《2019－TOF 元年》

MEMS, Sep 3th 2019
Contents

- Information about ESPROS and TOF history
- Enhanced Camera manufacture calibration & compensation
- Image application improvement
- Next generation TOF - pTOF
Foundation
- established in 2006 by
- Beat De Coi
- privately held corporation
- 75 million CHF initial investment

Locations
- Sargans, Switzerland
- USA, China

Activities
- Design and manufacturing of photonics chips and TOF cameras

Facilities
- 600m² class 1 cleanroom for backside processing
- 360m² class 100 cleanroom for testing and backend
- 80m² qualification facilities according JEDEC standards
- 60'000m² space built into solid rock for further expansion
Key ingredients for high performance TOF imaging

NIR Sensitivity

CMOS digital/analog signal processing

Cost efficient packaging

High performance CCD imaging

- Monolothic CCD/CMOS
- QE > 70% @ 905nm
- Pixel Rise < 7ns
- CG 50µV/e-
# ESPROS' Offerings

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<th>Standard Chips</th>
<th>ASIC and Foundry</th>
<th>Modules</th>
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<td>![ASIC Image]</td>
<td>![Module Image]</td>
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<td>- TOF 8 x 8</td>
<td>- TOF 160 x 60</td>
<td>- 150nm CMOS process</td>
<td>- TOF&gt;range 611</td>
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<td>- TOF 160 x 60</td>
<td>- TOF 320 x 240</td>
<td>- 8&quot; wafer size</td>
<td>- TOF&gt;frame 611</td>
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<td>- TOF 320 x 240</td>
<td>- Line Imager 1024 x 1</td>
<td>- 6 metal layers</td>
<td>- TOF&gt;cam635</td>
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<tr>
<td>- Line Imager 1024 x 1</td>
<td>- Photo diode amplifiers</td>
<td>- 1 poly layer</td>
<td>- TOF&gt;cam660</td>
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<td>- Photo diode amplifiers</td>
<td>- Photo diode arrays</td>
<td>- 1V8 core, up to 12V mixed signal</td>
<td></td>
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<tr>
<td>- Photo diode arrays</td>
<td>- High voltage output switches</td>
<td>- Photonics ASIC, focused on</td>
<td></td>
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<tr>
<td>- High voltage output switches</td>
<td>- Spectral sensing</td>
<td>- cwTOF</td>
<td></td>
</tr>
<tr>
<td>- Spectral sensing</td>
<td></td>
<td>- pTOF / LiDAR</td>
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<td></td>
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<td>- TDI imaging</td>
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<td>- Ultrafast imaging</td>
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<td>- Pixel design</td>
<td></td>
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<td>- TCAD simulation</td>
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<td></td>
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<td>- IP building blocks</td>
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<td>- Project management</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>- PDK for Cadence design environment</td>
<td></td>
</tr>
</tbody>
</table>

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The history of ESPROS TOF chips

- First lock-in pixel on research-level OHC15L technology
- First system-on-chip 3D TOF imager chip
- Release of the first samples of QVGA imager
- First pTOF imager chip (up to 300 meters)

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## TOF Imager Product Family

### epc611
- **8x8 pixel**

### epc635
- **160x60 pixel**

### epc660
- **320x240 pixel**

<table>
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<tr>
<th>Product</th>
<th>epc611</th>
<th>epc635</th>
<th>epc660</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel field</td>
<td>8 x 8</td>
<td>160 x 60</td>
<td>320 x 240</td>
<td></td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>20 x 20 µm</td>
<td></td>
<td></td>
<td>100% fill factor</td>
</tr>
<tr>
<td>Photosensitive area</td>
<td>0.16 x 0.16 mm</td>
<td>3.20 x 1.20 mm</td>
<td>6.40 x 4.80 mm</td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td>CSP24</td>
<td>CSP44</td>
<td>CSP68</td>
<td></td>
</tr>
<tr>
<td>Packaging size</td>
<td>2.8 x 2.8 x 0.25 mm</td>
<td>6.3 x 4.2 x 0.25 mm</td>
<td>9.7 x 8.7 x 0.25 mm</td>
<td></td>
</tr>
<tr>
<td>Frame rate</td>
<td>up to 8’000 fps</td>
<td>up to 488 fps</td>
<td>up to 156 fps</td>
<td>Rolling mode, $t_{\text{INT}} = 100\mu$s</td>
</tr>
<tr>
<td>Output data</td>
<td>up to 18 bit DCS</td>
<td>12 bit DCS</td>
<td>12 bit DCS</td>
<td></td>
</tr>
<tr>
<td>Data interface</td>
<td>SPI up to 16MHz</td>
<td>TCMI up to 80MHz</td>
<td>TCMI up to 80MHz</td>
<td></td>
</tr>
<tr>
<td>Control interface</td>
<td>SPI</td>
<td>I2C</td>
<td>I2C</td>
<td></td>
</tr>
</tbody>
</table>

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Enheinced Camera manufacture calibration&compensation
Introduction

- The speed of light is 30cm/ns
- On-chip delay of electrical signals on tracks is 1cm/ns
- If we want to achieve 1.5cm accuracy, we have to control all distance measurement signals on-chip in total to better than 100ps!

- The purpose of the calibration and compensation is to present a way, how imaging errors can be reduced by software.

However, they cannot fully eliminated!
Main parts of TOF cameras

- **Lens**
- **Illumination**
- **Software**
  - Acquisition
  - Readout
  - Filtering
  - Calculation
  - Filtering
  - Compensation
  - Filtering
  - Transformation
  - Data out
- **TOF imager**
- **Illumination driver**
- **Interface**
- **Power supply**
- **Controller or FPGA**
- **Various**
  - Thermal
  - Housing
  - Eye safety
  - Functional safety
  - Cost
Camera calibration

**Theory**
- Correlation samples
- Distance
- Amplitude

**Error sources**
- Modulation distortion
- Demodulation distortion
- Pixel non-linearity
- Distance noise
- Fix-pattern noise
- Object reflectivity
- Ambient-light
- Temperature
- System clock
- ...

**Camera chip**

**Measured data**
- Correlation samples
- Distance
- Amplitude
- Ambient-light
- Temperature
- Integration time
- Mod. frequency

**Compensation**
by look-up table or algorithm
- Modulation distortion
- Demodulation distortion
- Pixel non-linearity
- Amplitude
- Distance noise
- Fix-pattern noise (FPN)
- Object reflectivity
- Ambient-light
- Temperature
- System clock
- ...

**Correct distance**
according the needs of the application

**Sensor calibration**
- Modulation distortion
- ...
- ...

Intelligent calibration of each individual camera and clever image improving SW algorithms are needed

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Calibration: physical target

- Slow, expensive, needs huge space
- Big FOV → very big target at larger distances
- Dust and ambient light, geometry dependent TOF amplitude
A more clever solution: Calibration box

Cheap, small, fast, no dust or ambient light in the box, the same TOF amplitude signal is on each pixel due to flat-field illumination
Compensation procedure

- Do the following steps during runtime:

<table>
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<tr>
<th>Step #1</th>
<th>Calculate ambient light compensation</th>
</tr>
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<tbody>
<tr>
<td>Step #2</td>
<td>Calculate the raw distance $d_{\text{Raw}}_{x,y}$</td>
</tr>
<tr>
<td>Step #3</td>
<td>Interpolation between $d_{\text{Raw}}<em>{x,y}$ and $\text{DRNUcalib}</em>{x,y,DLL\text{Step}}$</td>
</tr>
<tr>
<td>Step #4</td>
<td>Apply Formula to remove temperature drift</td>
</tr>
</tbody>
</table>
Compensation: Step #1

Ambient light compensation:

- Take a non illuminated image (Grayscale image)
- DCS0 and DCS1 have to be compensated
- DCS2 and DCS3 are not affected
- \( k \) is a global correction value and needs to be evaluated once

\[
\text{DCS0/1}_{x,y, \text{BGComp}} = \frac{\text{DCS0/1}_{x,y} - \text{BG}_{x,y} \cdot k}{\sqrt{t_{\text{int}}}}
\]
Compensation: Step #2

Calculate raw distance:

- Use the well known formula:

\[
d_{\text{Raw}}(x,y) = \frac{c}{2} \cdot \frac{1}{2\pi f} \cdot \text{atan}\left(\frac{DCS3_{x,y} - DCS1_{x,y,BGComp}}{DCS2_{x,y} - DCS0_{x,y,BGComp}}\right)
\]
Compensation: Step #3

Interpolation between $d_{\text{Raw}}_{x,y}$ and $\text{DRNUcalib}_{x,y,\text{DLLStep}}$ LUT

**FORMULA (8):**

$$d_{\text{Corr}}_{x,y} = \frac{d_{\text{DLL}}}{(M_{b,x,y} - M_{a,x,y})} \times (d_{\text{Raw}}_{x,y} - M_{a,x,y}) + S_{a,x,y} + o_{\text{cal}}$$

**FORMULA (9):**

$$\text{DRNUcalib}_{x,y,\text{DLLStep}} = \text{DRNUerror}_{x,y,\text{DLLStep}} + d_{\text{DLL}} \times i + o_{\text{zero}}$$

for $(x...\text{maxX}, y...\text{maxY})$

$i = 0$

$\text{do}$

$M_{a,x,y} = \text{DRNUcalib}_{x,y, i}$  // **FORMULA (9)**

$M_{b,x,y} = \text{DRNUcalib}_{x,y, (i+1)}$

if ($(d_{\text{Raw}}_{x,y} + AD \geq M_{a,x,y}) \text{ AND } (d_{\text{Raw}}_{x,y} + AD < M_{b,x,y})$)

$S_{a,x,y} = i \times d_{\text{DLL}}$

$S_{b,x,y} = S_{a,x,y} + d_{\text{DLL}}$

$d_{\text{Corr}}_{x,y} = \text{FORMULA (8)}$

end if

if $(i = 49)$

$i = 0$

$AD = \text{unambiguity distance}$  // Comment: roll over situation

else

$i = i+1$

$AD = 0$

endif

while $(i < 50)$

endfor
Compensation: Step #4

- Use the following formula to calculate a temperature compensated distance:

\[
d_{x,y,\text{Comp}} = d_{\text{Corr},x,y} - (T_{\text{ACT}} - T_{\text{CAL}}) \times (TC_{\text{Pix}} + TC_{\text{OD}} + n \times TC_{\text{DLLn}})
\]
TOF error correction
Image application improvement
Reflectivity and Ambient light performance

Reflectivity Improve:
- ADC Linearity
- Pixel Linearity
Result:
- No Reflectivity compensation needed

Ambient light performance Improve:
- Pixel Design
- Read out data chain
Result:
- Enhanced out door performance up to 130lux
- No compensation needed < 20klux
- No compensation needed @940nm
Multi camera: detection in practice

- Multi camera without disturbance detection
- Multi camera with disturbance detection
Multi camera: detection in practice

TOFcam 635 Interference Test Video
Next generation - pTOF(pulsed time-of-flight)
TOF distance measurement principles

Time-of-flight (TOF)

Gated Imaging TOF
Pulse modulated

pTOF
Pulse modulated

cwTOF
Continuous wave modulated

Emitter

Receiver

Emitting pulse
Pulse echo

Continuous wave modulated emission
Continuous wave modulated echo

→ ratio between A and B
→ Distance camera to object

→-> time of flight
→-> Distance camera to object

Backscattered light with a time delay dependent on the distance between the object and the device
Distance measurement principle

Working principle:
- Sampling of arriving light pulses into fast CCD
- A/D conversion of the sampled signal
- Calculation of the exact pulse arrival time point
- Multiple echoes from one laser pulse are detectable
Distance measurement principle:
Let's talk about projects and future cooperation

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