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Sub-picosecond photon-efficient imaging using single-photon sensors

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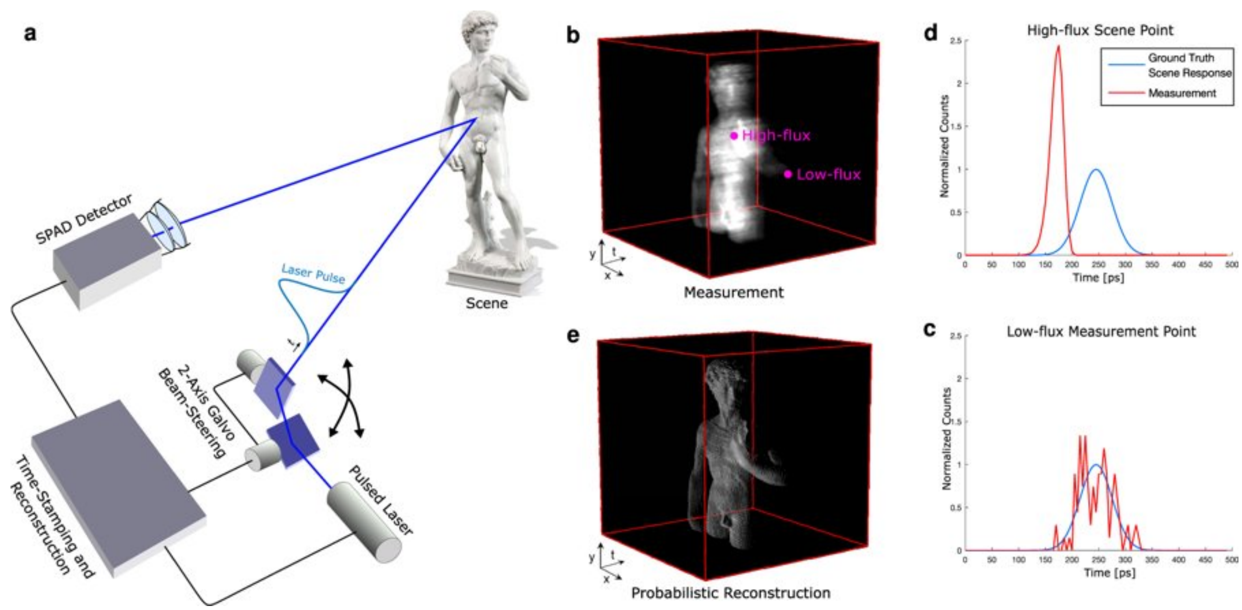

Sub-picosecond 3D Imaging Framework. (a) A collimated, pulsed laser illuminates the scene at a single point. The laser is laterally scanned using a 2-axis mirror galvanometer. Timing and control electronics time-stamp each detected photon arrival relative to the last emitted pulse and accumulate these events in a histogram of spatio-temporal photon counts (b). This histogram is processed to estimate both reflectivity and depth information (c). Two points are highlighted, one corresponding to high-flux (d) and the other to low-flux (e) measurements. Whereas the latter are noisy, high-flux measurements suffer from pileup distortion which introduce a significant bias for the depth estimation of conventional algorithms. The proposed estimation method accurately models both of these scenarios, allowing for reflectance information and travel time to be estimated with sub-picosecond accuracy from severely distorted measurements. Credit: *Scientific Reports*, Doi: 10.1038/s41598-018-35212-x

Single-photon avalanche diodes (SPADs) are promising detector technologies that may be used to achieve active 3D imaging systems with fast acquisition, high timing accuracy and high detection sensitivity. Such systems have broad applications in the domains of biological imaging, remote sensing and robotics. However, the detectors face technical impairments known as pileup that cause measurement distortions to limit their precision. In a recent study, conducted at the Stanford University Department of Electrical Engineering, scientists Felix Heide and co-workers developed a probabilistic image formation model that could accurately model pileup. Using the proposed model, the scientists devised inverse methods to efficiently and robustly estimate the scene depth and reflectance from recorded photon counts. With the algorithm, they were able to demonstrate improvements to the accuracy of timing, compared to existing techniques. More importantly, the model allowed accuracy at the sub-picosecond in photon-efficient 3D imaging for the first time in practical scenarios, whereas previously only widely-varying photon counts were observed. The results are now published in *Scientific Reports*.

Active imaging has broad applications across disciplines that range from autonomous driving to microscopic imaging of biological samples. Key requirements for these applications include high accuracy with timing, fast acquisition rates, dynamic operating ranges and high detection sensitivity to image objects hidden from a camera's view. Remote sensing and automated applications demand acquisition ranges from

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