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A Range-Gated CMOS SPAD Array for Real-Time 3D Range Imaging

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Abstract

A range image of a scene is produced with a solid-state time-of-flight system that uses active illumination and a time-gated single photon avalanche diode (SPAD) array. The distance to a target from the imager is measured by delaying the time gate in small steps and counting the photons of the pixels in each delay step in successive measurements. To achieve a high frame rate, the number of delay steps needed is minimized by limiting the scanning of the depth only to the range of interest. To be able to measure scenes with objects in different ranges, the array has been divided into groups of pixels with independently controlled time gating. This paper demonstrates an algorithm that can be used to control the time gating of the pixel groups in the sensor array to achieve depth maps of the scene with the time-gated SPAD array in real time and at a 70 Hz frame rate.

Introduction

3D range imaging is a popular topic at the moment since there are numerous applications that could use solid state, low cost, small imagers with high system performance (resolution >1 M pixels, frame rate of 60 Hz, range at least from 0 to 10 m preferably with centimetre depth accuracy) [1]. Various solutions for meeting these specifications are being explored.

Time-of-flight (ToF) techniques are commonly used if measurements over a range of a few metres are needed. Many of the ToF imagers on the market at the moment use in-pixel photon demodulation techniques, in which the pixel count can be higher than with other ToF pixel arrays, and already 1M pixels have been shown to achieve better than centimetre uncertainty at a frame rate of 30 Hz for a range from 0.4 to 4.2 m [2], although presumably at the cost of relatively high active illumination power.

To achieve a high performance system with low active illumination power, pixel arrays that could detect even a single photon would be an attractive solution, in principle. A single photon avalanche diode (SPAD) is such a device. SPAD-based sensor arrays have good performance, especially under dim ambient lighting conditions [3]. The drawback of their high sensitivity to photons is the high sensitivity to ambient lighting as well, but tolerance to this photon "noise" can be improved with optical filtering, for example. Also, modulation of the signal could be used, as in [4], [5], to separate the signal from noise. This would typically increase the illumination power consumption of the sensor under high ambient light conditions, however.

To achieve good single measurement precision, a pulsed laser source can be used with time-to-digital converters (TDC). With a short laser pulse (FWHM~100 ps) ~cm-level single measurement precision is achievable for a SPAD array with on-chip TDCs, although this kind of pulsed direct ToF (d-ToF) system also suffers from the ambient light problem. If a noise photon triggers the SPAD before the signal photon arrives at the detector, the signal cannot be detected. One solution is to use a free-running system or to impose time correlation of detections between neighbouring pixels, as in [6], but the power consumption of the sensor array would remain an issue if the in-pixel TDCs are activated by noise. Another approach would be to use a form of time gating that would activate the SPAD only for the range of interest, e.g. from 4 ns to 20 ns, corresponding to a range of ~2.5 m. The fill factor of in-pixel TDC-based SPAD arrays is usually only in the range of a few per cent, which would reduce the number of detectable signal photons in homogeneously illuminated systems.

In order to get a higher fill factor for the sensor while reducing the need for in-pixel time-to-digital converters, the possibility for time-gating the SPAD could also be used to produce a 3D range image. In this type of imager the image is produced by shifting the position of the time gate over the desired range (range scanning). 3D range imaging employing the time gate method (sometimes called a range-gated system) is usually slow due to the large number of time gate positions that need to be measured in order to get an accurate 3D range image [7]. To solve this problem, the SPAD array designed here has been divided into subarrays for which time gating can be controlled independently. This makes it possible to limit the range scan more efficiently around the surfaces of multiple targets, see Fig. 1.

We thus propose here a 3D range imager that uses a time-gated SPAD array chip enabling the per-pixel measured range to be limit to a small area of interest which can adaptively follow the movement of the target. The short time gate (FWHM~400 ps) reduces the effect of ambient light and with a short laser pulse (FWHM~200 ps) the range can be closely confined around the surface of the target. The detailed electronic construction of the SPAD array receiver chip with 80 x 25 pixels that was used for this purpose has been presented in [8].

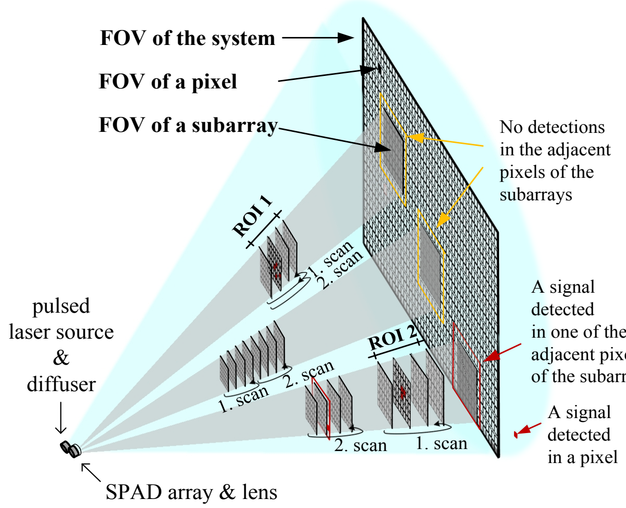

Figure 1. A time-gated 3D range imaging system and a flexible scanning algorithm.

The timing information of the detected photons is produced only by the time gating of the SPAD array. This paper presents the controlling algorithm for the chip and new 3D range imaging results with improved frame rate and noise tolerance due to the increased active illumination power and pulsing rate.

The SPAD Array Chip

Each of the 2000 pixels of the SPAD array may receive a signal photon from a laser pulse which has been spread to illuminate the whole target scene. The flight times of the photons depend on the distances to the targets and back. Each SPAD is activated for a small period of time (time gate) after a predetermined delay relative to the laser pulse emission. Multiple photons are counted at each time gate position by successive measurements. The distance to the target for each pixel is derived from the photon counts when the time gate has been shifted, e.g. in 200 ps steps.

Fig. 2. shows an example of photon detections made by three SPADs when the time gate has been shifted in 200 ps steps from the laser pulse triggering signal. The time-of-flight of the laser pulse to the target and back to the receiver can be determined from the peak in the photon detections accumulating from multiple successive measurements. The range of interest can be set, for example, to 2 ns around the reflected laser pulse, see Fig. 2.

The 80 x 25 SPAD array used here has been divided into 40 subarrays, each of the time-gate positions of which can be independently controlled, see block diagram of the SPAD array chip in Fig. 3. The time-gate positions for each of the subarrays can be selected from the outputs of the on-chip delay-locked loop (DLL) within a time period of 24 ns. The delay line outputs of the DLL are enabled for time period of 24 ns, the delay of which relative to the laser pulse triggering signal can be selected by choosing one of the on-chip counter values, see the timing diagram in Fig. 4. 1-bit results for each SPAD at the trailing edges of the time gates are sampled into in-pixel flip-flops which are connected in series of 80 registers when reading out the data from the sensor chip to the FPGA with an 83.3 MHz clock, which limits the maximum laser pulsing rate to 1 MHz.

The Scanning Algorithm

In the measurement operation the averaging factor, scanning depth and scanning step size are first selected by the user. The FPGA then starts the distance measurement by sending the time gating position information to the SPAD array, followed by the triggering signal for the measurement. The scanning depth range can be selected to be 21, 30 or 60 cm, with 3 or 1.5 cm step sizes. Depending on the selected depth range, the frame rate is 16, 11 or 5.5 times higher compared to full scan of the 3.3 m range. Shifting of the depth range of each subarray in order to follow the movement of the target has been incorporated into the FPGA.

The histogram from which the time-of-flight of the reflected laser pulse is calculated (see Fig. 2) can be created quite straightforwardly when using only the time gating approach since only one histogram bin is measured at a time. Consequently, the histograms can be filtered simultaneously as the scan proceeds. A 3-tap FIR filter was used here, as a result of resource optimization and its adequate performance. When the position of the reflected laser pulse in each pixel has been determined, the range of interest for each subarray of pixels is updated and the procedure for the next scan position begins.

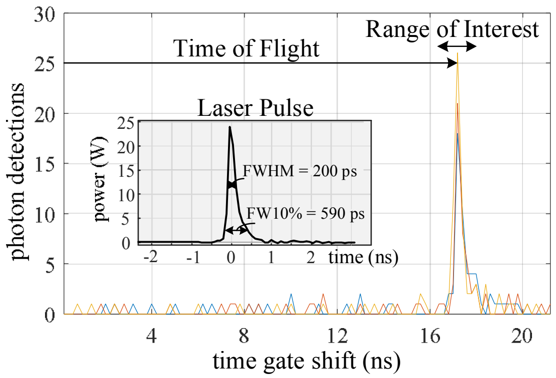

Figure 2. An example of photon detections by three SPADs when the time gate position has been shifted over a range of 22 ns in 200 ps steps. Inset: the shape of the laser pulse used in the measurements.

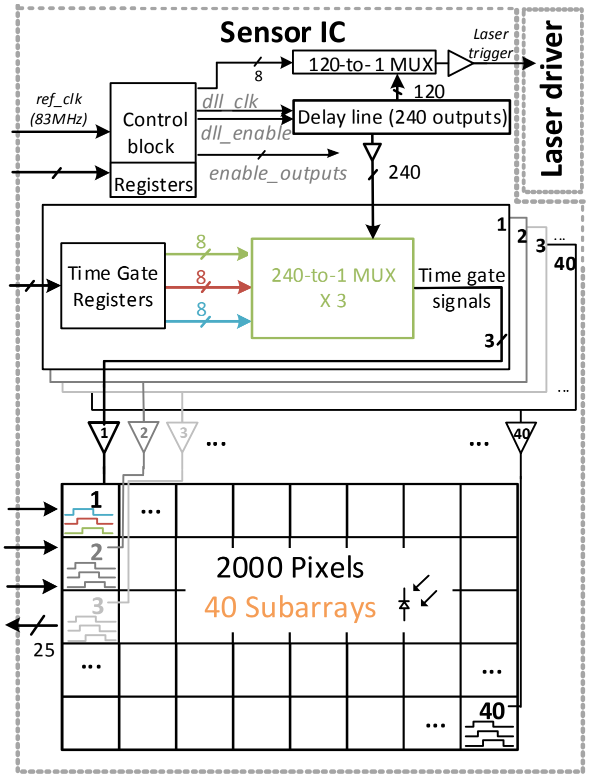

Figure 3. Block diagram of the SPAD array chip.

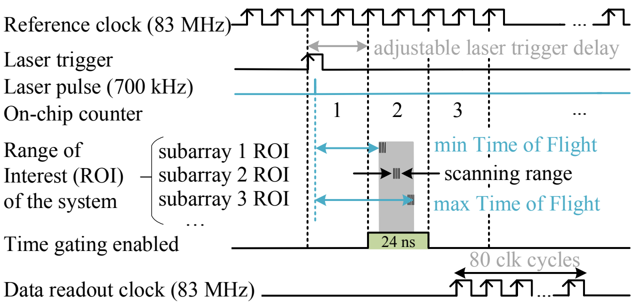

Figure 4. Timing diagram of one measurement.

The algorithm sets the scanning range around the target position without extracting the direction or speed of the movement of the target. If none of the pixels in a subarray have detected a signal, the next scanning range will be positioned further away from the imager, as demonstrated in the middle of the array in Fig. 1 (scan 2.). The scanning continues until a signal is detected or the whole range (24 ns) has been scanned. If a signal has been detected, the next scanning range will be advanced from the detected signal delay position in order to follow the movement. The range is placed as close to the surface of the target as possible to achieve maximum depth measurement for the other pixels in a subarray, see ROI 1 in Fig. 1. The scanning range of a subarray is also shifted if a signal is detected in the nearest pixels in the adjacent subarray, see ROI 2 in Fig. 1. This configuration makes it possible to follow the xy-movement of a target without first defining the direction of its movement. Obviously, the measurement speed and next scanning range need to be calculated rapidly in order to keep up with the movement of the target.

A threshold for shifting the scanning range was also implemented to make the algorithm robust with respect to noise. After the range image has been calculated the third signal position in each subarray (together with the nearest pixels of the adjacent subarray) sets the next scanning range position, so that a threshold of 2 provides tolerance for 2.4% hot pixels (noisy pixels). A block diagram of the range-gated SPAD array controller implemented in Arria V FPGA is shown in Fig. 5.

Experimental Results

This work allowed the laser pulse energy to be increased from ~1 nJ [8] to over 6 nJ by increasing the active volume of the laser diode [9]. The pulsing rate used in the experimental result was 700 kHz, but a lower pulsing rate, e.g. 100 kHz, could be used if a lower frame rate were permissible and a lower power consumption were desired. The wavelength of the laser was 882 nm, the line width 4.6 nm, and the shape of the laser pulse in Fig. 2 shows an FWHM of 200 ps. The system has a FOV of 18° x 28° and the experimental results were obtained in office lighting (~200 lux) unless otherwise stated. A 50 nm bandpass filter centred at 875 nm was used in front of the detector. A short time gate of FWHM~0.4 ns was used in the measurements.

Fig. 6 shows start position and two frames from a video of distance measurement results taken at 70 frames per second from a dropping ball (diameter 22 cm) to demonstrate the speed of the algorithm in changing the scanning range from the back wall to a fast moving target if the adjacent pixels of a subarray have detected a signal.

The range image results for a person in ~200 lux ambient lighting and also when the ambient light was increased by directing halogen lamps towards the FOV of the system are shown in Fig. 7. The lighting increase was measured using a lux meter (Voltcraft BL-10L), which showed a maximum of 1.2 klux at the range of the target and 600 lux on the back wall. It can be seen from the figure that the signal can still be detected but not as well as in lower ambient lighting. The averaging factor was 960 pulses per delay step and a depth range of 60 cm was measured with 3 cm scanning steps for each subarray resulting frame rate of 36 frames per second.

An intensity and 3D range image of a person taken at frame rate of 63 fps is shown in Fig. 8. The intensity result represents the maximum intensity of photon detections for the scanned range, and this is available for every 3D range image.

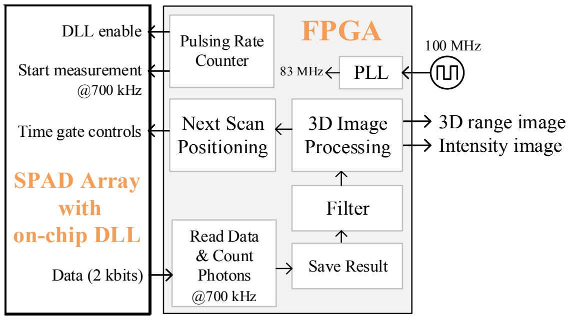

Figure 5. Simplified block diagram of the system.

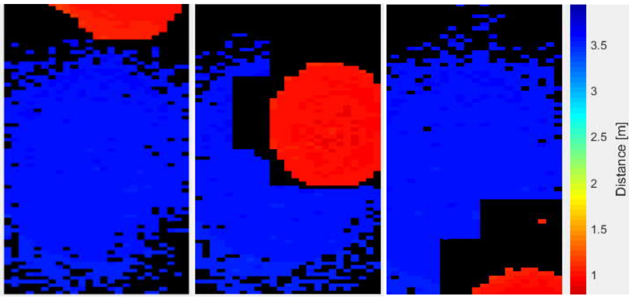

Figure 6. Demonstration of shifting the range scan of the subarrays from the back wall at 3.5 m to the front when a ball has been dropped. The depth scan range was set to 30 cm and the frame rate of the 3D measurement was 70 Hz

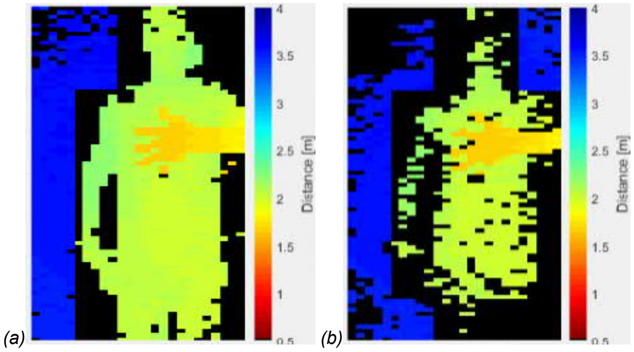

Figure 7. 3D range image in (a) 200lux ambient light and (b) additional lighting with halogen lamps (max 1.2 klux measured at the range of the target).

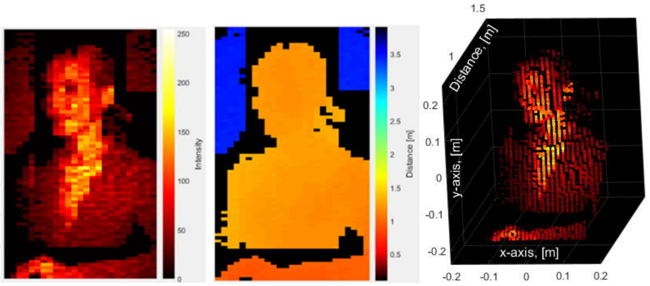

Figure 8. An intensity, 3D range and point cloud image of a person taken at 63 frames per second.

Discussion

A comparison with other solid state SPAD-based sensors that have been used for 3D range imaging is presented in Table 1. The fill factor of the proposed imager is much better than in those that have time-to-digital converters integrated in-pixel, and the power consumption is not stated for some of the TDC-based systems, e.g. that in [11]. Many TDC-based solutions have variations in their power consumption depending on how many photons are detected, which can lead to very high power consumption when the number of photon detections needed is high, e.g. due to ambient lighting. The average power consumption of time gating at the sensor IC is 56 mW, and most of the current consumption is due to the readout of all the data from the IC to the FPGA (115 mA from a 3.3 V power supply at a pulsing rate of 700 kHz). This could be reduced by implementing some of the counters on the sensor IC rather than on the FPGA, for example.

The algorithm described here is aimed at achieving fast signal processing with moderate depth precision, although the precision of the system can be improved by increasing the number of samples taken for each delay step and using more sophisticated filtering to detect the position of the laser pulse. Also, the algorithm could be modified to adapt the scanning ranges of the subarrays, depending on the depths of the targets located in the FOV of each subarray.

The areal resolution of the imager could be increased by copying the layout of the SPAD array by two or even four, pipelining the registers and rearranging the power supply lines.

Table 1. Comparison of SPAD-Based 3D Range Imagers

	[10]	[11]	This work
Pixels	64 x 64	128 x 128	25 x 80
CMOS Tech.	0.18 µm	0.35 µm HV	0.35 µm HV
Fill Factor	2.7%	6%	32%
FOV	22° x 29°	5°	18° x 28°
Active Ill. (λ , P_{avg})	640 nm 0.16 mW	635 nm 1 mW	882 nm 4.7 mW
Measured range	70 cm	3.75 m	3.5 m
Power* (timing, readout)	1.8 mW/ TDC	not stated	56 mW 380 mW
ToF tech.	direct ToF	direct ToF	Time gating

* power consumption of the SPAD array IC

Conclusions

The FPGA-based algorithm for controlling a range gated SPAD array presented here was designed for an 80 x 25 pixels SPAD array that allows flexible changing of the time gating of 40 subarrays. Experimental 3D range and intensity image results are also shown that were obtained with pulsed laser diode active illumination that used laser pulses with a FWHM of 200 ps and a pulsing rate of 700 kHz with an average optical power of 4.7 mW.

An algorithm is presented which is capable of changing the range of interests in real time, making it possible to follow moving targets by measuring only limited ranges around their surfaces. A 3D range imaging frame rate of 70 Hz has been demonstrated for targets at 3.5 m.

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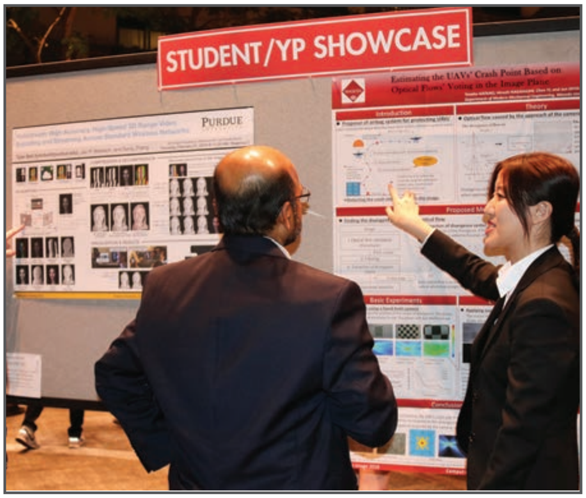
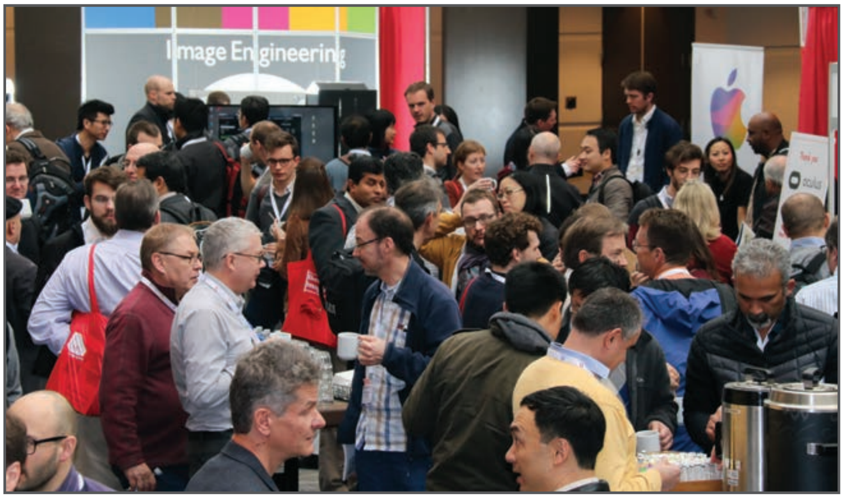
Author Biography

Henna Ruokamo received her Master's Degree from the University of Oulu, in 2007. She had been a mixed-signal IC design engineer in semiconductor industry until she joined the Circuits and Systems Research Unit in the University of Oulu in 2015. Currently she is working towards her Ph.D. degree. Her research interests include electronic design of SPAD arrays.





AR is a fundamental and transformative interface and platform.
20+ years from my initial working demo to today's AR displays
Optimistic that it won't take another 20 to reach ubiquitous consumer AR!