# Photon Counting and Direct ToF Camera Prototype Based on CMOS SPADs

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***Abstract*—This paper presents a camera prototype for 2D/3D image capture in low illumination conditions based on single-photon avalanche-diode (SPAD) image sensor for direct time-of-flight (d-ToF). The imager is a 64×64 array with in-pixel TDC for high frame rate acquisition. Circuit design techniques are combined to ensure successful 3D image capturing under low sensitivity conditions and high level of uncorrelated noise such as dark count and background illumination. Among them an innovative time gated front-end for the SPAD detector, a reverse start-stop scheme and real-time image reconstruction at 1kfps are incorporated by the imager. To the best of our knowledge, this is the first ToF camera based on a SPAD sensor fabricated and proved for 3D image reconstruction in a standard CMOS process without any opto-flavor or high voltage option. It has a depth resolution of 1cm at an illumination power from less than 6nW/mm$^2$ down to 0.1nW/mm$^2$.**

***Keywords—2D/3D image reconstruction; direct time-of-flight; SPAD image sensor; time gating; low illumination***

## I. INTRODUCTION

**S**ingle-**P**hoton **A**valanche-**D**iode (SPAD) image sensors have experienced a tremendous evolution in the last years. The performance of the detector itself has been constantly improved thanks to customized CMOS processes optimized for this kind of photodiodes [1]. Their ability to precisely measure the time-of-flight has fueled a diversity of applications, among them 3D vision or 3D ranging. Nowadays smart pixels based on SPADs are becoming a leading technology for ToF imagers. They have been approved even by a very demanding sector such as automotive [2].

When it comes to achieve very high frame rate, an architecture with in-pixel time-to-digital converter (TDC) is more appropriate [3]. Moreover, the integration of 2D imaging by photon counting along with the time resolved functionality has been already proved [4].

Pixel-level depth estimation can be performed by either indirect ToF (i-ToF) or direct ToF (d-ToF) techniques. The former relies on phase difference between the incoming and outgoing continuous or pulsed light-waves [5], [6]. It is less accurate but achieves a higher frame rate and relaxes the requirements of the illumination source. The latter technique directly measures the time elapsed for the light wave to travel from the laser to the target and back to the sensor [7], [8], [9]. It is more accurate but demands picosecond-jitter lasers.

This paper reports a prototype of a SPAD camera for 3D image reconstruction based on a 64×64 d-ToF imager with in-pixel TDC of less than 150ps time resolution. It also incorporates a 2D vision capability by photon counting.

The main motivation of this project was to build a SPAD based camera in a cost-effective standard CMOS technology for mixed signal circuit design but with moderate performance for integrated photodiodes [10]. In this case the noise has an average count rate of 42kHz and a photon detection probability of 6.5% at 520nm. Under these circumstances we had to face big challenges to be able to retrieve depth and brightness images.

In order to counteract the weaknesses of the SPAD detector, several techniques have been employed such as: fast active quenching/ recharge circuit, time gating of the SPAD front-end, reverse start-stop. They have a contribution at circuit design level which also helps to reduce the power consumption which is crucial for large arrays of SPADs and in-pixel TDCs. Moreover, embedded real-time image reconstruction at 1kfps has been implemented off-chip.

By applying the aforementioned design strategies we have been able to reconstruct 2D and 3D images with performances close to the state-of-the-art. The prototype of the camera has also a graphical user interface (GUI) and command-line interface built in Matlab and C++.

The principle of d-ToF is explained in the diagram of the experimental setup depicted in Fig. 1. A picosecond laser sends a short light pulse towards an object plane, which can be at any position between P$_i$ and P$_f$. At the same time, an electrical signal is sent to the global shutter of the imager. Some of the outgoing photons reflected by the object reach the active surface of the sensor and are eventually detected.

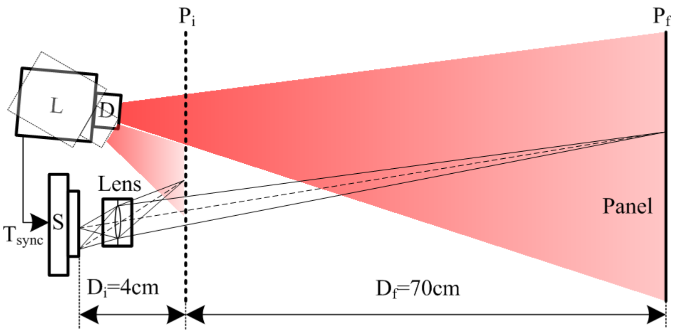

Fig. 1. Top view of the setup for distance measurement and array uniformity. L = picosecond laser; D = diffuser; S = SPAD image sensor

The time elapsed between the detection of one photon and the synchronization signal is actually a direct estimation of the time-of-flight, which in turn is proportional to the distance between the sensor and the object. Notice that, in our case, the maximum distance is limited by the available equipment, i.e. optical table dimensions and laser power.

The rest of the paper is organized as follows: Section II introduces the camera prototype and its most innovative features. Section III explains the experimental setup employed for 3D image reconstruction in low illumination conditions. Section IV is dedicated to experimental results, including snapshots of the camera configured both for 2D and 3D vision. Section V draws the conclusions of this work.

## II. PROTOTYPE OF THE SPAD CAMERA

The d-ToF system is composed by the SPAD camera (Fig. 2) and the picosecond laser. The housing of the camera, built by a 3D printer, accommodates an 8mm F1.2 lenses focusing on the 64×64 array of SPADs and pixel-level TDCs. These lenses perform a proper framing of a 30.5×41cm panel placed at 74cm from the sensor. The control signals are provided by an FPGA board located below the PCB of the image sensor. It also implements a real time 2D and 3D image reconstruction and an USB link used for luminous intensity (2D) and depth (3D) image streaming and some configurations of the camera. A user-friendly GUI has been built in Matlab. The camera also has the possibility to record videos at 1kfps and sent them to the computer in raw format. Afterwards the user can play them off-line at 50fps.

The camera can be also connected to an in-house designed **T**ime **I**nterval **G**enerator (TIG) of 8ps incremental resolution. In this way the array of TDCs is tested much more efficiently comparing with the amount of data and acquisition time required by the code density test. Using a command-line interface, the user can run a specific test and save the static characteristics of the TDCs.

The SPAD imager has been fabricated in UMC 0.18µm technology. It is composed by the pixel array and some on-chip peripheral circuits such as: PLL-based global compensation loop for **P**rocess parameters, **V**oltage supply and **T**emperature (PVT) variations, analog buffers for uniform distribution of the input reference voltages for the TDCs, clock tree distribution of the START and STOP signals across the array and a readout back-end which serializes data at 50MHz. This technological limitation can be counteracted by parallelizing the output. Thus the imager can reach a theoretical speed of 32kfps. Each pixel contains the SPAD detector with a fast quenching/ recharge circuit, the start-stop logic, the programmable time bin TDC and a static memory module with output buffers. A time gated SPAD front-end has been integrated in order to mitigate the high level of uncorrelated noise and to reduce power consumption. The start-stop logic block implements the reverse start-stop technique which leads to further decrease of the power consumption. Therefore a TDC can be triggered by a SPAD pulse and turned off by a synchronization pulse. In addition to that it takes into account only the first pulse in the time gate, ignoring all the others. Moreover the sensor integrates the control for the test of the TDC array by means of a TIG embedded in the system. Each TDC employs a **V**oltage-**C**ontrolled **R**ing-**O**scillator (VCRO) as time interpolator such that it has a few nanoseconds conversion time [11].

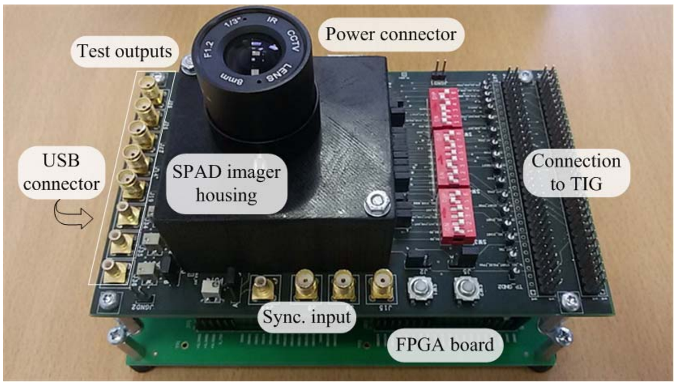

Fig. 2. Prototype of the SPAD camera

The most exciting features of this camera are the time-gated pixel and the real-time image reconstruction. The former one has been integrated by a novel time-gated active quenching/ recharge circuit. By playing with the size of the time-gate, we can increase the **S**ignal-to-**N**oise **R**atio (SNR) in photon timing applications. The latter feature is based on pixel level histogram building of a certain number of measurements which from now on will be called inter-frames. There is a trade-off between accuracy and overall frame rate of the reconstructed images [12]. This is because the jitter FWHM of a ToF measurement decreases by the square root of the number of inter-frames. Note that the jitter in this case is mainly due to the jitter of the SPAD detector and the jitter of the TDC. Last but not least, the minimum number of inter-frames to achieve certain accuracy depends also on the **P**hoton **D**etection **E**fficiency (PDE) of the detector and the amount of the uncorrelated noise. The specifications of the picosecond laser employed in the measurements are presented in the next sections.

## III. LOW ILLUMINATION SETUP

In order to acquire depth images by d-ToF in low illumination conditions, we have employed a PicoQuant D-C-640 pulsed laser [13] and a Thorlabs ED1-S50 diffuser [14]. This combination outputs a square pattern and guarantees uniform distribution of light over the scene.

The wavelength is 640nm with an average output power of 160µW, and a repetition rate of 2.5MHz. The pulse width is below 90ps and the jitter of the synchronization signal is 20ps.

The reflected power received by the sensor is measured by using a Newport 918-SL photodetector. The photodetector is coupled with the 8mm lenses. The setup diagram is similar with the one depicted in Fig. 1.

The distance between the photodetector and the panel varies in our experimental setup from 88cm to 11cm with 1cm step. The measured irradiance is depicted in Fig. 3. The maximum irradiance is below 10nW/mm$^2$ which is consistent with the illumination condition for single photon detection. Notice that the distance range in this experimental setup is limited by the power of the laser.

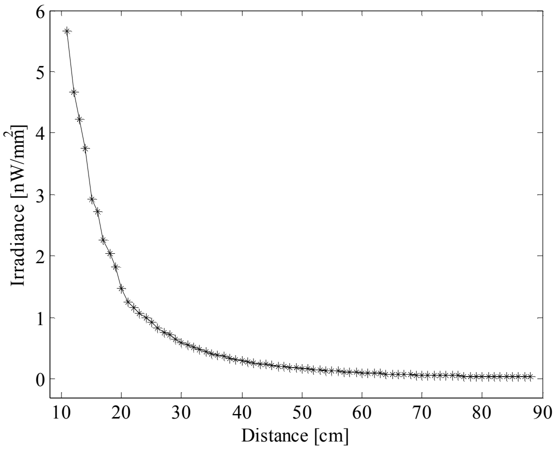

Fig. 3. Measured irradiance of the reflected light

## IV. EXPERIMENTAL RESULTS

### A. 3D ranging

The aim of this experimental setup is to measure the depth resolution, linearity and array homogeneity for short distances. We have employed a panel to provide a homogenous background for the shapes to be reconstructed. This panel has been displaced towards the sensor-laser ensemble from 74cm down to 4cm with 1cm step (see Fig. 1). For better illustration of the spatial linearity, only the closest and farthest depth images are depicted in Fig. 4. Each measurement is obtained by averaging 65k inter-frames.

Any pixel of the same tier has to estimate the same distance. Therefore the incremental resolution is improved even further by spatial averaging these pixels (see Fig. 5). Notice that in the middle range from 13cm to 66cm the sensor behaves quite linear, having an incremental depth resolution of 1cm. The distortion below 13cm is caused by the reflections of the lens which is less than 2cm close to the panel. These reflections increase the jitter of the SPAD detector, lowering the accuracy of the measurement. The nonlinearities above 66cm are due to the low amount of light that reaches the sensor. In this case the sensor is mostly triggered by noise. Therefore in order to achieve the same accuracy as in the middle range, more than 65k inter-frames would be needed.

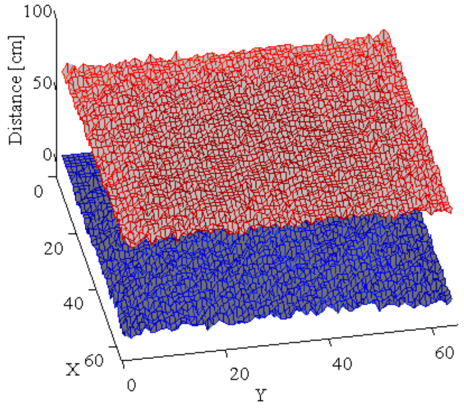

Fig. 4. The panel is placed at 4cm (bottom plate) and 74cm (upper plate) towards the sensor

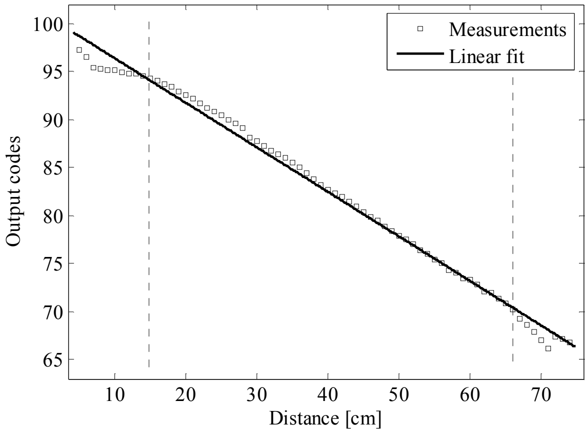

Fig. 5. Distance measurement by averaging all the pixels of the array. The depth resolution is 1cm.

### B. 2D and 3D imaging

The camera is able to capture 2D and 3D images. The experimental setup is depicted in Fig. 6 a). The scene consists of a geometric object $O_2$ placed in front of a white panel located in position $P_2$. The SPAD array is biased at an excess voltage of 1.1V.

The brightness map is obtained by merely counting photons. This is done at pixel-level by a gated 8b counter which is actually the coarse counter used by the TDC for 3D imaging. The depth map is computed from the d-ToF measured by every pixel of the array.

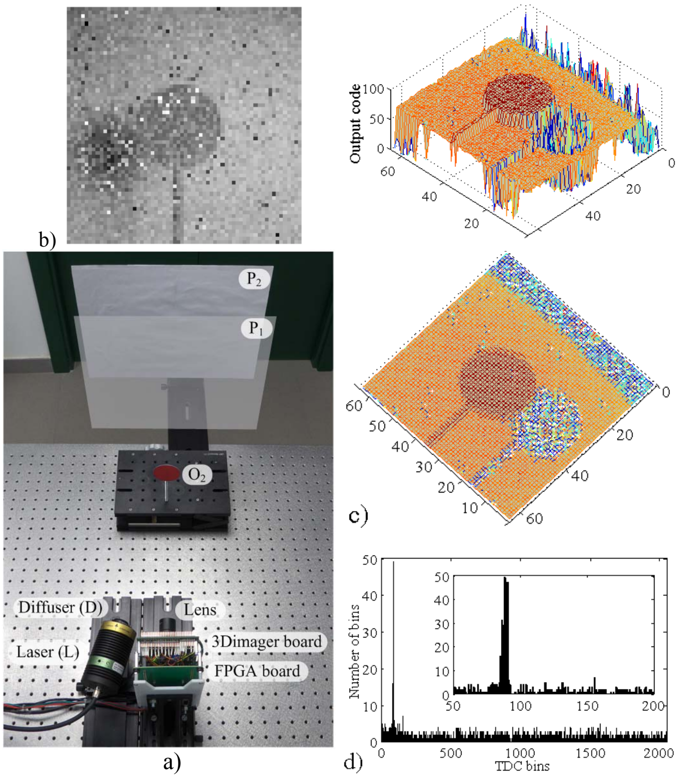

Fig. 6. a) Experimental setup for 2D and 3D imaging; b) 2D shape reconstruction; c) 3D shape reconstruction; d) ToF IRF of pixel (32, 32).

*2D vision:* The scene is lighted up with an illuminance of 100 lux. This amount of light is enough to ensure the minimum count rate required at the input of the CMOS counters which are driven by the SPAD detectors. The 2D image obtained by averaging 100 inter-frames is depicted in Fig. 6 b). In this case the frame rate of the reconstructed images is about 10fps. Notice the shadow of the object placed in front of the panel.

*3D vision:* The laser is setup as explained in Section III. The raw image is shown in Fig. 6 c) from two angles of view. It is reconstructed from 65k inter-frames. Even more, it still has a quite good accuracy only with 4k inter-frames. The pixels from the upper side of the image are out of the panel area while those from the right side of the geometric shape are shaded by it. In both cases the pixels are triggered only by noise since no reflected laser light reaches them back. Moreover, the histogram for the pixel (32, 32) is depicted in Fig. 6 d). It is built off-chip at 1kfps, based on the ongoing inter-frames. The SNR of the ToF measurement is about 24dB. The jitter FWHM is about 735 ps.

Thanks to the reliability of the time-gated and 3D image reconstruction technics employed at circuit and system level, this camera is able to work in 3D mode even when the uncorrelated noise rate is 20 times larger than the average DCR. In this case at least 40k inter-frames are required to reconstruct the 3D image.

A comparison with the state-of-the-art SPAD camera prototypes is performed in TABLE I. As can be seen, the performance of our camera is in the state-of-the-art, despite of the poor sensor characteristics. Thanks to the features highlighted in Section II, our camera is able to build 2D and 3D images even in the harsh condition of low performance SPAD detectors such as a high average DCR of 42kHz and a low PDE of 5% at 640nm.

TABLE I. COMPARISON WITH THE STATE-OF-THE-ART

| **Performances** | **[6]** | **[7]** | **[9]** | **This work** |
|---|---|---|---|---|
| Technology | 0.35µm(1) | 0.35µm(1) | 0.13µm(2) | 0.18µm(3) |
| No. of pixels | 64×32 | 32×4 | 32×32 | 64×64 |
| SPAD size | 30µm | 30µm | 15µm | 12µm |
| Fill factor | 3.14% | 3.14% | 2% | 2.7% |
| Imaging lens | 1.4 | n.a. | n.a | 1.2 |
| Illumination average power | 800mW | 100nW | 2mW | 160µW |
| Illumination wavelenght | 850nm | 555nm | 405nm | 640nm |
| Median DCR | 100Hz | 70Hz | 100Hz | 42kHz |
| PDE @ λ | 5% @ 850nm | 30% @ 520nm | 25% | 5% @ 640nm |
| In-pixel TDC architecture | U/D Counter | Delay line | Delay line | VCRO |
| TDC res. | n.a. | 400ps | 119ps | 150ps |
| Depth res. | 10cm | 1cm | 1cm | 1cm |
| Power/ TDC | n.a. | 6mW | n.a | 1.8mW |
| ToF technique | CW-i-ToF | d-ToF | d-ToF | d-ToF |

(1) Very low defect, customized for SPADs; (2) Customized for CMOS image sensors; (3) Mixed-signal standard technology without any opto-flavor or high voltage option.

## V. CONCLUSION

This paper presents a camera prototype for 2D/3D image reconstruction based on photon counting and d-ToF. Taking into account that the overall frame rate is limited by the required large number of inter-frames and image serialization, we are planning to move the real-time image reconstruction on chip and parallelize the sensor reading.

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