Focal Sweep for Large Aperture Time-of-flight Cameras

September 27, 2016

Outline

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Continuous-wave ToF imaging

Working principle

- Captures depth by measuring phase delay of an optical signal:

$$z_p = \frac{c\tau_p}{2} = \frac{c\phi_p}{4\pi f_M}$$

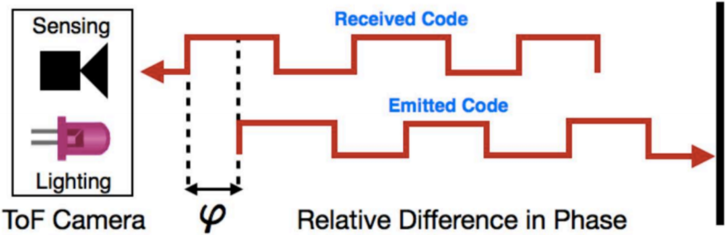


Figure: ToF working principle (Source: A. Kadambi, ICCV 2015 tutorial)

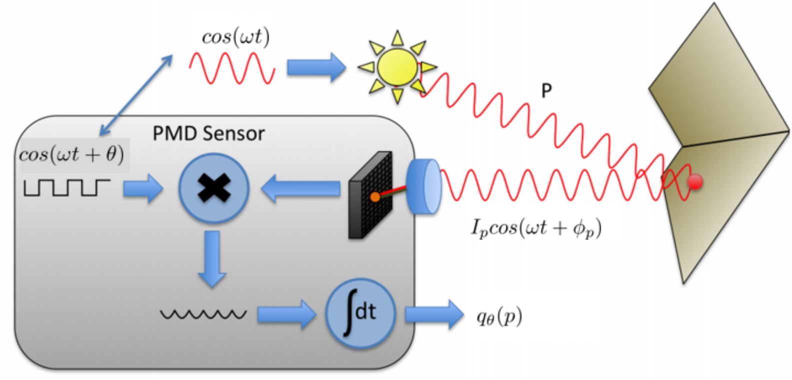


Figure: Continuous-wave ToF sensing (Adapted from Heide et al, 2013)

- Emitted signal: $cos(\omega t)$
- Received signal: $a_p cos(\omega t + \phi) + \beta$
- Cross-correlation:

$$q(\theta, p) = \frac{a_p}{2} cos(\theta + \phi) + \beta$$

- Four such correlation measurements, called quadrature channels, $q_i(p); i = \{0, 1, 2, 3\}$ captured with four different values of $\theta = i\frac{\pi}{2}; i = \{0, 1, 2, 3\}$
- Using the quadrature measurements $q_i(p)$, the depth and amplitude can be computed as

$$z_p = \tan^{-1}\left(\frac{q_1(p) - q_3(p)}{q_0(p) - q_2(p)}\right)\frac{c}{4f\pi}$$

$$a_p = \sqrt{(q_0(p) - q_2(p))^2 + (q_1(p) - q_3(p))^2} \qquad (1)$$

Outline

Defocus blur in ToF cameras

- Poor light throughput
  - Active light source intensity limited - safety and power restrictions
  - Exposure duration should be small - Motion blur
- Large numerical aperture lenses to capture more light
- Side-effect: Defocus blur and limited depth of field
- Blurry quadrature measurements: $y_i(p) = K(z_p) * q_i(p)$, where $K(z_p)$ is the depth-dependent PSF

Defocus blur in ToF cameras

Illustration

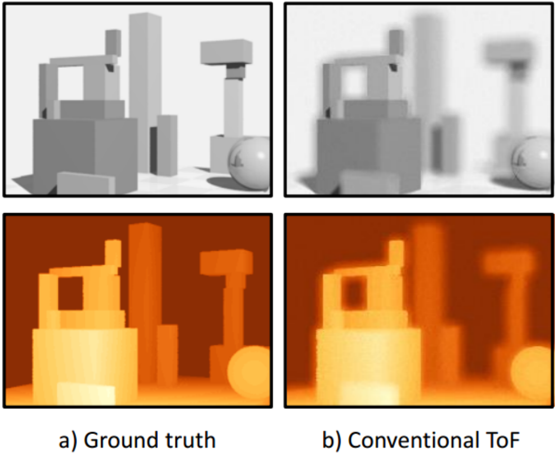


Figure: Illustration of defocus blur in amplitude and depth images captured with ToF camera with f/1.4 lens and sensor pixel size 45μm

Prior work

- Godbaz et al, 2010
  - Coded aperture for stable deconvolution
  - Gaussian derivative prior for quadrature channels
  - Employ spatially-varying iterative deconvolution technique for deblurring
- Xiao et al., 2015
  - Use image-formation model to address defocus blur
  - Instead of deconvolution, directly estimate latent amplitude and depth from degraded quadrature measurements
  - Three unknowns: depth-dependent PSF, all-in-focus amplitude and all-in-focus depth map
  - ADMM (Alternating Direction Method of Multipliers) used to solve for all-in-focus amplitude and depth map

Outline

Focal sweep technique

- Distance between lens and sensor varied at constant rate during exposure
- Resultant blurred image has a depth-independent PSF
- Hence, by estimating a single PSF and using non-blind deconvolution techniques, a sharp all-in-focus image can be obtained

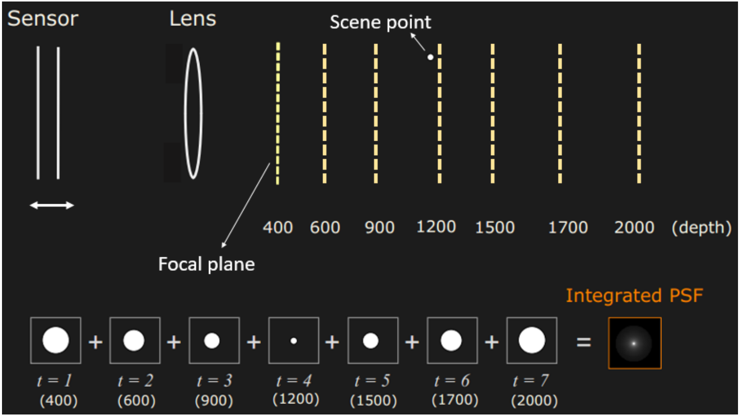


Figure: Illustration of focal sweep technique and how it leads to depth-invariant blur [Source: Nagahara et al., 2010]

Outline

1. Background and Motivation
   - Continuous-wave ToF imaging
   - Defocus blur in ToF cameras
2. Prior Work
3. Proposed method
   - Focal sweep technique
   - System Overview
   - Image capture and deblurring method
4. Results

Overview

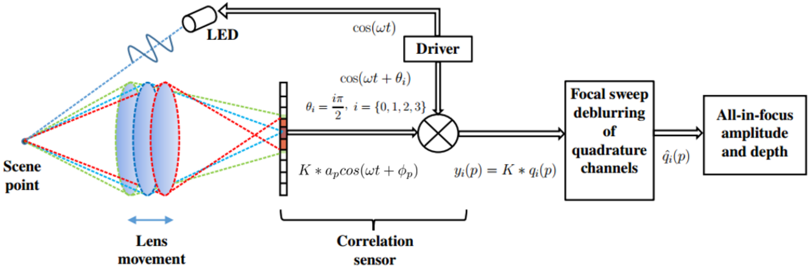


Figure: Overview of the proposed method

Outline

- Each quadrature channel is captured by sweeping the focus over the scene depth range
- This results in a depth-invariant blur in the ToF quadrature measurements
- Obtain the two independent channels from the blurry quadrature measurements: $h_{re} = \frac{(y_0 - y_2)}{2}$ and $h_{im} = \frac{(y_1 - y_3)}{2}$
- h_{re} and h_{im} are also blurred versions of corresponding sharp channels blurred by the same depth-invariant PSF:

$$h_{re} = K * X_{re};\ h_{im} = K * X_{im}$$

$$X_{re} = a\cos(\phi);\ X_{im} = a\sin(\phi)$$

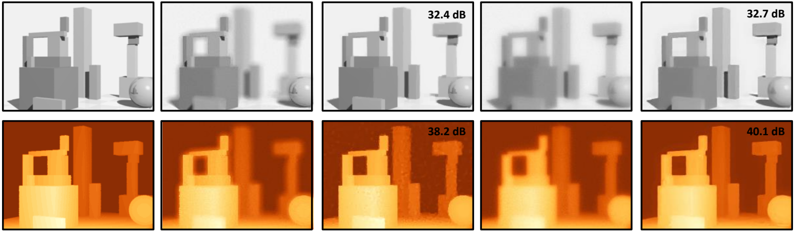
- Sharp channels $\widehat{X_{re}}$ and $\widehat{X_{im}}$ estimated using non-blind deconvolution with TV regularisation prior:

$$\widehat{X_{re}} = \text{argmin}_{X_{re}} ||h_{re} - K * X_{re}||^2 + \lambda ||X_{re}||_{TV},$$

and similarly for $\widehat{X_{im}}$.

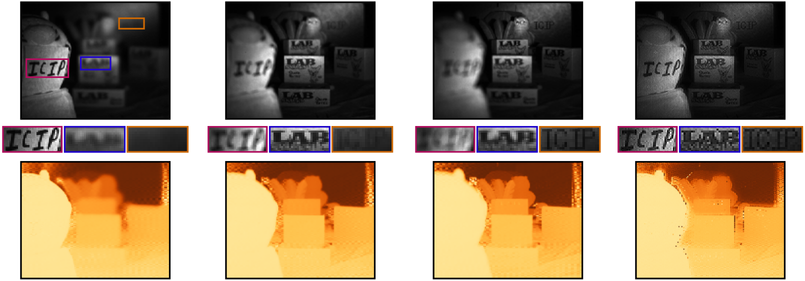
- All-in-focus amplitude and depth map obtained from Equation 1 by appropriate substitution of $\widehat{X_{re}}$ for $q_0 - q_2$ and $\widehat{X_{im}}$ for $q_1 - q_3$

Simulated scene



a) Ground truth b) Conventional ToF c) Recovered by Xiao et al d) Focal sweep e) Proposed method output

Real scene



a) Near focus b) Middle focus c) Far focus d) Focal sweep all-in-focus

Individual images captured with a standard ToF camera

Post-capture refocusing and tilted DOF

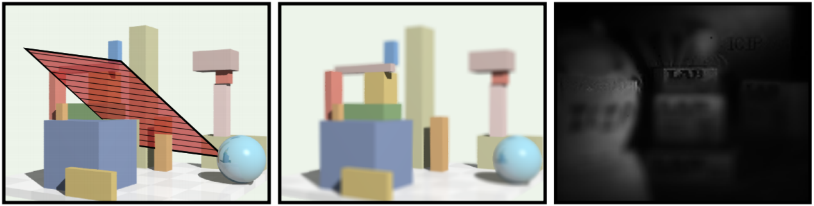


Figure: Left: Ground truth. Middle: Refocused scene along red plane. Right: Refocused real scene

Conclusions and Future Work

- Novel methodology for extending DOF in ToF imaging using focal sweep
- Simple recovery algorithm using non-blind deconvolution enabling real-time operation and straightforward scale-up for future generation ToF cameras
- Future work:
  - Better priors than TV norm regularization for ToF quadrature measurements?
  - Novel view synthesis and other applications using ToF focal stack