Real-time computational 3D reconstruction from single-photon Lidar data

when image processing meets computer graphics

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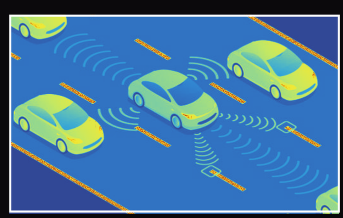
STEM for BRITAIN

CONTEXT (3D imaging)

Applications



- Autonomous navigation
- Environmental monitoring
- Defence
- Underwater imaging

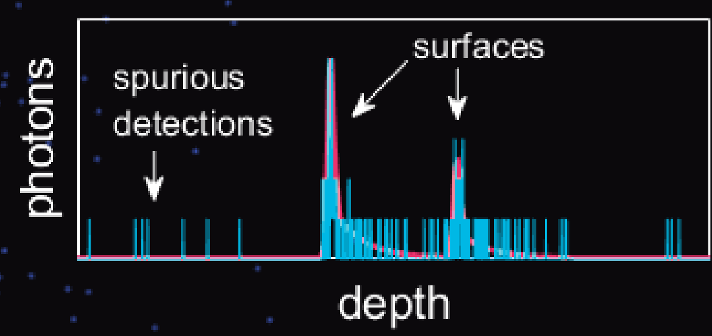
UK funding

£315m | UK national quantum technologies programme

£4m | University Defence Research Collaboration

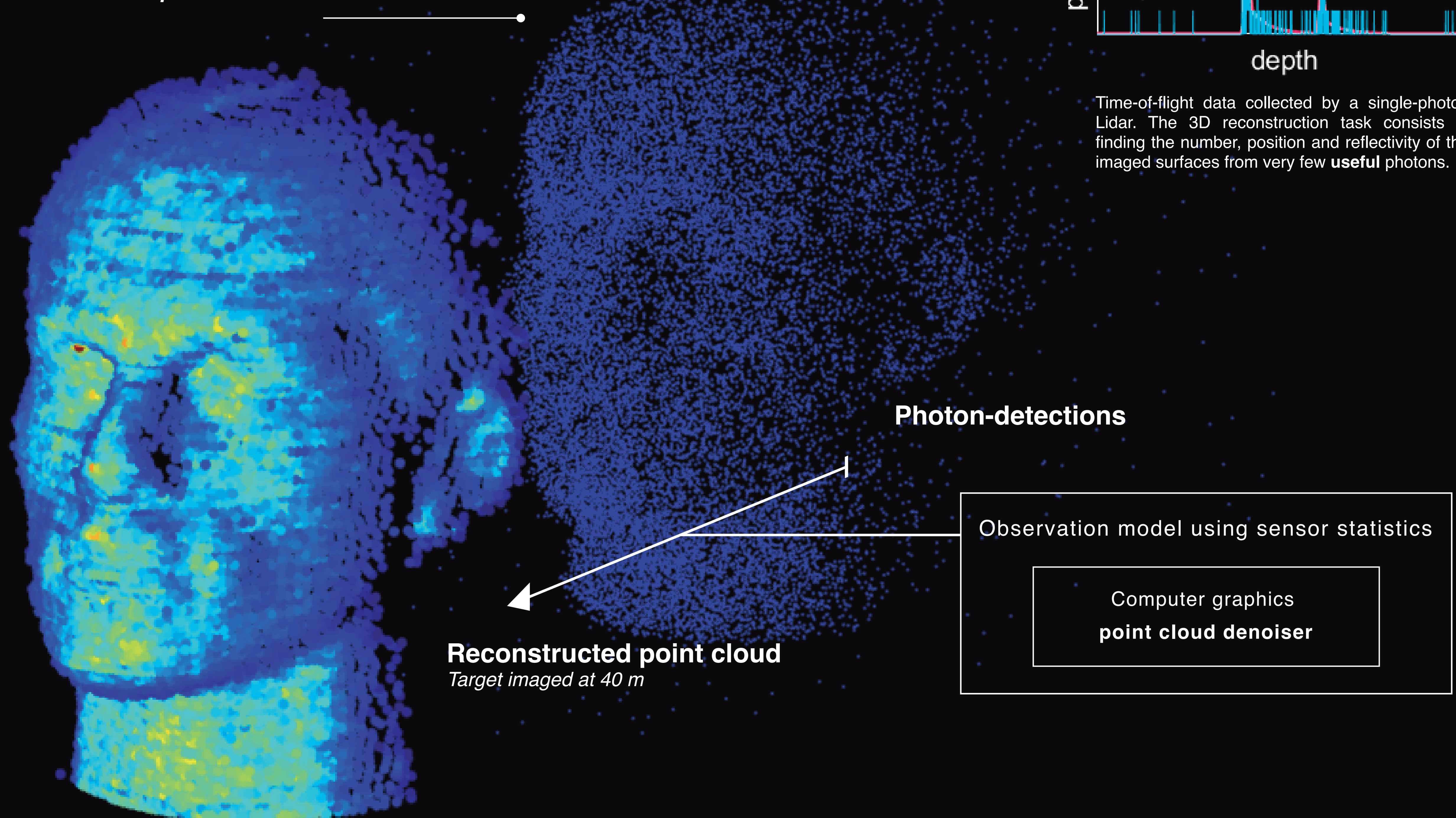
Why single-photon Lidar?

Single-photon light detection and ranging (Lidar) technology is **pushing the frontiers of 3D imaging**: the high sensitivity of single-photon detectors allows for the use of **low-power** laser sources and the **high precision** of such detectors offers an accuracy in the order of centimetres at **very long range** (hundreds of meters). However, **extracting the information** from the raw data poses **many challenges for the computational methods.**



Time-of-flight data collected by a single-photon Lidar. The 3D reconstruction task consists in finding the number, position and reflectivity of the imaged surfaces from very few **useful** photons.

4. Proposed framework

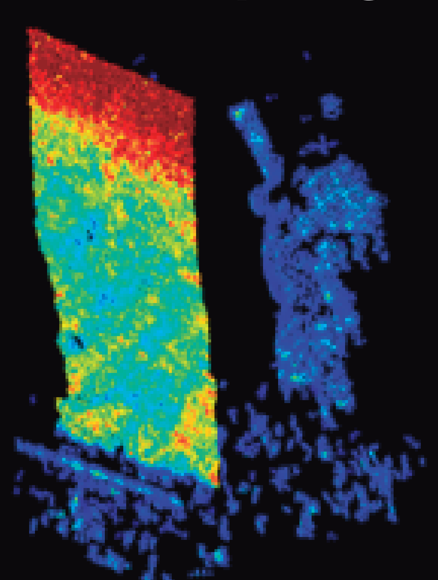


CHALLENGES

1. **Noisy data and complex 3D scenes**
   (few useful photons)
2. **Extreme environments**
   (underwater, kilometre-range)
3. **Confidence on the estimates**
   (can we trust the reconstructions?)
4. **Very large data volumes**
   (real-time processing for autonomous systems)

SOLUTIONS

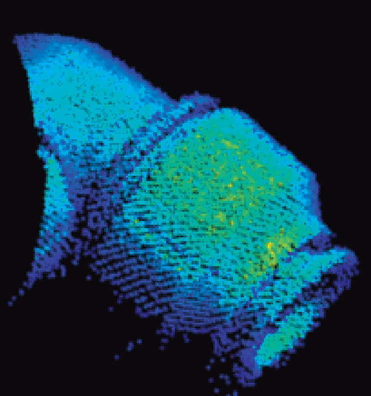
1. Adapting to real-world scenes



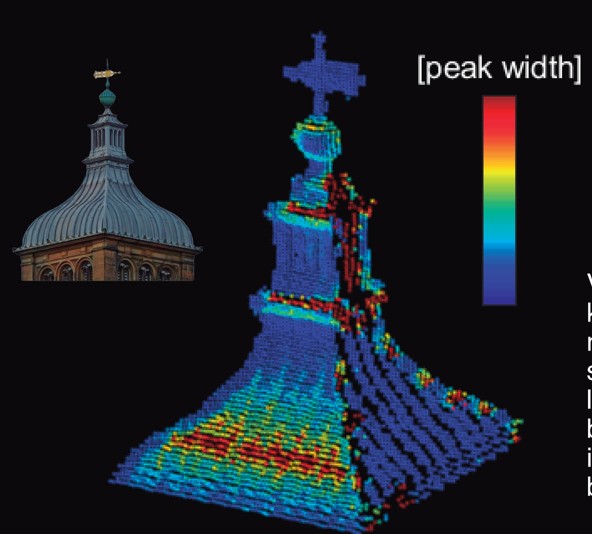
Most of the previous algorithms assume only one surface per pixel, which does not hold in most realistic scenes. Outdoor scenes generally present image patches without any surfaces. Moreover, scenes where the light goes through windows or camouflage (as shown on the left[3]) contain multiple surfaces per pixel. To address this problem, I proposed a spatial point process model that captures the structure of 2D surfaces without **making any strong assumptions**[1].

2. Taking into account physical effects

Lidar signals can present additional deviations from the classical observation model, such as broadening of the instrumental response or highly attenuating media (**underwater imaging and atmospheric turbulence**). To tackle these problems, I proposed **an algorithm that incorporates these effects** from a Bayesian modelling perspective[2].

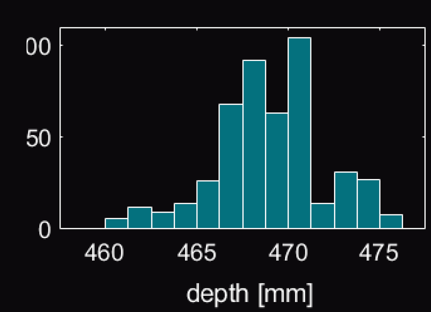


We achieve good reconstructions in highly-attenuating underwater environments (e.g., the pipe shown above)



Very long range scenes (e.g., 3 kilometres[6]) present a broadening of the instrumental response due to the divergence of the laser beam. In this case, the broadening is more pronounced in patches of large curvature and borders of the dome.

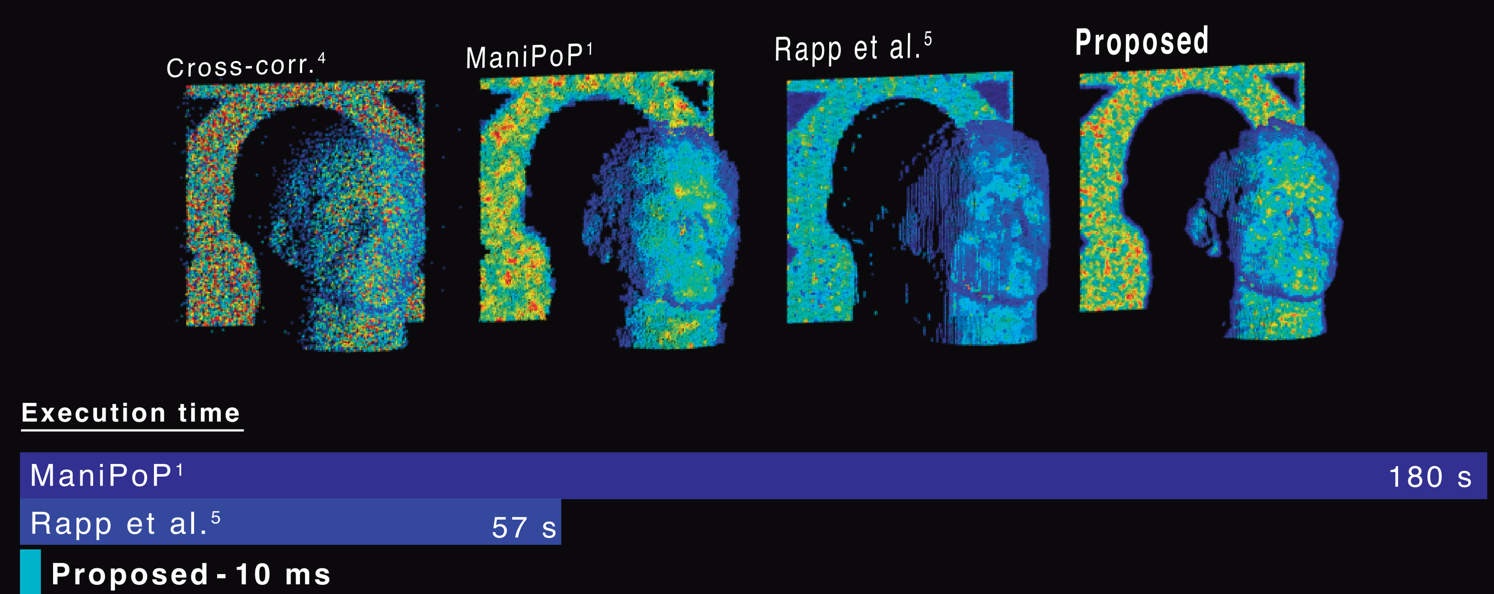
3. Quantifying uncertainty



Adopting a Bayesian framework and employing statistical simulation methods, we can provide **accurate reconstructions** from **very few photons** and provide **confidence intervals** for the estimates. For example, the depth distribution of a detected 3D point is shown on the left.

4. Towards real-world applications
REAL-TIME PROCESSING

While some **existing algorithms** can provide very good reconstructions, they all require computing times in the order of minutes, which **are still prohibitively long** for any real-time processing, e.g., **self-driving cars**. To address this issue, I combined 3D modelling and parallel processing techniques from the **computer graphics community** with the large body of research on inverse problems and high-dimensional optimization in the **image processing literature**, yielding new real-time reconstruction algorithms that outperform those based solely on computer graphics or image processing techniques.



References:

[1]Tachella et al. *SIAM* (2019)
[2]Tachella et al. *ICASSP* (2019)
[3]Halimi et al. *EUSIPCO* (2017)
[4]McCarthy et al. *Optics express* (2013)
[5]Rapp et al. *Trans. on Comp. Imag.* (2017)
[6]Pawlikowska et al. *Optics express* (2017)

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QUANTIC

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