《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 and fab vision

**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

- Monolithic CCD/CMOS
- QE >70% @ 905nm
- Pixel Rise <7ns
- CG 50µV/e-

NIR Sensitivity

CMOS digital/analog signal processing

High performance CCD imaging

Cost efficient packaging
## ESPROS' offerings

### Key offerings

- TOF 8 x 8
- TOF 160 x 60
- TOF 320 x 240
- Line Imager 1024 x 1
- Photo diode amplifiers
- Photo diode arrays
- High voltage output switches
- Spectral sensing

### Standard Chips

- 150nm CMOS process
- 8" wafer size
- 6 metal layers
- 1 poly layer
- 1V8 core, up to 12V mixed signal
- Photonics ASIC, focused on
  - cwTOF
  - pTOF / LiDAR
  - TDI imaging
  - Ultrafast imaging
- Pixel design
- TCAD simulation
- IP building blocks
- Project management
- PDK for Cadence design environment

### ASIC and Foundry

- TOF>range 611
- TOF>frame 611
- TOF>cam635
- TOF>cam660

### Modules

- Standard Chips
- ASIC and Foundry
- Modules

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The history of ESPROS TOF chips

- **2009**: First lock-in pixel on research-level OHC15L technology
- **2012**: First system-on-chip 3D TOF imager chip
- **2015**: Release of the first samples of QVGA imager
- **2018**: First pTOF imager chip (up to 300 meters)
## TOF Imager Product Family

<table>
<thead>
<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>100% fill factor</td>
<td></td>
<td></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, $t_{int} = 100µs$</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>
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
  - Compensation
  - Transformation
  - Data out
- TOF imager
- Illumination driver
- Interface
- Power supply
- Controller or FPGA
- Various
  - Thermal
  - Housing
  - Eye safety
  - Functional safety
  - Cost
Camera calibration

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

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

**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 to the needs of the application

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

Intelligent calibration of each individual camera and clever image improving SW algorithms are needed
Calibration: physical target

- Slow, expensive, needs huge space
- Big FOV → very big target at larger distances
- Dust and ambient light, geometry dependent TOF amplitude

● 60° FOV
● 5m distance
→ 5.77m x 4.33m Target!
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>
<thead>
<tr>
<th>Step #1</th>
<th>Calculate ambient light compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step #2</td>
<td>Calculate the raw distance $d_{Raw_{x,y}}$</td>
</tr>
<tr>
<td>Step #3</td>
<td>Interpolation between $d_{Raw_{x,y}}$ and $DRNU_{calib_{x,y,DLLStep}}$</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

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

Calculate raw distance:

- Use the well known formula:

\[
d_{\text{Raw}}_{x,y} = \frac{c}{2} \cdot \frac{1}{2\pi f} \cdot \tan^{-1}\left( \frac{\text{DCS3}_{x,y} - \text{DCS1}_{x,y,BGComp}}{\text{DCS2}_{x,y} - \text{DCS0}_{x,y,BGComp}} \right)
\]
Compensation: Step #3

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

- **FORMULA (8):**
  \[
d_{\text{Corr}}_{x,y} = \frac{d_{\text{DLL}}}{\left(M_{b,x,y} - M_{a,x,y}\right)} \left( d_{\text{Raw}}_{x,y} - M_{a,x,y} \right) + S_{a,x,y} + o_{\text{cal}}
\]

- **FORMULA (9):**
  \[
  \text{DRNUcalib}_{x,y,\text{DLLStep}} = \text{DRNUerror}_{x,y,\text{DLLStep}} + d_{\text{DLL}} \cdot i + o_{\text{zero}}
  \]
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

±19cm

±5cm
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

Emitting pulse

Pulse echo

Continuous wave modulated emission

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

ratio between A and B
Distance camera to object

→ time of flight
→ Distance camera to object
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:

- **Echo 1**: Nearest object
- **Echo 2**: Farer object
- **Echo 3**: Farest object

- **Amplitude** vs. **time**

- **Chained conveyor belt (CCB)**
- **Selected pixel column**

- **Pixel field**: Location domain
- **Frame store**: Time domain

Every 4th shift clock a new value shows up at the ADC input.
ESPROS pTOF pixel (example)

Pixel & imager parameters:

- QE >70% @ 905nm
- Speed 6.5ns (FWHM)
- Sensitivity 20e-
- CCD sampling 250MHz
- CCD 450 stages (270m)
- Pixel field 262 x 150 pixel
- No. of pixels 38,864
- Frame rate >100fps (full 3D TOF)
Detection range system

**System parameters:**
- **Lens** F# 0.8
- **hFOV** 50°
- **vFOV** 25°
- **Laser power** 300W peak
- **Laser pulse** 5ns
- **Wavelength** 905nm
- **Ambient light** 100klux on target
Let's talk about projects and future cooperation

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