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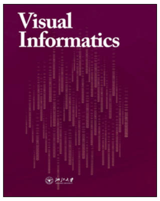

Recent advances in transient imaging: A computer graphics and vision perspective

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A B S T R A C T

Transient imaging has recently made a huge impact in the computer graphics and computer vision fields. By capturing, reconstructing, or simulating light transport at extreme temporal resolutions, researchers have proposed novel techniques to show movies of light in motion, see around corners, detect objects in highly-scattering media, or infer material properties from a distance, to name a few. The key idea is to leverage the wealth of information in the temporal domain at the pico or nanosecond resolution, information usually lost during the capture-time temporal integration. This paper presents recent advances in this field of transient imaging from a graphics and vision perspective, including capture techniques, analysis, applications and simulation.

1. Introduction

In 1964, MIT professor Harold Edgerton produced the now-iconic *Bullet Through Apple* photograph (see Fig. 1, left). His work represented an unprecedented effort to photograph events too fast to be captured with traditional techniques. He invented a new stroboscopic flash light (which he termed the stroboscope), which would shine for about 10 microseconds: bright enough, and short enough, to effectively freeze the world and capture ultrafast events such as the bullet bursting through the apple, a splash of a drop of milk, or the flapping wings of a hummingbird. Almost fifty years later, inspired by these images, the technique known as *femto-photography* (Velten et al., 2013) was introduced; it took Edgerton's vision to a whole new level, by allowing to capture movies of light in motion, as it traversed a macroscopic scene (Fig. 1, right).

This fifty-year span provides a clear example of the progress in ultrafast imaging. Many techniques have appeared in the last few years, some inspired by femto-photography, others following completely different approaches. They share the common goal of trying to make visible the invisible: Whether it is due to the speed of the event being captured, to the presence of scattering media, to the lack of photons, or to an occluding object, ultrafast imaging aims to leverage the wealth of information usually lost during the capture-time temporal integration. This has revolutionized the fields of imaging and scene understanding, opening up new possibilities, but also discovering new challenges.

In this paper, we provide an in-depth overview of the most significant works in this domain. We concern ourselves mostly with works in the areas of computer graphics and computer vision; as such, we deal only with visible light and infrared. For other techniques that make use of different wavelengths (such as microwaves, or techniques operating in the terahertz domain), we refer the reader to other excellent sources such as the recent survey by Satat et al. (2016). Similarly, another recent survey (Bhandari and Raskar, 2016) offers an overview of the field from a signal-processing perspective. From our graphics and vision view, we adopt the commonly used term *transient imaging*, referring to imaging techniques fast enough to capture transient information of light transport, as opposed to traditional techniques that capture steady-state information (such as regular images).

We have structured our work as follows: First, we introduce **capture** techniques in Section 2, separating techniques that directly obtain transient information (such as the previously mentioned femto-photography, or the recent interferometry-based works), from techniques that *reconstruct* that information from a sparse set of measurements, usually sacrificing temporal resolution (such as recent approaches based on time-of-flight (ToF) cameras). In Section 3 we proceed to discuss works whose main goal is to **analyze** transient light transport, both in the primary and frequency domains. We additionally discuss techniques involving spatio-temporal coding and modulation. In Section 4 we offer a cross section of existing techniques from an **application's** point

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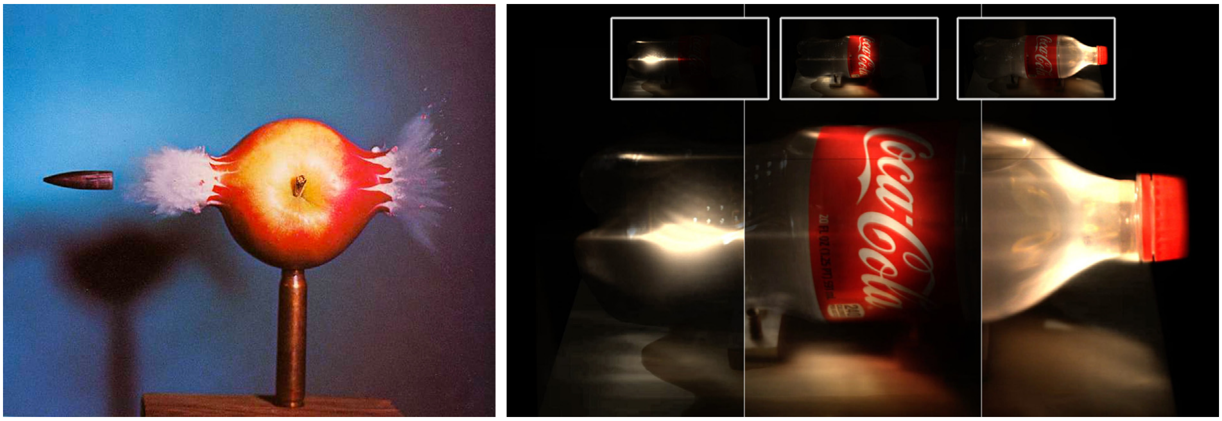

Fig. 1. *Left:* In 1964, Harold Edgerton captured the iconic *Bullet Through Apple* image (© MIT Museum). The bullet traveled at about 850 m/s, which translated into an exposure of approximately 4–10 millionth of a second. *Right:* Almost 50 years later, the femto-photography technique was introduced (Velten et al., 2013), capable of capturing *light in motion*, with an effective exposure time of one *trillionth* of a second. The large split image is a composite of the three complete frames shown in the insets.
Source: The complete videos of this and other scenes can be downloaded from http://giga.cps.unizar.es/~ajarabo/pubs/femtoSIG2013/.

of view. Again with a focus on graphics and vision, we subdivide this section in geometry reconstruction, motion estimation, and material estimation; a common problem in most of the applications discussed is the *multipath interference (MPI) problem*, which is tackled from many different angles. With the establishment of transient imaging, the **simulation** of time-resolved light transport is becoming an increasingly important tool, which we cover in Section 5. Last, Section 6 offers some final conclusions and discussions.

2. Capture

The interaction between light and matter is described as a linear operator by the light transport equation (Ng et al., 2003):

$$\mathbf{i} = \mathbf{T}\mathbf{p}, \tag{1}$$

where $\mathbf{i}$ is the 2D image (as a column vector of size I) captured by the camera, $\mathbf{p}$ is the vector of size P representing the scene illumination, and $\mathbf{T}$ is the scene transport operator encoded as a $I \times P$ matrix. Equation (1) assumes that the light transport has reached steady-state. In its transient form (O'Toole et al., 2014), incorporating the temporal domain to the light transport equation yields:

$$\begin{aligned}\mathbf{i}(t) &= \int_{-\infty}^{\infty} \mathbf{T}(\tau)\mathbf{p}(t-\tau)d\tau \\ &= (\mathbf{T} * \mathbf{p})(t),\end{aligned} \tag{2}$$

where $\mathbf{i}(t)$ stores the light arriving at time t, $\mathbf{p}(t)$ is the time-resolved illumination function at instant t, and $\mathbf{T}(t)$ is the transport matrix describing the light transport with a time-of-flight of exactly t. Note that from here on all terms are time-dependent. The second equality represents the convolution in the temporal domain between $\mathbf{T}$ and $\mathbf{p}$. In practice, the transient image cannot be captured at instant t directly, given physical limitations of the sensor. Instead, the signal is also convolved by the temporal response of the sensor $\mathbf{s}(t)$ centered at t as:

$$\begin{aligned}\mathbf{i}(t) &= \int_{-\infty}^{\infty} \mathbf{s}(t-\tau)(\mathbf{T} * \mathbf{p})(\tau)d\tau \\ &= (\mathbf{s}(t) * \mathbf{T} * \mathbf{p})(t).\end{aligned} \tag{3}$$

For transient imaging, we are interested in computing the transient image $\mathbf{i}(t)$ corresponding to the impulse response of the transport matrix $\mathbf{T}$ (i.e. Eq. (2)). This would effectively mean that the illumination $\mathbf{p}(t) = \delta_0(t)$ and sensor response $\mathbf{s}(t) = \delta_t(t)$ are Dirac deltas centered on 0 and t respectively. In order to capture this impulse response $\mathbf{T}$, several approaches have been presented, depending on the type of illumination and sensor response used. If we focus only on illumination, the main lines of work have used either impulse illumination, or coded illumination. In the case of the former, techniques have used either ultrafast imaging systems to directly record light transport (Section 2.1), or phase interferometry to recover the propagation of light (Section 2.2). In the case of the latter, the coded illumination has been usually correlated with the coded sensor response, allowing to recover the time-resolved response by means of post-capture computation (Section 2.3). A comparison of selected capture systems, including their spatio-temporal resolution, is summarized in Table 1.

2.1. *Straight temporal recording*

In theory, the most straightforward way to capture the impulse transport matrix $\mathbf{T}$ is to use an imaging system with impulse illumination, and extremely short exposure times. However, this is very challenging in practice. First, the signal-to-noise ratio (SNR) is extremely low, since very few photons arrive during the exposure time. On top of this, ultrashort illumination pulses are required, to avoid the effect of the convolution on the transport matrix. Further, ultrafast imaging systems (in the order of nano to picosecond resolution) do not exist for high-resolution, two-dimensional imaging.

Ultrashort (impulse) illumination is in general achieved by using laser-based illumination, such as femtolasers (Velten et al., 2013). Several different approaches have been proposed to capture transient light transport, and to mitigate the challenge imposed by the extremely low SNR. In the following, we categorize these works according to the imaging system they are based on. Note that we concern ourselves with ultrafast imaging techniques focusing on time-resolved light transport, recording either a single bounce (e.g., for LIDAR applications), or multiple scattering. Other impulse-based ultrafast imaging techniques, e.g., based on pulse stretching (Nakagawa et al., 2014; Lau et al., 2016), are not discussed in this work.

Conceived for range imaging, *laser gated viewing* (Busck and Heiselberg, 2004) exploits the repeatability of light transport in a static scene by sequentially imaging a set of frames. An ultrashort laser pulse is synchronized with an ultrafast camera equipped with a highly sensitive CCD, which images photons arriving during very small temporal windows (in the order of a few hundred picoseconds). Each frame is computed independently, by sliding the imaging window. This system was later extended to use area impulse illumination in the context of non-line-of-sight imaging (Laurenzis and Velten, 2014). In order to improve the SNR, hundreds of

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