Image Sensor Technologies for 3D Time-of-flight Range Imaging

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TOF Technologies

Content

• Overview 3D Technologies
• How does a 3D TOF demodulation pixel work?
• Why is a 3D TOF pixel 100 times bigger than state-of-the art CCD / CMOS pixel?
• Why does a 3D TOF pixel require extremely high-speed electron transfer?
• Overview of state-of-the-art 3D TOF pixel implementations
• Summary / Outlook
### Overview 3D Technologies

#### Comparison

<table>
<thead>
<tr>
<th></th>
<th>Triangulation (geometrical measurement)</th>
<th>Time-of-flight (TOF) (optical modulation)</th>
<th>Interferometry (optical coherence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range $R_0$</td>
<td>Basis dependent $\rightarrow$ mm to a few m</td>
<td>$R_0 \propto c/F$ $\rightarrow$ cm to 100m</td>
<td>$R_0 \propto \lambda$ $\rightarrow$ µm</td>
</tr>
<tr>
<td>Depth noise $\sigma$</td>
<td>$\sigma \propto R^2$</td>
<td>$\sigma \propto R$</td>
<td>$\sigma \propto \lambda$</td>
</tr>
<tr>
<td>Required computing power</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Miniaturization potential</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Economic potential</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Other</td>
<td>Passive: Texture required</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Overview 3D Technologies

Comparison

![Comparison Diagram]

3D TOF Imaging

Acquisition Samples

![Samples Images]
How does a 3D TOF pixel work?

1. **Amplitude / Quality**
   \[ A = \sqrt{\left( A_3 - A_1 \right)^2 + \left( A_0 - A_2 \right)^2} \]
   - \( A_0 \): Offset
   - \( A_1 \): Reflected signal
   - \( A_2 \): Emitted signal
   - \( A_3 \): Amplitude

2. **Intensity / BW**
   \[ B = \frac{A_0 + A_1 + A_2 + A_3}{4} \]
   - \( A_0 \): Offset
   - \( A_1 \): Reflected signal
   - \( A_2 \): Emitted signal
   - \( A_3 \): Amplitude

3. **Phase / Distance**
   \[ \phi = \arctan \left( \frac{A_3 - A_1}{A_0 - A_2} \right) \]
   - \( A_0 \): Offset
   - \( A_1 \): Reflected signal
   - \( A_2 \): Emitted signal
   - \( A_3 \): Amplitude
How does a 3D TOF pixel work?

Main challenges for 3D TOF pixels

Why a 3D TOF pixel requires high-speed?

Electron Transfer Time:

\[
\Delta t_{\text{diffusion}} = \frac{x^2}{D_n}
\]

\[
\Delta t_{\text{drift}} = \frac{x^2}{-u_n \cdot E} = \frac{x^2}{u_n \cdot dU/dx}
\]

Device Simulation:

- \( x = 7 \mu m \)
- \( \Delta U_{\text{drift}} = 2 V \)
Why a 3D TOF pixel requires high-speed?

System Simulation

- Diffusion-dominated Electron Transfer
- Drift-dominated Electron Transfer

Note:
- Modulation at 20MHz
- Ideal imager (perfect demodulation, no saturation, no noise)
- No background light
- Physical limitation (photon shot noise limit)
- 10mm standard deviation requires ~ 20ke- / sample

Why are 3D TOF Pixels that big?

No background light

"Modulated" electrons
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Why are 3D TOF Pixels that big?

Assumption:
• Camera with 1W/m² on target (typical for a target at 1m)
• Sun light ~50W/m²

Note:
• Modulation at 20 MHz
• Ideal imager (perfect demodulation, no saturation, no noise)
• Physical limitation (photon shot noise limit)
• 10mm standard deviation requires close to 1Me/tap modulated and dealing with 30Me-background

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Implementations (Canesta)

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Implementations (PMD Technology)

*Hagebeuker, „Mehrdimensionale Objekterfassung mittels PMD Sensorik“, Optik & Photonik, March 08

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Implementations (University Shizuoka)


• Interferometry, triangulation and TOF technologies offer approaches for different ranges and resolutions.

• Biggest challenges for TOF Pixel:
  • the high-speed demodulation
  • the required high dynamic range

• Compared to standard pixels, TOF pixel are much larger and have a lower fill factor.

• First industrial-grade TOF camera on the market in 2009.

• High volume applications represent interesting opportunity for TOF cameras.