Relativistic Ultrafast Rendering Using Time-of-Flight Imaging

Andreas Velten[1,2] Di Wu[1,3] Adrian Jarabo[4] Belen Masia[4] Christopher Barsi[1] Everett Lawson[1]
Chinmaya Joshi[1,5] Diego Gutierrez[4] Moungi G. Bawendi[6] Ramesh Raskar[1]*
[1]MIT Media Lab [2]Morgridge Institute,University of Wisconsin-Madison [3]Tsinghua University
[4]University of Zaragoza [5]College of Engineering, Pune [6]MIT Dept. of Chemistry

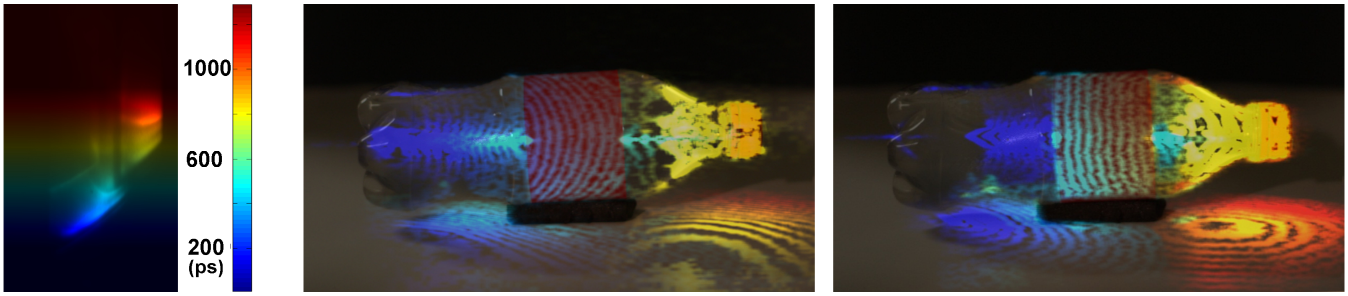

Figure 1: *Streak sensors are well-known devices in, e.g., chemistry and biology, but the space information acquired is incomplete. We re-purpose this hardware to capture ultrafast movies, with resolution of* $2 \cdot 10^{-12}$ *seconds (2 picoseconds) and synthesize physically valid visualizations of light in motion. Left: Single image from streak sensor. Center: Peak time visualization of a light wave in motion through a bottle. Right: time-unwarped visualization that accounts for the finite travel time of light from the scene to the camera to reveal observer-independent propagation. Note, the ripples on the table now correctly propagate outward from the bottle.*

Keywords: time-resolved imaging, ultrafast optics, relativistic effects, streak sensor

Introduction and Overview We capture ultrafast movies of light in motion and synthesize physically valid visualizations. The effective exposure time for each frame is under two picoseconds (ps). Capturing a 2D video with this time resolution is highly challenging, given the low signal-to-noise ratio (SNR) associated with ultrafast exposures, as well as the absence of 2D cameras that operate at this time scale. We re-purpose modern imaging hardware to record an average of ultrafast repeatable events that are synchronized to a streak tube, and we introduce reconstruction methods to visualize propagation of light pulses through macroscopic scenes.

Capturing 2D movies with ps resolution, we observe complex light transport effects, including multibounce scattering, mirror reflections, and subsurface scattering. We notice that recorded time instances, i.e., “camera times” are different from the events’ actual times at the scene location, i.e., “world times.” We introduce the notion of time warp between these space-time coordinate systems, and rewarp the space-time movie for a different receiver perspective, including relativistic.

Approach We use 50 fs long pulses from a mode-locked Ti:Sapphire laser at a center wavelength of 795 nm and a 75 MHz repetition rate. The pulse is focused onto a (Lambertian) diffuser to create a virtual point source, illuminating the entire scene with a spherical pulse. All pulses are statistically identical, so we average many recordings to achieve high SNR. The detector is fast streak sensor (Hamamatsu C5680), which is synchronized to the illumination by splitting off a portion of the beam and directing it onto a fast photodetector connected to the camera. The camera, which has an x-t resolution of 672×512, samples over a window of about 1 ns (i.e. less than 2 ps per sample) records and averages the light scattered by $4.5 \cdot 10^8$ pulses for a horizontal single line of the scene. A scanning mirror sweeps the line of view of the camera through the scene. The system integrates light for 6 seconds for each movie scan line. We choose this integration time to optimize SNR and minimize system vibrations due to fast motor and mirror movement. Alternatively one could use a brighter laser or increase camera gain.

Results and Discussion With our capturing of time-resolved table-top scenes, we must drop the typical assumption that the speed of light is infinite. Thus, we can examine, with much greater detail, many optical phenomena. For example, subsurface scattering can be computationally separated from surface scattering through distinguishing different time scales [Wu et al. 2012]. Similar studies allow for novel methods of material acquisition [Naik et al. 2011] and looking around corners [Velten et al. 2012]. Further, because time-resolved information is related to depth, three-dimensional depth maps can be calculated, especially in cases where conventional stereo might incur problems, i.e., multi-valued pixel depths (as occurs when imaging transparent/translucent objects). Novel visualizations of these phenomena will be presented.

Interestingly, arrival times of light rays depend on the *camera* position, so we may distinguish two types of reference frames. The first is the “camera time,” which is the *measured* light propagation (Figure 1, center). The second is the “world time,” i.e., the true propagation path lengths/times. By including relativistic effects, we transform from one frame to another, and synthesize new movies from a different camera perspective.

References

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*raskar@media.mit.edu

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