# 64x32 3D SPAD camera

## Features

- Multi-modality: photon-counting, 2D imaging, 3D time-of-flight ranging
- Image dimension: 64x32 (2048) pixels
- In-pixel counters: two 9 bit up/down
- Max frame rate: 100,000 fps (burst) and 10,000 fps (continuous)
- Max 3D frame rate: 33,000 fps
- Dynamic Range: 130 dB @ 100 fps
- Depth precision: ± 0.2 m @ 50 fps
- Gated acquisition: 80 ps steps up to 20 ns
- Hardware interface: USB 2.0
- Software interface: Matlab

## Applications

- Automotive Safety
- Short-range LIDAR
- Access Control
- Process Control
- Interactive Gaming
- Advanced 3D Gesture User Interface
- FLIM - Fluorescence Lifetime Imaging
- FCS - Fluorescence correlation Spectroscopy
- Single-photon time-gated counting

*Fig. 1: 3D single-photon counting camera with 64x32 pixels.*


*Fig. 2: Array chip containing the 64x32 pixels with 2048 SPAD detectors.*

## General Description

The phase-resolved 3D SPAD camera (Fig. 1) is based on a 64×32 SPAD (Single-Photon Avalanche Diode) array (Fig. 2) fabricated in CMOS technology [1]. It processes at the pixel-level intensity and, with an external illuminator, depth-ranging information through indirect Time-of-Flight (iTOF) measurement, by using either continuous-wave (CW) or pulsed light modulation. Each pixel of the sensor has independently selectable counters, which is the enabling key feature for the double-mode functioning. One of the three counters integrates the background light, thus storing 2D intensity information; the other two are bidirectional and perform light demodulation for either pulsed- or CW-iTOF calculation. Additionally, it can be operated in gated mode, where gates can be delayed at 80 ps steps up to 20 ns.

Thanks to very low noise, high dynamic-range (118 dB) is achieved at high speed (200 fps) during 3D depth measurements with high accuracy and precision. Moreover, an embedded 32 MB SDRAM allows ultra-high-speed (120 kfps) 2D imaging.

The module is connected to a PC through a USB 2.0 link and a FPGA manages the control signals, processes the data and uploads them to the remote PC. A Direct Digital Synthesizer (DDS) creates an analog waveform with arbitrary frequency, that is sent to the illuminator to modulate the laser source.

A MATLAB interface is used for setting all the parameters (frame time, number of frames to acquire, modulation frequency, system clock frequency, etc.) and plot data.

***For more information please contact:***

Prof. **Franco Zappa**

email: franco.zappa@polimi.it Phone: +39-02-2399-6149

Dr. **Alberto Tosi**

email: alberto.tosi@polimi.it Phone: +39-02-2399-6174

www.everyphotoncounts.com

## Electrical Characteristics with $V_{EX}$ = 5 V

| Parameter | Notes | Min | Typ | Max | Units |
|---|---|---|---|---|---|
| Resolution | number of pixels | | 64 x 32 | | pixels |
| SPAD diameter | diameter of the SPAD into each pixel | | 30 | | µm |
| Pixel pitch | size of each pixel | | 150 | | µm |
| Pixel fill-factor | with no microlense | | 3.14 | | % |
| Photon Detection Efficiency (PDE) of SPAD detectors | @ 420 nm | | 50 | | % |
| | @ 300 nm and @ 650 nm | | 20 | | % |
| | @ 800 nm | | 5 | | % |
| Dark count rate (DCR) | with $V_{EX}$ = 5 V | | 100 | | cps |
| Afterpulsing | with 20 ns hold-off time | | 2.6 | | % |
| Optical cross-talk | between nearest pixels | | 0.01 | | % |
| In-pixel counters | number of in-pixel up / down counters | | 3 | | |
| Photon-counting dynamics | number of bits of the in-pixel counters | | 9 | | bit |
| Gated acquisition with internal delayer | maximum delay | | 20 | | ns |
| | delay step | | 80 | | ps |
| | minimum gate width | | 2 | | ns |
| Frame-rate | Burst mode (limited by FPGA read-out) | no limit | | 100,000 | fps |
| | Continuous mode (limited by USB 2.0 link) | no limit | | 10,000 | fps |
| Full-scale depth range | user selectable | | | 90 | m |
| Illuminator modulation frequency | | 4.17 | | 12.5 | MHz |
| 3D frame rate | | | | 33,000 | fps |
| Precision @ 50 fps | CW modulation | | | ± 0.2 | m |
| Precision @ 50 fps | pulsed modulation | | | ± 0.2 | m |
| Accuracy @ 30 m, 50 fps | Indoor, CW modulation | | | 0.25 | m |
| Accuracy @ 30 m, 50 fps | Indoor, Pulsed modulation | | | 0.5 | m |
| Camera power supply | | | +5 | | V |
| Lens connector | | 12 mm – F/1.4 C-Mount | | | |

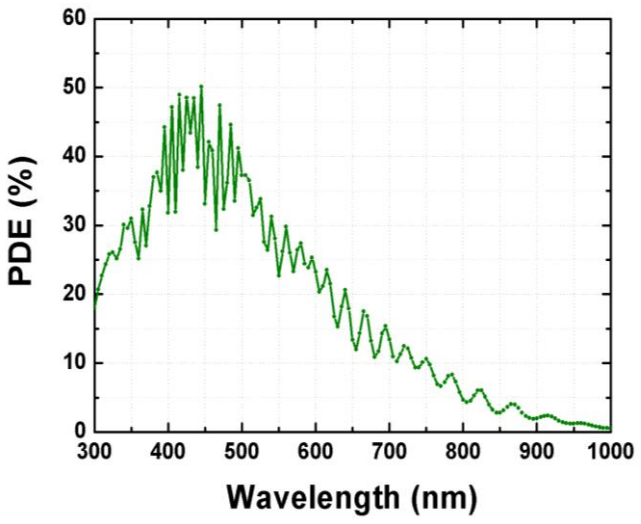


*Fig. 3: Photon Detection Efficiency at $V_{EX}$ = 5 V of the CMOS SPADs.*

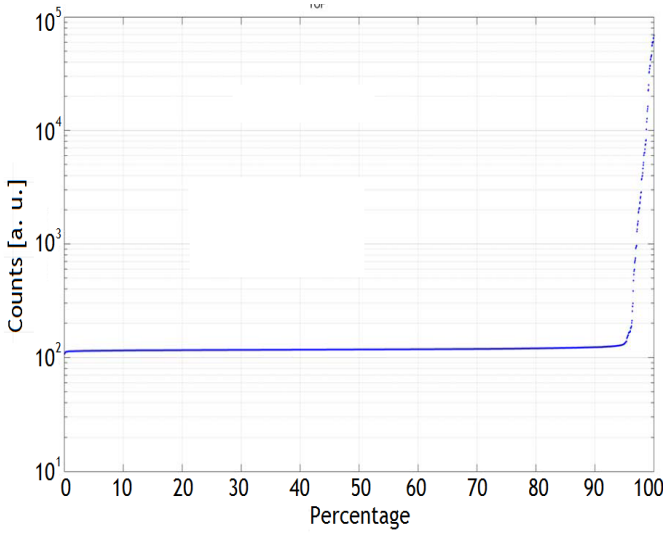


*Fig. 4: Dark Count Rate distribution at $V_{EX}$ = 5 V and at room temperature of the CMOS SPADs.*

[1] F. Villa, D. Bronzi, Y. Zou, C. Scarcella, G. Boso, S. Tisa, A. Tosi, F. Zappa, D. Durini, S. Weyers, U. Paschen, and W. Brockherde, "CMOS SPADs with up to 500 µm diameter and 55% detection efficiency at 420 nm," *J. Mod. Opt.*, pp. 1–14, Jan. 2014.

  

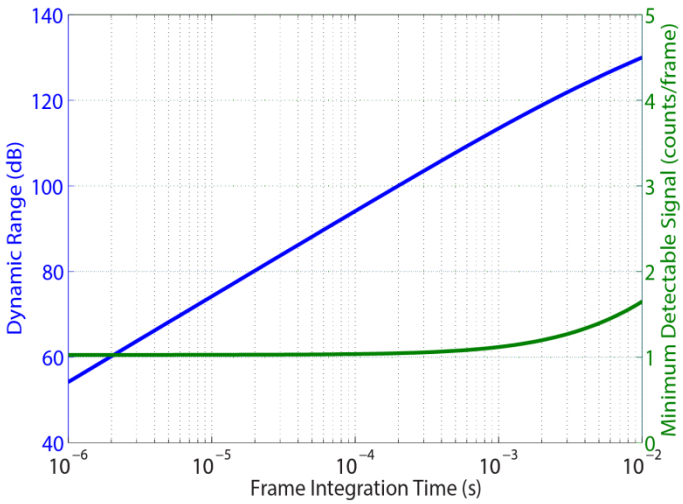


*Fig. 5: Dynamic Range (blu line) and minimum detectable signal (green line) as a function of the integration time. DCR enters into play only at frame rate slower than 100 fps.*

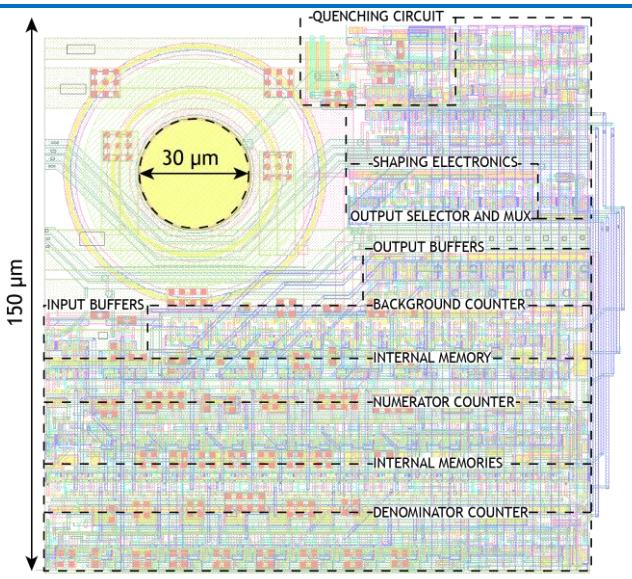


*Fig. 6: Layout and main building blocks of the pixel. The pitch (side) is 150 µm and the SPAD active area diameter is 30 µm.*

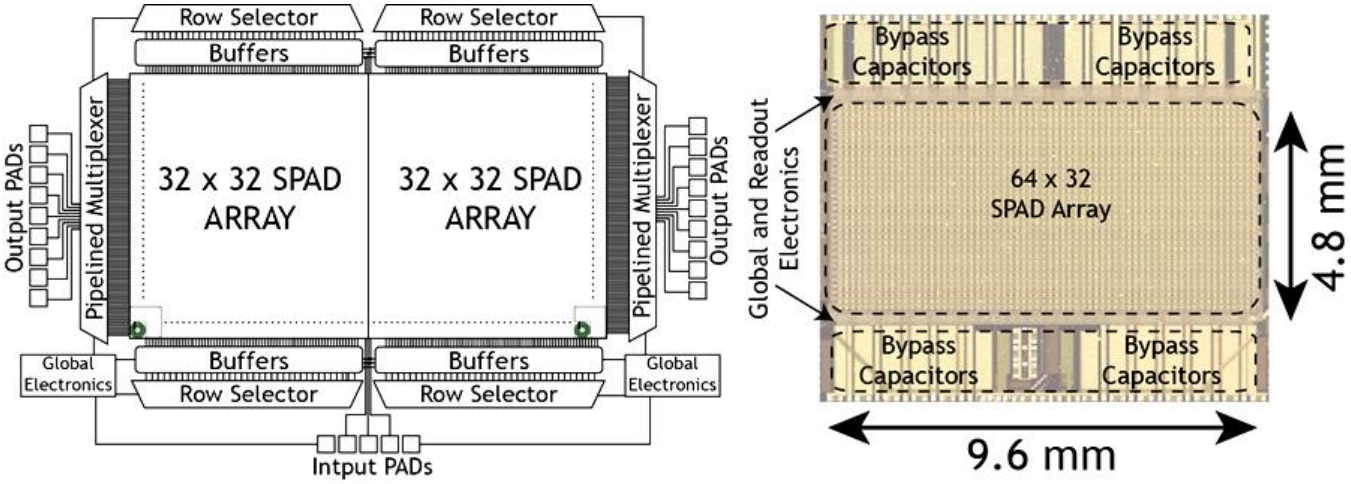


*Fig. 7: Block diagram of the 64×32 SPAD imager with peripheral electronics (left) and micrograph (right) with relative dimensions. Global and Readout electronics are placed between the capacitors and the SPAD array.*


*Fig. 8: Left: 64x32 SPAD camera with 3W laser illuminator at 808nm, for 3D ranging. Right: Matlab Graphic User Interface.*

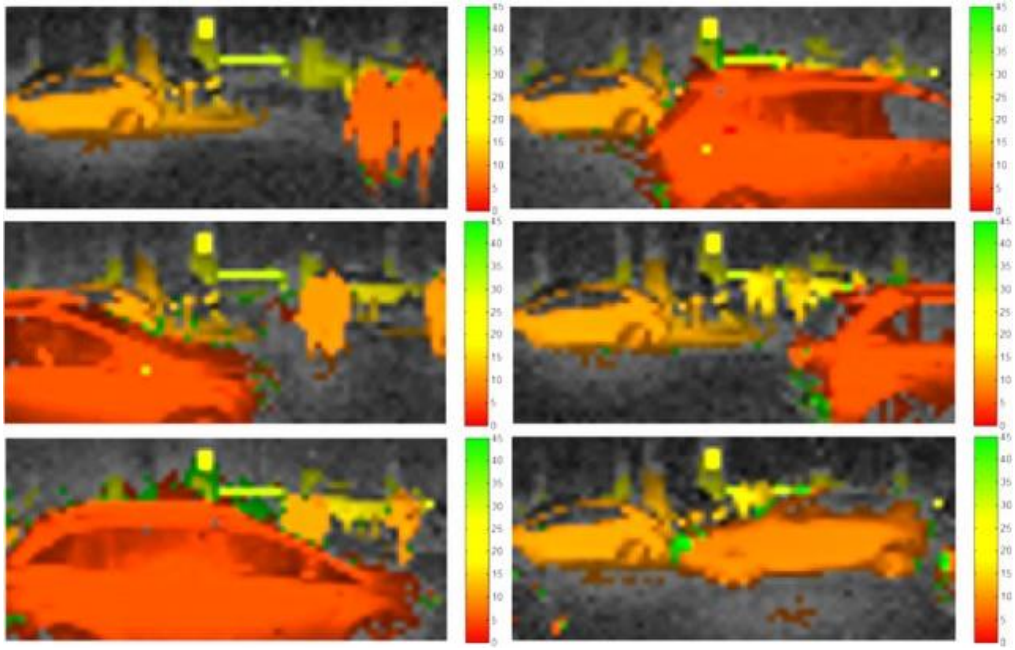

*Fig. 9: Frames from a 3D movie at 200 fps in a chaotic street, with moving cars and pedestrians. Frames were taken at about 1 s from each other, i.e. one frame out of about 200. Colors represent the distance: red is close, green is far (see colorbars in meters).*

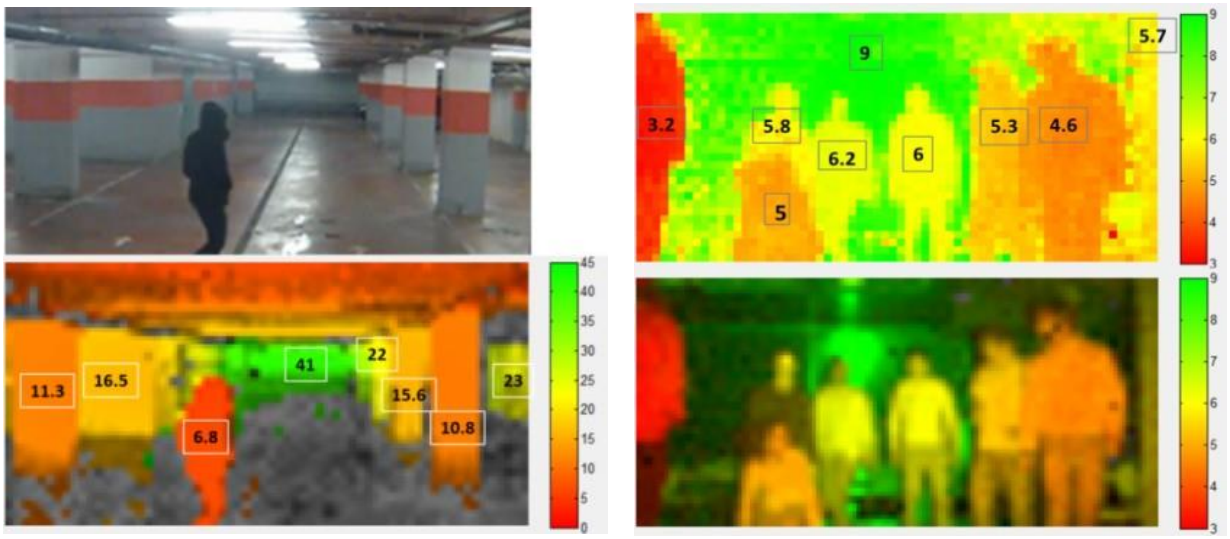


*Fig. 10: Left: Frame from a 3D movie acquired at 200 fps. Right: Frame from a 3D movie: 3D measurement (top) and 2D+3D overlay (bottom).*

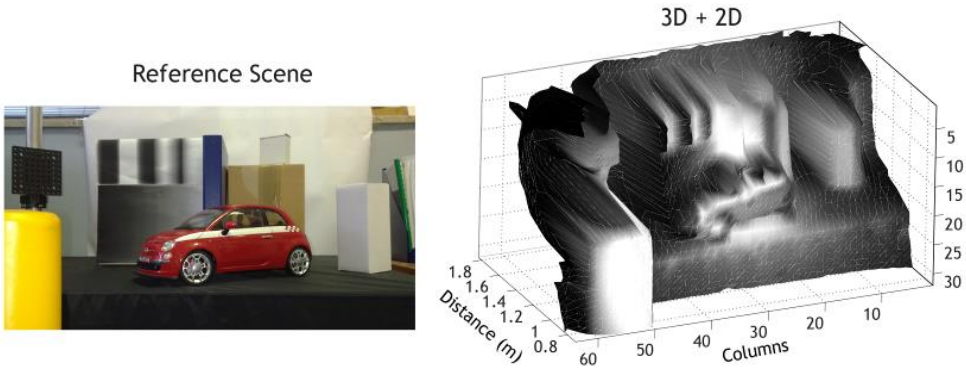


*Fig. 11. Reference scene (a) and combined 3D/2D image.*

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*Fig. 12. Propagation of a laser pulse in an acrylic slab, as seen by the SPAD camera. Each frame is taken each 80 ps, for an equivalent frame rate of 12.5 Gfps!*

  