Active Light – Time-of-Flight Imaging
Time-of-Flight – Pulse-based

- time-of-flight scanners [Gvili03]
- NOT triangulation based
- short infrared laser pulse is sent from camera
- reflection is recorded in a very short time frame (ps)
- results in depth profile (intensity image)
Time-of-Flight – Pulse-based

- time-of-flight scanner – examples
- accuracy 1-2 cm in a range of 4 – 7 m
- applications:
  - "depth keying" replaces chroma keying
  - 3D interaction
  - large scale 3D scanning (LIDAR – light detection and ranging)
PMDs – Photonic Mixer Devices

Also called “multi-bucket sensors”

Chip layout

Schematic view

Fast on-chip modulation

Electric symbol

[Luan’01]
PMDs – Photonic Mixer Devices

- Working principle: Measure phase difference of emitted, modulated signal and received one

\[ d = \frac{c}{f_{\text{mod}}} \cdot \frac{1}{2} \cdot \frac{\phi_d}{2\pi} \]

- Current hardware: \(~20\text{MHz modulation frequency – in practice square wave}\)
Photonic Mixer Device (PMD) sensor:
Single-path Time-of-Flight depth imaging:
Single-path Time-of-Flight depth imaging:

\[ f_\omega(t + \phi) \rightarrow \mathbf{X} \rightarrow \int dt \rightarrow H_{\omega,\phi} \]

g_\omega(t) \rightarrow \text{distance-dependent correlation} \rightarrow P

\[ \alpha_p g_\omega(t + \tau) \]
See [Kolb et al. 10], EG STAR for more details

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Active Light – Transient Imaging
What is Transient Imaging?

a.k.a. Light-in-Flight Imaging

- Ultrafast imaging of non-stationary light distribution in scenes
- Tracking of wavefronts of light as they propagate in the scene
- Equivalent to imaging ultrashort pulses of light
Applications of Transient Imaging

Many applications by analyzing a transient image!

Understanding light transport:
- Velten et al.´2013

Surface reflectance capture:
- Naik et al.´2011

Decomposing light transport:
- Wu et al.´2012

Reconstructing hidden object geometry (and motion):
- Velten et al.´2012
- Pandharkar et al.´2011

[slide by Felix Heide]
Visualizing Light in Motion

- Repetitive Event, 1012 FPS, 672 x 1000 pixel resolution, 1 ns+ capture time
- Light moves 0.6 mm per frame
- Ability to see light transport

[Velten et al. 13]
Ivo Ihrke / Autumn 2015
Streak Cameras

- Picosecond time resolution
- 1D: 1x672 pixels
- Result as 2D image ("Streak Photo")

[Velten et al. 13]

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Experimental Setup

- Ti:Sapphire Laser
- Camera
- Scanning Unit
- Synchronization

[Velten et al. 13]
Actual Setup

[Velten et al. 13]
Streak Camera Picture
Scattering in Real Scenes

[Velten et al. 13]
Transient Imaging

- With PMD Devices – linked to the “multi-path” or “mixed pixel” problem
Multi-path contributions:

\[ f_\omega(t + \phi) \rightarrow \times \rightarrow \int dt \rightarrow H_{\omega,\phi} \]

\[ g_\omega(t) \rightarrow \text{sun} \rightarrow P2 \rightarrow \alpha_{p1} g_\omega(t + \tau_{p1}) \]

\[ \alpha_{p2} g_\omega(t + \tau_{p2}) \]

[Slides by Felix Heide]
Recovering multi-path contributions:

\[ g_{\omega_1}(t) \rightarrow \text{PMD Sensor} \]

\[ f_{\omega_1}(t + \phi_1) \rightarrow H_{\omega_1,\phi_1} \]

(slides by Felix Heide)
Recovering multi-path contributions:

\[ g_{\omega_2}(t) \]

PMD Sensor

\[ f_{\omega_2}(t + \phi_2) \]

\[ \int_{dt} \]

\[ H_{\omega_1,\phi_1} \]

\[ H_{\omega_2,\phi_2} \]

[slides by Felix Heide]
Recovering multi-path contributions:

\[ g_{\omega_2}(t) \]

\[ f_{\omega_2}(t + \phi_2) \]

\[ \int dt \]

\[ H_{\omega_1,\phi_1} \]

\[ H_{\omega_2,\phi_2} \]

\[ \vdots \]

\[ H_{\omega_n,\phi_n} \]

\[ \vec{h} \]

PMD Sensor

P1

P2

[slides by Felix Heide]
Image formation model:

- Relation of Transient Image to PMD measurement:

\[ H_{\omega_i, \phi_i} = \sum_{\tau=0}^{n} I(x, y, \tau) c_{\omega_i, \phi_i}(\tau) = \vec{i} \cdot \vec{c} \quad \rightarrow \quad \vec{h} = C \cdot \vec{i} \]

- Linear system is ill-posed: multiple measurements

  - assume model for temporal response (signal sparsity)
    Mixture Model: Gaussian + Exponential
  - and spatial smoothness
  - solve non-linear system

Spatial coherence  Temporal model
PMDTechnologies CamBoard nano

Too slow

Fixed frequency

LED unit
PLL 25MHz
PMD sensor
ADC
Control
FPGA

Power supply
USB...

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Modifications to the hardware

Prototype: Max mod. frequency 180 MHz, stable up to 110 MHz
Prototype setup

Used for results in paper
Result ‘Discoball’:

Color coding of strongest component:
Results ‘Discoball’:

Different time-steps:
Results ‘Discoball’:

Different time-steps:

[Image of a discoball at different time-steps]
Results ‘Discoball’: 

Different time-steps:
Results ‘Discoball’:

Different time-steps:
Results ‘Discoball’:  

Different time-steps:
Result ‘Bottles’: 

Color coding of strongest component:
Emerging Technologies prototype

Camera unit

AD9958 DDS (function generator) 0-180 MHz

Control

Light source

PMD sensor

ADC

PLL 25 MHz

FPGA

Control

MOD

TRIG

Power supply

USB

[slides by Felix Heide]
Results: People
References

- Curless, Levoy, “Better optical triangulation through spacetime analysis“, CVPR 1995
- Velten et al. “Femto-photography: capturing and visualizing the propagation of light”, SIGGRAPH 2013