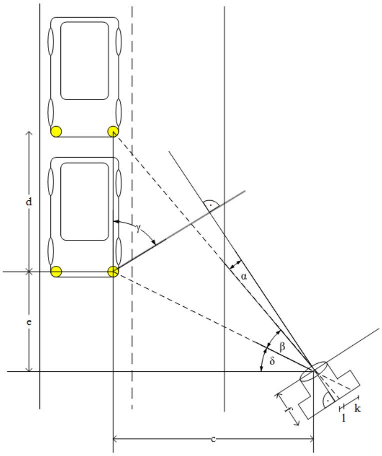


Figure 4: The proposed measurement geometry.

be derived from trigonometric functions, based on the projection of the light source trajectory on the image.

$$d = c(\tan(\gamma - \alpha) - \tan(\gamma - \alpha - \beta)) \tag{2}$$

$$v = \frac{d}{\tau_2 - \tau_1} \tag{3}$$

As speed measurement can be interpreted as angle measurement using the camera, the error of speed measurement is equivalent with the error of the intra-frame trajectory length measurement on the image. I estimated the achievable accuracy in a specific measurement situation – where the geometry and camera parameters are given – using the headlight of a moving target vehicle. In a realistic setup, where the ground truth was captured using a GPS data acquisition device, I experienced 1,3% error in speed measurement.

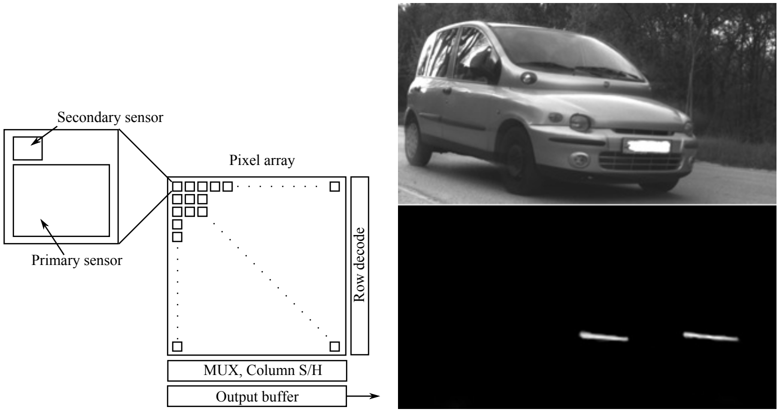
As Figure 3. shows, the most limiting factor of speed estimation using a superimposed image, is the uncertainty introduced by the localization of the light source. This is caused by the saturated area around the light source. I created a method using a second camera to eliminate this uncertainty.

Thesis Group 2: Dual-pixel CMOS APS architecture for vision based speed measurement

The fundamental problem of the method described in Thesis Group 1 is that the localization uncertainty of the light source introduces a significant error in the speed measurement. In Thesis Group 2, I propose a sensor structure, aiming at overcoming this uncertainty with the separation of the intra-frame motion information from the rest of the image on the sensor level.

Corresponding publications: [C2], [C3]

Thesis 2.1 *I created a pixel-level integration method for vision based speed measurement sensors, which allows the separated capture of the component images of a superimposed image, defined in Thesis 1.1. This method increases the measurement accuracy by lowering the localization uncertainty of the light source.*



(a) (b)

Figure 5: (a) The proposed sensor architecture with the subpixels; (b) A sample of the expected image pair of the sensor.

The dual-pixel sensor structure optimized for intra-frame speed estimation is based on the double exposure sequence defined in Thesis 1.1. The architecture has been created in a way that two type of subpixels are present in the sensor array, each implementing the appropriate phase of the dualexposure in the sensor.

As a result, every pixel in the array contains two subpixels (shown in Figure 5.), one of them is responsible for capturing a good quality image of the scene (corresponds to the primary exposure), the other one -– with much less sensitivity — will be used to measure the intra-frame movement of the vehicle (corresponds to the secondary exposure). Both primary and secondary sensor arrays have separate readout and exposure control circuitry, as well as separate output images. 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. This way the intra-frame motion information is separated from the visual information of the scene in the sensor. With the scaling of the secondary sensors sensitivity, one can achieve that only the high intensity regions of the scene appear on the secondary image.

Thesis 2.2 *I showed a quantitative pixel masking method for the dual-pixel structure described in Thesis 2.1, which enables the sensitivity calibration of the secondary subpixel, used for the intra-frame speed measurement, through the scaling of the photoactive region of the photodiode.*

The basis of this method is that, while the primary sensor captures the scene, only high intensity areas have other than zero pixel response at the output of the secondary sensor, at the same luminous flux. Notice that this does not require scaling on an absolute scale, the sensitivity ratio of the two subpixels is the determining characteristic feature. The voltage swing at the output of the pixels can be approximate with the following equation:

$$\mathrm{V} = \frac{\mathrm{A}_{eff}\, t_{int}}{\mathrm{C}_{jdep}} \int \mathrm{R}(\lambda) f(\lambda)\, d\lambda \tag{4}$$

where A_{eff} is the photoactive region, t_{int} denotes the exposure time, C_{jdep} is the parasitic capacitance of the pn junction, $\mathrm{R}(\lambda)$ corresponds to the responsivity function of the photodiode, while $f(\lambda)$ is the spectral power density distribution of the light source. This way, if the technology defined parameters are given, the pixel response can be controlled through the size of the photoactive region. I utilized this phenomenon in the scaling process of the secondary subpixels.

4 Applicability of the Results

An obvious application of the intra-frame speed measurement, formulated in the theses is speed estimation of moving vehicles. Nowadays mostly lidar or radar based active sensor systems or speed guns are used for this purpose. These are expensive devices and have high power consumption, besides they have an integrated camera for vehicle identification. Based on the above statements, it would be profitable to use a single camera for the speed estimation and the identification.

The proposed two camera intra-frame speed measurement method – based on the error analysis – seems suitable to fullfill the requirements, but it would require further studies and validation to prove this statement. The single camera method, using the trace length correction process could be suitable for less critical applications. Such an application with less strict specification could be to use the sensor as a sensing node in a distributed sensor network of a traffic management and observation system. As it is a small, cost effective device with low power consumption, it could be used even in large numbers for example in the Smart City concept.

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[J3] Tamás Zsedrovits and Péter Bauer and Antal Hiba and Máté Németh and Borbála Jani Mátyásné Pencz and Ákos Zarándy and Bálint Vanek and József Bokor “Performance Analysis of Camera Rotation Estimation Algorithms in Multi-Sensor Fusion for Unmanned Aircraft Attitude Estimation,” *JOURNAL OF INTELLIGENT & ROBOTIC SYSTEMS*, vol. 84, no. 1-4, pp. 759–777, 2016

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