Jing-yu Lin, Ri-hui Wu, Hong-man Wang, Ye-bin Liu. Transient imaging with a time-of-flight camera and its applications. *Frontiers of Information Technology & Electronic Engineering*, 2017, **18**(9):1268-1276.
http://dx.doi.org/10.1631/FITEE.1700556

Transient imaging with a time-of-flight camera and its applications

Key words: Transient imaging; Time-of-flight (ToF) camera; Scattering media; Around corners

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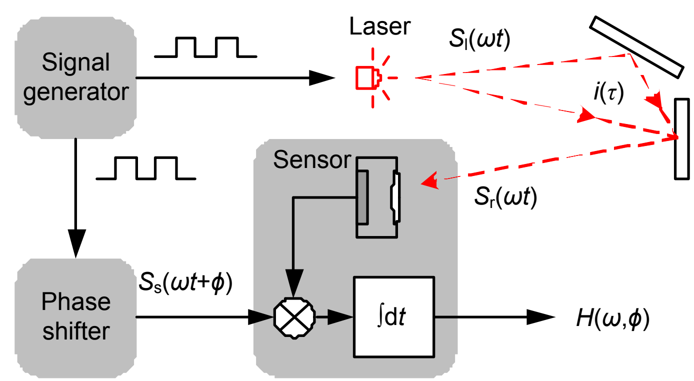
Motivation

- The classical imaging model, which integrates the photons of incident light over time, cannot record phenomena at the level of light speed.
- Recording the process of light propagation before it reaches a stationary state requires new imaging systems, like a time-of-flight (ToF) camera, and new imaging models.



Three Imaging Models

Model 1: Correlation Model

- The obtained image $H(\omega, \varphi)$ at each pixel is the integration of the product of the transient image $i(t)$ and the correlation function $C(\omega,\varphi,\tau)$ between the modulated laser signal and the modulated sensor gain:

$$H(\omega,\varphi)=\int i(\tau)C(\omega,\varphi,\tau)\mathrm{d}\tau.$$

- This model is in the time domain.

Three Imaging Models

Model 2: Frequency-Domain Model

- The obtained image $H(\omega)$ is composed of the Fourier transform of the transient image $I(\omega)$ and its harmonic components:

$$H(\omega) = \sum_{n=1}^{\infty} A_n I(n\omega)$$

- The high-order harmonic components with nontrivial amplitudes can be exploited to improve the modulation frequency of the camera and consequently improve the temporal resolution of transient imaging.

Three Imaging Models

Model 3: Compressive Sensing Model

- The obtained image $H(\omega)$, defined as the acquired measurement signal Y, is the linear combination of a sparse signal θ:

$$Y = S\theta$$

- The signal θ is recovered using the orthogonal matching pursuit algorithm, and full measurement signal X is computed from θ.

Two Applications

App 1: imaging through scattering media

- The light inside scattering media can be modeled as

$$S(t) = \frac{I\beta\, e^{-2\beta x(t)}}{4\pi(ct_0/2 + x(t))^2} 1_{t\in[t_0,t_R)} + \frac{I\rho\, e^{-2\beta x(t_R)}}{(ct_0/2 + x(t_R))^2}\delta(t - t_R)$$

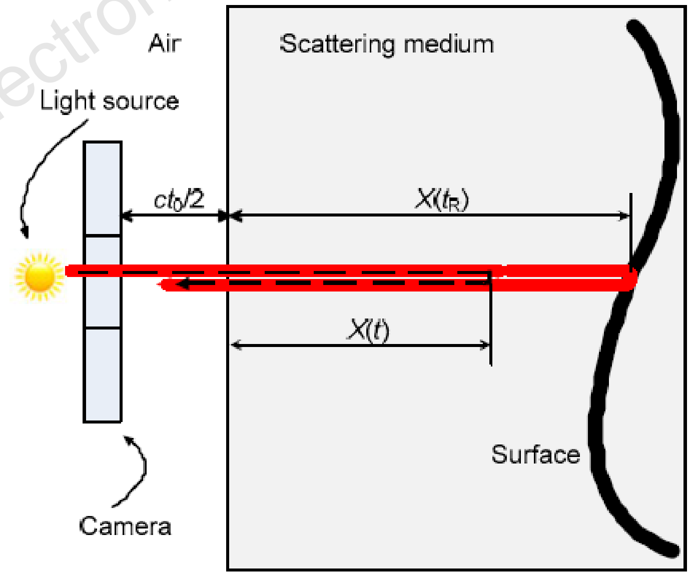


Fig. 10 Transient single scattering model

- The texture *I* can be solved from the equation of the transient image *y*(*t*) derived from the above model:

$$y(t) = I f_S(t) + I\rho f_R(t)$$

Two Applications

App 2: imaging around corners

- The setup of the system is shown in the figure (right) and the imaging equation is as follows:

$$I(\omega, \boldsymbol{x}^p) = \int r(\boldsymbol{x}) h^z(\omega, \boldsymbol{x}, \boldsymbol{x}^p) \mathrm{d}\boldsymbol{x}$$

- The shape $z(\boldsymbol{x})$ can be solved by classic vision methods, for example, the methods of depth from defocus. The strength $r(\boldsymbol{x})$ can be solved next.

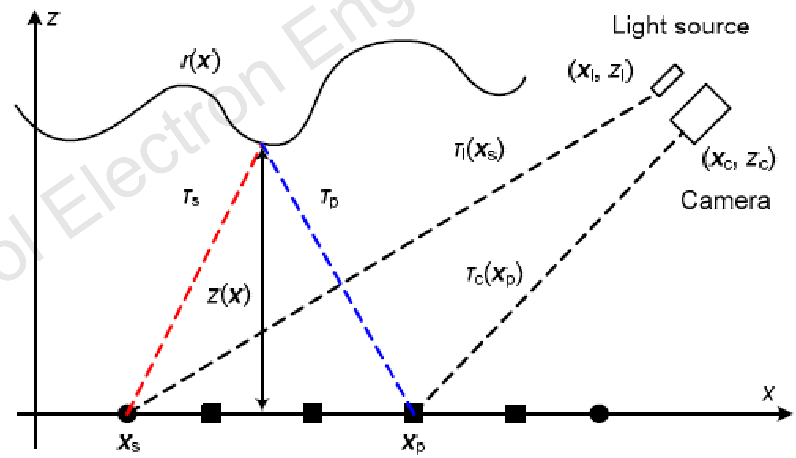


Fig. 11 Setup of the imaging system for looking around corners

Conclusions

- Applications of transient imaging are mostly based on the fact that the paths of light rays can be resolved from a transient image.
- The difficulties of using transient imaging include:
  - Measurement takes too much time
  - Intensity of reflected light is too weak