3D measurements using SPC2

Three dimensional (3D) image acquisitions is the enabling technology of a great number of applications such as culture heritage morphology studies, industrial robotics, automotive active safety and security access controls. We can divide 3D ranging systems into two groups: double acquisition, or stereoscopic, and single-sensor active-illumination systems.

The former is based on two different acquisitions of the same observation scene, observed from two points, separated by only few centimetres but each one at the same relative distance from the scene. In this case, depth information is obtained with complex algorithms for triangulation.

The latter is based on a single imaging sensor, and depth information is obtained by means of an active illumination of the observed scene and the analysis of the reflected light (e.g. measuring amplitude and phase changes in the backscattered light compared to the illumination one).

This Application Note explains how to employ the SPC2 (Single-Photon Counting Camera) for performing this particular type of 3D acquisitions. Figure 1 shows four samples of a 3D acquisitions obtained by using a SPC2 camera.

3D cw-iTOF technique

Among different active illumination techniques, the continuous-wave indirect Time-of-Flight (cw-iTOF) is the one more suited for the use with a SPAD camera [1]. It is based on the illumination of a scene with a light source whose amplitude is sinusoidally modulated, at a fixed high frequency, and synchronous with a reference signal within the camera. The emitted light that reaches the scene and is reflected back to the camera is then acquired. Of course this light is subject to a phase shift proportional to the distance between the scene and the camera. This time delay, or more correctly this time of flight, can be evaluated by means of intensity measurements in particular time windows, synchronized with the camera internal reference signal. In this way, starting from the phase delay measurement, it is possible to compute the distance of the acquired scene from the camera, pixel by pixel. In case of 3D acquisitions, phase measurements are much more suitable than intensity one. In fact, since the ambient conditions in which the camera can be used are subject to change (with unpredictable intensity variations due to changes in local reflectivity, distance and background

Figure 1: Examples of 3D acquisitions of a human hand with a SPC2 and the cw-iTOF technique
light), it is not possible to ascertain the time of flight by means of an intensity measurement at high speed, aiming at reconstructing the shape of the wave. It can be demonstrated using Fourier transform, that in order to measure the phase delay it is necessary to sample the back reflected light at least four times per period, as shown by Figure 2. Starting from this four samples (c0, c1, c2 and c3, see Figure 2) it is then possible to calculate the phase delay $\phi$ (Eq. 1), the amplitude $A$ of the reflected light (Eq. 2) and the average illumination level $B$ of the scene (Eq. 3). Once known the phase delay, the distance can be computed thanks to Eq. 4, where the maximum measurable distance $R_D$, which depends on the frequency of the sinusoidal light wave $f$, is given by Eq. 5. The average illumination level $B$ contains the information about the standard 2D image of the scene (as can be acquired by a normal image sensor). It is of course also possible to compute the expected accuracy of the phase delay measurement (Eq. 6) and the resulting distance accuracy (Eq. 7).

Obviously, these accuracies depend on the amount of detected photons. The longer the measure, the higher the precision. For this reason the accuracy depends on the number of acquired periods $N$ of the illuminating wave; moreover, the higher is the ratio between $A$ and $B$ (called

$$ \phi = \tan^{-1} \left( \frac{c_3 - c_1}{c_0 - c_2} \right) $$

$$ A = \frac{\sqrt{(c_3 - c_1)^2 + (c_0 - c_2)^2}}{2} $$

$$ B = \frac{c_0 + c_1 + c_2 + c_3}{4} $$

$$ d = R_D \cdot \frac{\phi}{2\pi} $$

$$ R_D = \frac{c}{2f} $$

$$ \sigma_\phi = \frac{\sqrt{B \cdot T}}{2A\sqrt{N}} \cdot \frac{\pi f}{2c_m} \cdot \sqrt{\frac{f}{N \cdot B}} $$

$$ \sigma_d = \frac{R_D}{2\pi} \cdot \sigma_\phi = \frac{c}{8c_m} \cdot \sqrt{\frac{1}{f \cdot N \cdot B}} $$

Figure 2: Sinusoidal reflected light compared to the reference signal. The amplitude of the reflected light is lower than that of the emitted light because of the partial reflection of objects in the scene.
cm), the better is the accuracy. It is therefore important to calculate for each pixel and frame, together with the phase shift also the values of A and B. It is thus possible to establish if each pixel detected enough photons to achieve the required accuracy. For this purpose, it is useful to separate the average illumination level B into three components: the ambient light Qb (e.g. sun light or artificial road light), the offset of the received active light Q0 and its amplitude A. In this way it is possible to define the mean number of photons per pixel Qm required in a measurement to reach a certain accuracy; starting from Eq. 7 and with some math one can thus obtain Eq. 8.

\[
Q_m = \frac{1}{32 \cdot c_m^2} \cdot \frac{1 + 64 \cdot c_m^2 \cdot Q_b \cdot \left( \frac{ \sigma_d }{ R_D } \right)^2}{
1 + \sqrt{1 + 64 \cdot c_m^2 \cdot Q_b \cdot \left( \frac{ \sigma_d }{ R_D } \right)^2} \cdot 2\}

(8)

**SPC² as a 3D camera**

SPC² camera is based on 1024 independent SPADs designed and produced in standard CMOS technology. The detectors are organized in a 32×32 array of smart pixels, featuring both detection and pre-processing of the measured photons. A SPAD [2] is a reverse-biased pn junction, which is operated well above its breakdown voltage. Under this biasing condition the absorption of a single photon causes the generation of an electron-hole pair, which is accelerated by the electric field across the junction. The energy of the charge carriers is eventually sufficient to trigger a self-sustained macroscopic avalanche current of few milliamperes through the device.

A quenching circuit based on a time-varying active load (Variable-Load Quenching Circuit, VLQC) [3] has been integrated for sensing the SPAD ignition, quenching the avalanche and resetting the detector to its initial condition. Compared to quenching circuits based on passive loads, the VLQC has the major advantage of speeding up the quenching action, thus minimizing the charge amount which flows through the SPAD after ignition. Moreover the VLQC controls SPAD dead-time, i.e. the minimum time interval between two detection events. In case of 3D measures it is recommended to set it to the minimum possible value, which guarantees a low or moderate afterpulsing probability (AP). Currently this value is equal to 200 ns. Thanks to the integrated VLQC, the SPADs achieve moderate detection rates up to a saturation limit of 5 Mcps per second and per pixel without a significant decrease in the TCSPC dynamic range (low AP). The VLQC output, which is synchronous with the avalanche sensing, triggers the processing electronics and an 8-bit Linear-Feedback Shift-Register (LFSR) counts the detection events (Figure 3). Routing electronics is then implemented on the same chip to read-out the counter values and to transfer them to the off-chip electronics. This design allows the measurements of up to 48’000 frames per second for the full array acquisition.

The use of a SPAD as photodetector has major advantages for imaging applications concerning the signal-to-noise ratio. Since the detector acts as a digital Geiger-like counter, no analogue measure of voltage or current is needed. Hence, no read-out noise is added to the measurement.

![Figure 3: Front-end electronics inside each pixel of the SPC2, showing the gatable counter.](image-url)
3D measurements using SPC²

A 3D process. This is a very important advantage for high-frame imaging, since the probability of detecting a single photon per frame and per pixel is usually low (<<1). A second major advantage of the presented pixel structure concerns the controllable dead-time, which has a lower limit of about 50 ns. In case the AP can be tolerated, the dead time can be reduced to such a low value, thus raising to 20 Mc/s the maximum number of photons which can be processed per second.

The in-pixel front-end additionally allows the gating of the LFSR counters for a very short time between 1.5 ns and 20 ns (Figure 3). In this way, the trigger signal by the VLQC circuit increments the LFSR counter only when the signal GATE is enabled (logic level ‘1’). Otherwise, the detected photons are not counted (logic level ‘0’). The gate signal can be provided by the user through the GATE_IN input of the camera, or can be internally generated by the camera itself.

The circuit that implements the gate generation is shown in Figure 4, and allows both for gate width adjustment and for gate shifting with respect to the internal reference clock. It is based on the internal Delay Locked Loops (DLLs) of the FPGA device that controls the SPC2 camera. FPGA devices require DLLs to de-skew the internal digital paths and to fine-tune the sampling time of fast serial communication lines. They are designed to produce a precise phase shift between 10 and 40 ps, which can be dynamically controlled during operation. This dynamic phase shift is well suited to generate periodic sequences of pulses.

The internal 50 MHz clock (Int_Clk) is sent to DLL1 which halves the frequency and de-phases the clock of a delay ΔΦ1. This clock signal, Int_ClkD1, is then sent to a second DLL (DLL2), which creates an additional phase shifted clock (ΔΦ2, Int_ClkD2). The XOR between Int_ClkD1 and Int_ClkD2 creates short pulses at the same repetition rate of the internal reference clock, with adjustable phase and duration. The phase

![Figure 4: Circuit implemented inside the FPGA to generate the variable width/shift gate signal.](image)

![Figure 5: Acquisition of the four samples required for 3D cw-ITOF measurement by employing the internal gate shift capability of SPC2 camera.](image)
difference between Int_Clk and Int_Clkd1 will be referred to as gate shift while the phase between Int_Clkd1 and Int_Clkd2 will be denoted gate width. Both gate shift and gate width can be dynamically adjusted during data acquisition.

This advanced gating capability enables the easy use of SPC2 as a 3D camera. In fact, it is possible to configure the gate width and the shift values in order to acquire the required four samples c0, c1, c2, c3, as shown in Figure 5. The principle of operation to perform the cw-iTOF 3D acquisition is here described.

The SYNC_OUT output from the camera should be connected to a proper light source (e.g. LED) able to sinusoidally modulate the emitted light at 50 MHz, which is the fixed frequency of the sync. Then a series of four snap acquisitions, each with a gate width of 25 % and progressively shifted of 0 %, 25 %, 50 %, 75 % should be acquired. The integration time of these snaps has to be selected based on the available signal and desired precision. Finally, for each pixel, the phase shift and thus the distance is calculated using previously reported equations. By employing a modulation frequency of 50 MHz, a maximum unambiguous range of 3 m is possible (see Eq. 5). If a different range is needed, it is still possible to employ the SPC2 but not the internal gate generation, i.e. the gate signal must be externally provided.

Using SPC2-SDK for 3D

As described above, cw-iTOF 3D measurements can be performed with a SPC2 either by providing an external gate signal, or by employing the embedded gate generation feature. Of course, the latter is for sure the more straightforward option thanks to the availability of two specific DLL functions devoted to easily setting the internal gate:

SPC2Return SPC2_Set_Gate_Mode(SPC2_H spc2, GateMode Mode)

SPC2Return SPC2_Set_Gate_Values(SPC2_H spc2, Int16 Shift, Int16 Length)

Enabling the SYNC_OUT in order to output the internal reference clock is also very simple using the specific function:

SPC2Return SPC2_Set_Trigger_Out_State(SPC2_H spc2, TriggerMode Mode)
The suggested flow chart to follow for writing the necessary programming code with the aim of successfully perform a cw-iTOF 3D measurement with the SPC2 is shown in Figure 6. The starting point is the initialization of the camera witch can be done as in the example below where the SPC2 is initialized by enabling the full 32x32 pixels in advanced mode, by setting a dead-time of 200 ns, an hardware exposure time of 4096x20 ns, an internal sum of 1000 hardware exposure times to obtain a single frame and the acquisition of 1 frame.

```c
out=(int)SPC2_Constr(&spc2,1,32,1,32, Advanced,"";
SPC2_Set_Camera_Par(spc2, 4096, 1000,1);
SPC2_Set_DeadTime(spc2, 200);
SPC2_Apply_settings(spc2);

Then the SYNC out is enabled by using the function already shown above, and, immediately afterwards the internal gate is also enabled:

SPC2_Set_Trigger_Out_State(spc2, Gate_Clk);
SPC2_Set_Gate_Mode(spc2, Pulsed);

Then the loop starts by setting the gate width and phase like below, where the gate signal has a 5 ns width and is shifted 0 ns respect to the internal reference clock:

```c
SPC2_Set_Gate_Values(spc2, 0, 25);
   //Shift %0 of 20 ns --> 0 ns,
   //Length 25% of 20 ns --> 5ns
SPC2_Apply_settings(spc2);
```

The counts for this gate values can then be acquired and saved as a snap:

```c
SPC2_Prepare_Snap(spc2);
SPC2_Get_Snap(spc2);
SPC2_Save_Img_Disk(spc2, 1, 1,
   "Snap1_sample_c0.spc2",
   SPC2_FILEFORMAT);
```

Given the settings of this example the number N of acquired periods (in other words the accuracy) is:

$$N = \frac{4096\times20\text{ns}\times1000}{20\text{ns}} = 4096\times1000 = 4,096,000$$

Of course N should be optimized depending on the actual user experiment conditions. Also, as already said, one iteration of the loop is not enough and the three operations above must be repeated other three times, in order to acquire also sample c1, c2, c3. Now on the HDD are saved four files in SPC2 format, which can be processed in order to obtain phase (and hence distance), amplitude and intensity values for each pixels. If another 3D frame is required, a new acquisition loop can be performed, otherwise the camera can be closed.

Please note that it is not necessary to save each snap on the HDD and then perform the processing offline: the expert user can also process data in real-time by accessing SPC2 buffer after each snap acquisition by using the corresponding SDK function:

```c
SPC2_Get_Image_Buffer(SPC2_H spc2,
   BUFFER_H* buffer);
```

### Gate and 3D camera calibration

The actual width and phase of the gate signal, obtained for a given set of parameters used with the SPC2_Set_Gate_Values function, may vary among different SPC2 units due to FPGA fabrication tolerances. While the gate width is calibrated by MPD before shipping the camera, the gate shift is not. This is done on purpose. In fact, the final shift of the gate signal with respect to the modulated light is not only related to the shift internal to the camera, but also (and probably largely) to the delays introduced by
cables and the light source itself. A calibration of the actual gate shift with respect to the modulated light is therefore necessary after the camera is mounted into the measurement setup. This is easily done by performing a real 3D measurement on a known target (it is suggested to use a plain board covering all the camera field of view), and then introducing an offset in order to obtain measured distances consistent with real distances. For instance, if the target is 1 m away, and the camera measures 1.5 m, it means that all measurements must be corrected by subtracting 0.5 m. It is advisable to perform this calibration pixel-wise rather than camera-wise. In fact the gate applied to each pixel of the camera has a small skew compared to any other pixel. While these relative skews are small and totally negligible in case of other kinds of acquisitions, such as FLIM measurements, they might not be negligible for 3D indirect time of flight measurements in which the absolute delay is the measures itself.

References


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Contact

For further assistance and information please write to imaging@micro-photon-devices.com