COMPUTER GRAPHICS I
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LITERATURE REVIEW II

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LOW- BUDGET TRANSIENT IMAGING USING PHOTONIC MIXER DEVICES

In this paper the authors presented a method for transient imaging with PMD sensors, a technology that is widely available in commercial time-of-flight cameras. The hardware was modified to allow for different modulation frequencies and phase for both the sensor and illumination.

A transient image is a rapid sequence of images representing the impulse response of a scene. Transient imaging refers to a recent imaging modality in which short pulses of light are observed "in flight" as they traverse a scene and before the light distribution achieves a global equilibrium. Recently, interest in transient imaging has been rekindled by the development of ultra-fast camera technologies, which allow for simplified setups compared to the holographic approach, and significantly more general scene geometries.

One disadvantage of transient image is it depends on expensive custom hardware. To gather all the components required take hundreds of thousands of worth equipment. Even the capture time for a single transient image have been reported of an hour or more.

To overcome this complex setup, this paper uses a simple Photonic Mixer Device(PMD). PMD sensors are commonly used in time-of-flight cameras, and can be obtained for a few hundred dollars. This model is inspired by the work of Wu et al and applies to each pixel independently. In this paper, the authors demonstrate how models for local light interaction similar to the ones used by Wu et al. can be used to extract transient images from such a setup. The main contributions of the authors are,

1. A theoretical model for the relationship between transient imaging and traditional time-of-flight imaging using PMD is derived.
2. The estimation of transient images from PMD measurements is formulated as an inverse problem that is ill-conditioned but can be solved by introducing regularization terms as well as a model of local surface/light interactions.
3. A prototype system with modified PDM cameras is demonstrated which allows for flexible measurements of time-of-flight images using a range of different modulation frequencies and phases.

Heterodyne modulation of light and PMD sensor are included in recent improvements and extensions to PMD design and operation to resolution. Using these measurements, a novel optimization strategy is derived which allows the authors to infer the full transient image under global illumination and complex lighting by solving an optimization problem.

For time-of-flight (TOF) applications, PMDs are used in conjunction with illumination that is also modulated in intensity. Standard TOF applications are said to assume that the modulated irradiance arriving at a sensor pixel is due only to direct illumination of a single object point by a single point light source, effectively meaning that only a single light path contributes to the sensor reading.

In this paper a transient image from the sensor measurements is reconstructed. To solve the challenging inverse problem, both spatial and temporal regularization terms are introduced, i.e. impose a non-linear model m(u)~ i for the local interaction of light with objects, and optimize for both the transient image i and the model parameters u in a least-square sense.

The gradients for both the spatial and temporal slices are expected to be sparse, but with casual outliers. This motivates the use of robust norms in both regularization terms. Three additional priors are used to regularize the strongly ill-conditioned problem, i.e.

1. By using a model m(.)
2. A temporal smoothness regularizer
3. A spatial smoothness regularization.

A splitting algorithm for reconstruction is used to minimize the equation, by alternating between i and u. With optimization split into two stages, the i-problem is fast and convex, and provides a data term plus spatial and temporal regularization, with the tendency to overly smoothen the results. The u-problem on the other hand, is a very expensive, non-convex fitting of the model parameters, that produces higher temporal resolution, but may in turn introduce some visually objectionable spatial artifacts. Because of the trade-off between temporal sharpness and spatial artifacts, it may in some cases be preferable to only run the i subproblem, depending on whether the goal is to obtain the most detailed measurements possible, or simply to produce visually pleasing results.

This system does not require ultrafast temporal sensing or illumination for the capture of transient images, but works with correlation measurements are obtained over longer integration periods. A disadvantage of the system is the limited spatial and temporal resolution of the sensor used. The technology is also inexpensive enough that multiple sensors could be tiled together for applications that require higher resolution.

As a result, this work achieves transient images with hardware costing a fraction of the price of the femtosecond laser/streak camera combination described above. This approach models the transient image as a sparse signal in a basis that corresponds to certain light-object interactions.

The main hope of the authors is that their approach might reduce the barrier of entry for performing research in transient imaging and its applications, including the use of transient images for reconstructing geometry from indirect illumination.

SNAPSHOT DIFFERENCE IMAGING USING CORRELATION TIME-OF-FLIGHT SENSORS

In this paper an innovative approach to capturing difference images in a single exposure and generalize difference imaging to a variety of applications is explored. Over the last two decades, research in computational photography has been striving to overcome the limitations of conventional imagers via a co-design of optics, sensors, algorithms, and illumination. Unfortunately, difference imaging is challenging for dynamic scenes because motion creates misalignment between successively captured photographs which is in many cases difficult to mitigate in post-processing.

In this paper, the authors propose to re-purpose time-of-flight (TOF) sensors to facilitate instantaneous difference imaging. The usual application for these sensors is depth imaging. Rather than computing scene depth, the authors demonstrate how ToF sensing technology can be used to conventionally implement a range of computational photography techniques, including direct-global separation, direct edge imaging, spatio- temporal gradient imaging, and more.

The contributions made by the authors in this paper are,

1. The concept of generalized difference imaging and development of an image formation and noise model has been introduced.
2. A prototype difference imager is constructed using a modified time-of-flight camera combined with multiple, spatio-temporally coded light sources.
3. The two images can be recovered from a single difference image is demonstrated by exploiting characteristics of the proposed image formation model.

A pixel in ToF sensor measures the amount of correlation between the incoming temporally varying photon flux and a sensor modulation signal that also varies in time. Of all the technologies that can be used for time-of-flight imaging, correlation sensors are the most widespread and affordable ones. At the end of integration phase, the difference between the two wells is read out and digitized.

The differential measurement scheme, and in particular the multi-tap measurement schemes typically used in ToF operation, cancel out many of the systematic errors introduced by the hardware. However, none of these measures are capable of removing shot noise, which is the uncertainty that occurs during the counting of photoelectrons. As the difference of two independent random variables, the final pixel value is also a random variable.

Two different time-of-flight sensing platforms have been constructed. The first prototype is a recreation of Heide et al.'s system that is based on the discontinued PMD technologies CamBoard nano. The second prototype combines the Texas Instruments evaluation module with external modulation and light sources in a similar way to the system described by Shrestha et al.[2016]. Both imagers have their infrared-pass filters removed so that they can sense the visible light.

To reduce the fixed pattern noise, a black frame was recorded before the data acquisition and later subtracted from each measured frame, which resulted in the difference image pixels obtain negative and positive values, depending on the charge balance of the two potential wells.

This work has been applied in Biopolar color matching functions, patches that reflect red and blue to equal parts, like the greyscale, result in a response that is approximately zero .And also, polarization-based direct-global separation, many computational imaging techniques are based on a decomposition of light transport into a direct component, i.e. light that has undergone exactly one scattering event between light source and camera, and a multiply scattered indirect, or global component.

This work can be used to produce directional gradient images of scene, and visualizing depth continuities. This can be done by placing two identical light sources of opposite polarity on opposite sides of a sensor. Whenever a depth discontinuity shadows one of the light sources, the resulting image displays positive or negative values. All other pixels obtain a value around zero. By varying the distance between the light sources, different edge widths are obtained.

One of the key advantages of snapshot difference imaging is that it is immune to scene motion, whereas multi-shot techniques typically suffer from alignment issues when objects are rapidly moving. The single- shot difference images are significantly clearer with more consistent leaf shapes than the two-shot ones, and virtually free of ghosting artifacts. On the other hand, the single-shot images show a slight increase in fixed-pattern noise. The authors state they can recover two original images from a single difference image by exploiting the noise characteristics of both the photon limited signals.

A feature of difference imaging is its capability to extract essential information from heavy streams of image data. This method has two main advantages,

1. Capturing a difference image within a single exposure allows for faster time scales to be recorded than capturing two separate images and subtracting them digitally.
2. The noise properties of difference imaging before A/D conversion are shown to be favorable over digital subtraction post A/D conversion.

The approach also has a limitation, that is it relies on ToF sensors, which currently provide much lower resolution and signal quality than well-established CMOS or CCD sensors.

To summarize this paper proposes a new imaging system for direct recording of image differences in a snapshot. The paper directly maps to the merging technology of time-of-flight sensors and will therefore continue to benefit from the ongoing technological development in that area.

SIMILARITY BETWEEN THE TWO PAPERS

The primary and secondary paper have a major similarity between them and that is, both are based on Computational photography concept, a concept referring to digital image capture and processing techniques that use digital computation instead of optical processes. Computational photography encompasses a diversity of imaging techniques, but one of the core operations performed by many of them is to compute image differences. Both the papers use Time -of-flight sensors to attain their goal. The primary paper introduces a snapshot difference image approach that is directly implemented in the sensor hardware of emerging time-of-flight cameras whereas the secondary paper explores the use of photonic mixer devices, commonly used in inexpensive time-of-flight cameras, as alternative instrumentation for transient imaging.

REFERENCES

PRIMARY PAPER:

SNAPSHOT DIFFERENCE IMAGING USING CORRELATION TIME-OF-FLIGHT SENSORS

ACM Transactions on Graphics (TOG) - Proceedings of ACM SIGGRAPH November 2017

SECONDARY PAPER:

LOW BUDGET TRANSIENT IMAGING USING PHOTONIC MIXER DEVICES

ACM Transactions on Graphics (TOG) - Proceedings of ACM SIGGRAPH July 2013