Single-Photon Time-of-Flight camera for 3D ranging and TCSPC

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We present the exploitation of a camera based on a chip with 32 × 32 smart-pixels, each one integrating a CMOS Single-Photon Avalanche Diode (SPAD) and a 350 ps resolution 10-bit Time-to-Digital Converter (TDC) [1]. Two different operating modes are implemented in the camera: in *photon counting* mode each pixel provides a 6-bit resolution counting of the number of photons detected therein in each frame, down to the µs time scale (e.g. to acquire high-frame-rate 2D videos of a target scene or luminescence/reflectance faint signals, see Fig.1 left); in *photon timing* mode each pixel measures the arrival time of the first photon detected in each frame thanks to the integrated TDC. Photon timing information can be exploited in both Time-Correlated Single-Photon Counting (TCPSC) applications, down to hundreds of ps time scale, and for time-of-flight (TOF) 3D ranging when using a sub-nanosecond pulsed laser active illumination of the scene (see Fig. 1 center). Thanks to the single-photon sensitivity, the illuminator power can be very low and the achievable maximum depth-range and frame-rate can be very high compared to traditional systems.

The achievable frame-rate in photon counting mode is 100,000 fps (frames per second), limited by chip readout. Since in photon timing mode each TDC performs at most one conversion per frame, blocks of consecutive frames are accumulated to compute the mean photon arrival time, in order to reconstruct the 3D map (or TCSPC waveform) by discerning between signal photons and noise events and improving the single-shot resolution (about 6 cm on the round-trip, given the 350 ps TDCs resolution) down to < 1 cm, with a still high 200 fps frame rate. For increasing even further the signal-to-noise ratio and the dynamic range in photon timing, we exploited also TDC refolding, activating the TDCs for a time window longer than the Full-Scale-Range (FSR) and illuminating the scene every FSR, thus increasing the probability to detect a photon in each frame. Moreover, since the chip provides both photon counting and photon timing information in consecutive frames, we implemented a simple 2D+3D data merge in order to augment the image quality and data richness (see Fig. 1 right). Thanks to its high sensitivity (hence frame-rate), the camera x-y resolution can be improved through both intra- and inter-pixel scan. For example, Fig. 1 right shows a small statue acquired at 8 m distance, with 50 scans of the target scene, thus achieving 51 kpixel resolution, by employing a 750 nm wavelength, 100 ps FWHM, 90 mW pulsed four wave mixing laser.

We have also developed in the same technology a chip with 64 × 32 pixels [2], integrating a 9-bit counter into each pixel, to be exploited either for very high frame-rate 2D scenarios or for 3D-ranging reconstruction. Moreover the chip can be operated also in gated-mode, to perform smart ultra-fast gating (with activation windows as short as 2 ns that are shifted at 80 ps steps) of very fast events at the picosecond time-scale, to be exploited in Fluorescence Lifetime Imaging Microscopy (FLIM) [3] applications, to reconstruct fast and very faint optical signals.

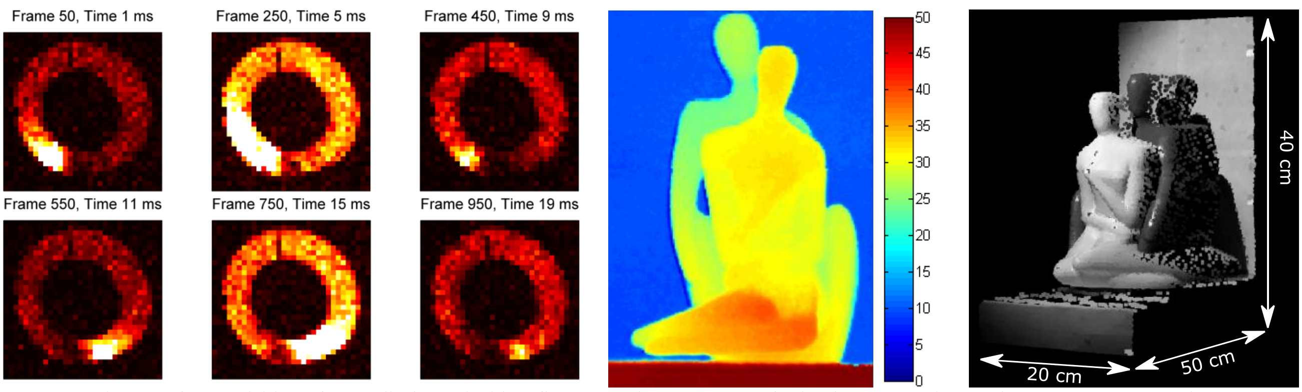

Fig. 1. Left: Acquisition of a gas discharge inside a fluorescent lamp at 50,000 fps in photon counting mode. Center: 3D scanned scene acquired in photon timing mode, where distance is expressed in centimeters. Right: The SPAD camera allows a simple 2D+3D merge and scanning, as shown with this small statue with 51 kpixel lateral resolution and 5 mm depth resolution, acquired at 8 m distance.

References

[1] F. Villa *et al.*, "CMOS imager with 1024 SPADs and TDCs for single-photon timing and 3D time-of-flight," IEEE Journal of Selected Topics in Quantum Electronics, **20**(6), 3804810, (2014).

[2] D. Bronzi *et al.*, "100 000 Frames/s 64 × 32 Single-Photon Detector Array for 2-D Imaging and 3-D Ranging," IEEE Journal of Selected Topics in Quantum Electronics, **20**(6), 3804310, (2014).

[3] M. Vitali *et al.*, "A Single-Photon Avalanche Camera for Fluorescence Lifetime Imaging Microscopy and Correlation Spectroscopy," IEEE Journal of Selected Topics in Quantum Electronics, **20**(6), 3804010, (2014).