Single-Photon LiDAR

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A new camera can photograph you from 45 kilometers away

Developed in China, the lidar-based system can cut through city smog to resolve human-sized features at vast distances.

by Emerging Technology from the arXiv

May 3, 2019
Using a large number of photon detections (thousands per pixel), we obtain Reflectivity from number of detected photons at each pixel. Detecting fewer photons (hundreds per pixel) leads to image degradation due to shot noise. Degradation is traditionally modeled as additive Gaussian noise. 3D from time-of-flight info (shift of photon-count histogram’s peak) at each pixel.
Active imaging with 1 photon per pixel??

- **Pulsed light source**
- **Time-resolved sensor**
- **Background light (noise)**
- **Scene**

Reflectivity image is **featureless**

3D image is severely **degraded** by background light
Single-Photon VS Conventional

<table>
<thead>
<tr>
<th></th>
<th>Conventional LiDAR</th>
<th>Single photon LiDAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>~1 nW ($10^9$ photons)</td>
<td>~1 photon</td>
</tr>
<tr>
<td>Power</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Range</td>
<td>~10 kilometers</td>
<td>&gt; 100 kilometers</td>
</tr>
<tr>
<td>Accuracy</td>
<td>~10 cm (ns)</td>
<td>~mm (ps)</td>
</tr>
</tbody>
</table>

How to do it?

- New software: Computational Algorithm
- New hardware: Single-Photon Imaging System
Results with 1 photon per pixel

Conventional algorithm

Our algorithm

Nat. Commun. 7, 12046 (2016); see also Science 343, 58 (2014)
Computational algorithm

**Step 0:** calibration
- Calibrate $B$ and also identify set of “hot pixels” $\mathcal{H}$

✔ **Filter noise in time domain**
✔ **Spatial correlations**

**Step 1:** estimate scene reflectivity
Combine photon-count likelihood with spatial correlation to solve regularized ML estimation \(\text{(convex)}\)

\[
\begin{align*}
\text{minimize}_A & \quad \sum_{(i,j) \notin \mathcal{H}} \mathcal{L}(A_{i,j}; C_{i,j}, B_{i,j}) + \tau_A \text{pen}(A) \\
\text{subject to} & \quad A_{i,j} \geq 0 \\
& \quad \text{data fidelity of photon counts} \\
& \quad \text{spatial correlations of scene reflectivity}
\end{align*}
\]

**Step 2:** censor noise photons
Use $\text{OMP}(T_k, N_k)$ to locate photon clusters and reject photon arrival times not near to them by pulsewidth

**Step 3:** estimate scene depth
Combine arrival-time likelihood with spatial correlation to solve regularized ML estimation \(\text{(convex)}\)

\[
\begin{align*}
\text{minimize}_D & \quad \sum_{(i,j) \notin \mathcal{H}} \sum_{T_{i,j} \in U_{i,j}} \mathcal{L}(D_{i,j}; T_{i,j}) + \tau_D \text{pen}(D) \\
\text{subject to} & \quad D_{i,j} \geq 0 \\
& \quad \text{data fidelity of filtered arrival times} \\
& \quad \text{spatial correlations of scene depth}
\end{align*}
\]

_Nat. Commun._ 7, 12046 (2016); see also _Science_ 343, 58 (2014)
Push the range limit

\[ R_{\text{limit}} \propto SNR \cdot \eta_a = \frac{PA\eta_s}{R^2hv\bar{n}} \cdot \eta_a \]

- \( \eta_s, \bar{n} \)
  - **Experiment**
    - High coupling efficiency
    - Low distortion
    - High transmittance
    - Noise reduce
  
- \( \eta_a \)
  - **Algorithm**
    - Denoise $\sim 1$ PPP
    - Low SNR reconstruction

- Optimize the optical design of the hardware system
- Propose a new algorithm for outdoor environments

Laser power \( P \)
Telescope aperture \( A \)
Single-Photon Imaging

- 1550 nm: eye safe, reduced solar, low loss
- Use polarization to reduce the noise (x100)
- High coupling efficiency (50%)
- Compact, dual-axis scanning

arXiv:1904.10341
Algorithm

Challenges

- A large FoV in far field covers multiple reflectors
- A strong background noise in outdoor environment
- Only few signal photons can return (~1 photon)

Solutions

- **Global gating** to unmix signal from noise
- Modified SPIRAL-TAP solver to solve the deconvolution problem with **3D matrix**
- Impose a transverse-smoothness using the **3D TV norm**
Hardware + Software

Conventional LiDAR
~10 kilometers [OE, 2017]

New hardware:
Single Photon detection
High coupling and detection
Advanced noise-suppression

New algorithm:
Sensitivity ~ 1 photon per pixel
SNR = 0.031 (200ns time gate)

Laser power: reduced by ~100 times
Imaging distance: extended by ~10 times

Long-range 3D imaging
45-km results

<table>
<thead>
<tr>
<th>Range</th>
<th>45 km</th>
<th>Sensitivity</th>
<th>2.59 photon/pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>16 k</td>
<td>Spatial resolution</td>
<td>0.6 m</td>
</tr>
</tbody>
</table>

Li et al., arXiv:1904.10341 (2019)
22-km imaging in daylight

- Ground truth
- Visible-band image
- Pixelwise ML

- PSNR=5.65 dB
- PSNR=11.40 dB
- PSNR=19.58 dB

- Shin et al. 2016
- Rapp and Goyal 2017
- Proposed method
3-km Complex Scenes

A complex natural scene with multiple trees and buildings.
Super-Resolution in long range

At 45 km:
• Diffraction limit: ~ 1 m
• Our resolution: ~ 0.6 m

Motivated by the Nobel Prize in Chemistry 2014 for "super-resolved fluorescence microscopy"
Future work

**Longer**
~200-km stand-off distance

**Faster**

*Speed up* the imaging and provide *real-time* imaging for rapid moving targets

**Satellite 3D imaging**

Low-power single-photon LiDAR mounted on LEO satellites
Other on-going research

- Non-line-of-sight imaging
- Diffuse imaging at near-infrared wavelength
- Advanced algorithms, e.g., machine learning

Xu et al., Opt. Express 26, 9945 (2018); Xu et al., in preparation (2019)
Non-Line-of-Sight Tracking over 1.4 km
People

Kejin Wei
Wei Li
Zhengping Li
Yuzhe Zhang
Bin Wang
Xin Huang

Juntian Ye
Hao Tan
Yu Hong
Jinjian Han
Pengyu Jiang

Director: Jian-Wei Pan
Collaborators: Cheng-Zhi Peng, Qiang Zhang, Jun Zhang, Yuan Cao & Hai-Yun Xia, Xian-Kang Dou
Keep smiling, our LiDAR may be watching you 😊

Thank you!

Li et al., arXiv:1904.10341 (2019)
Email: feihu.xu@ustc.edu.cn
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Our system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>45 km</td>
</tr>
<tr>
<td>Scene</td>
<td>Building</td>
</tr>
<tr>
<td>Size</td>
<td>128×128, 64m×64m</td>
</tr>
<tr>
<td>Average Photon Number/Pixel</td>
<td>2.59</td>
</tr>
<tr>
<td>SNR</td>
<td>0.031 (a time gate of 200 ns, 30 m)</td>
</tr>
<tr>
<td>Detector</td>
<td>InGaAs, 15%, 500-ps jitter, 2200 dark count</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Objective Lens</td>
<td>f=2800 mm, D=280 mm</td>
</tr>
<tr>
<td>Laser Repetition Rate</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Laser Pulse Width</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Average Output Power</td>
<td>120 mW, 1.2 µJ per pulse</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>11.3 µrad</td>
</tr>
<tr>
<td>TDC</td>
<td>Tailored, 50-ps jitter</td>
</tr>
<tr>
<td>Optical Box Size</td>
<td>30×30×35 cm³</td>
</tr>
<tr>
<td>Coupling Fiber</td>
<td>62.5 µm</td>
</tr>
</tbody>
</table>