Stress Testing of Spiking Neural Network-based TDC-less dToF

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Applications of dToF

Drones

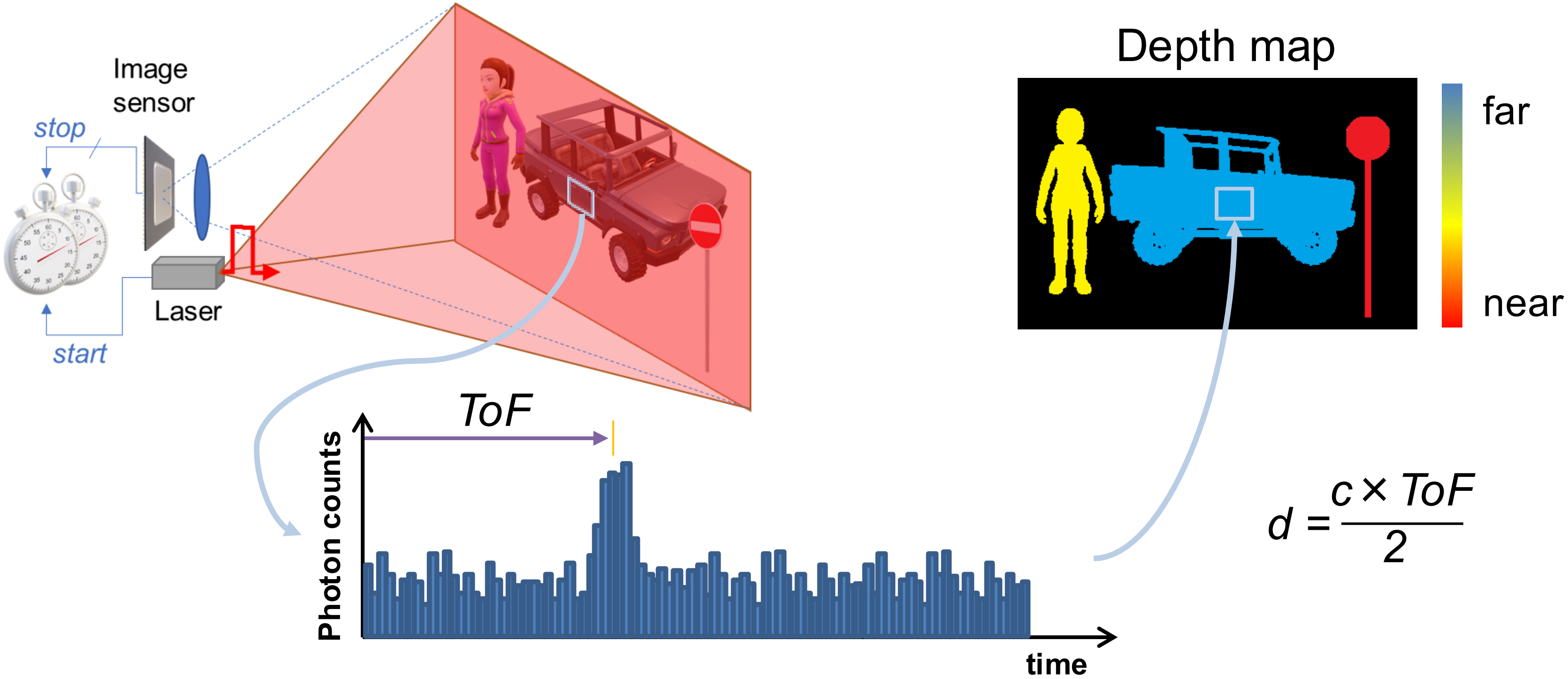
Automotive

Touchless UI

Robots

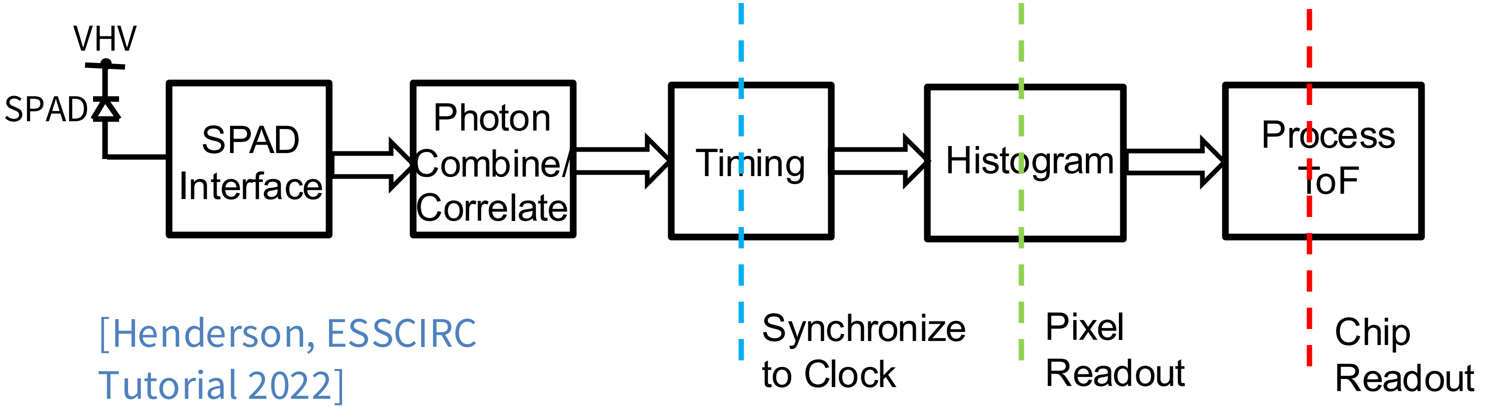
Smartphone

Solid-state dToF with SPAD



$$d = \frac{c \times ToF}{2}$$

Conventional processing pipeline



[Henderson, ESSCIRC Tutorial 2022]

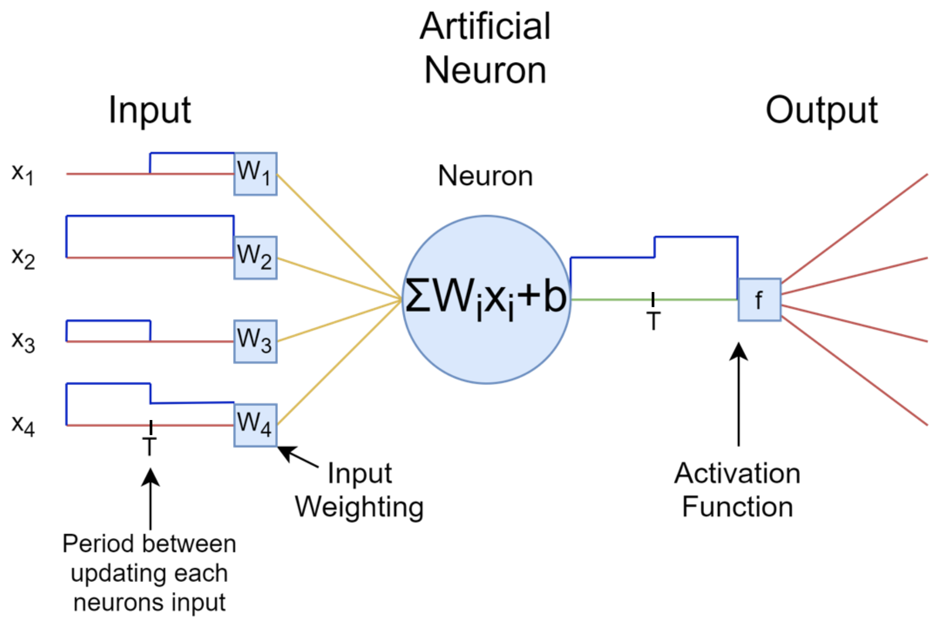
- Conventional histogramming: high speed clock and significant memory resource → impact on power consumption, latency and scalability
- Adaptive histogramming: reduced memory (can be integrated into pixel) but higher transmitter power, susceptibility to motion artefacts [Taneski, IEEE JLT 2022]

Alternative dToF processing schemes

- Spline-based sketches [Sheehan, IEEE TCI 2024]
- Count-free histograms [Ingle, IEEE TPA 2023]
- Histogram-free processing (averaging) of photon time stamps [Tontini, IEEE Sensors 2024]
- Neural network-based processing [e.g. Milanese, IISW 2023]

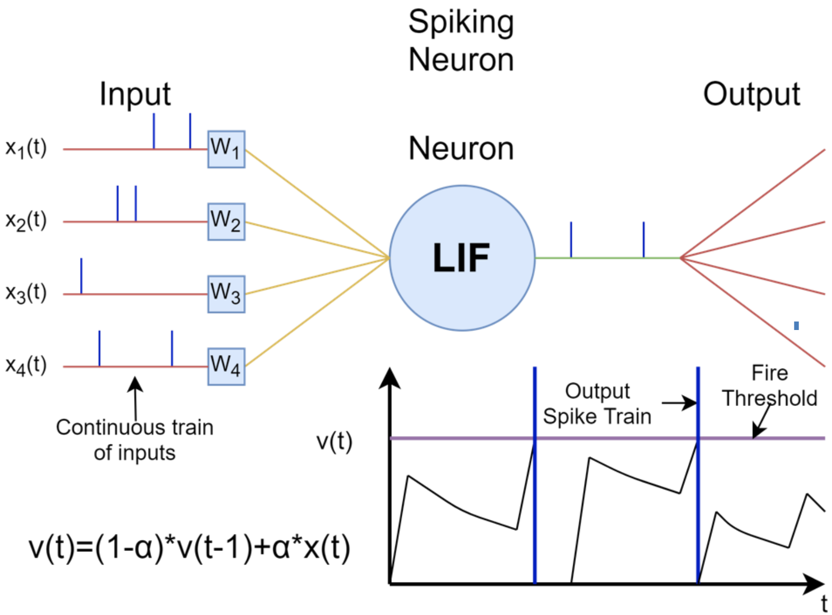
Can we develop a neural-network approach that is TDC-less?

Traditional artificial neurons



- Clock driven
- Processes layer by layer
- Represents data as scalars
- Typically applies activation function to the output of the summation

Spiking neurons

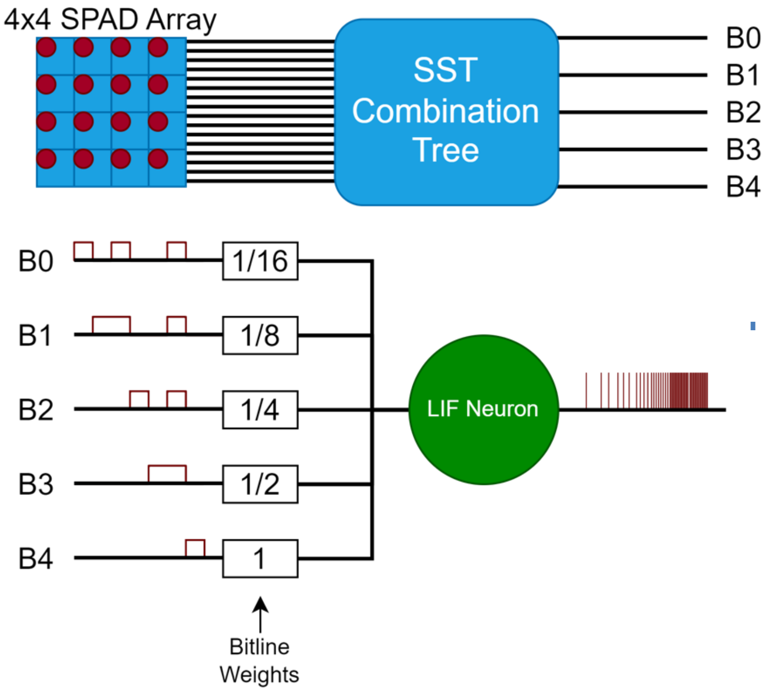


- Asynchronous (though can be clock driven)
- Processes information as the spikes propagate through the network
- Information represented as binary discrete spikes
- Activation function inherent in the neuron dynamics

SNN vs ANN comparison

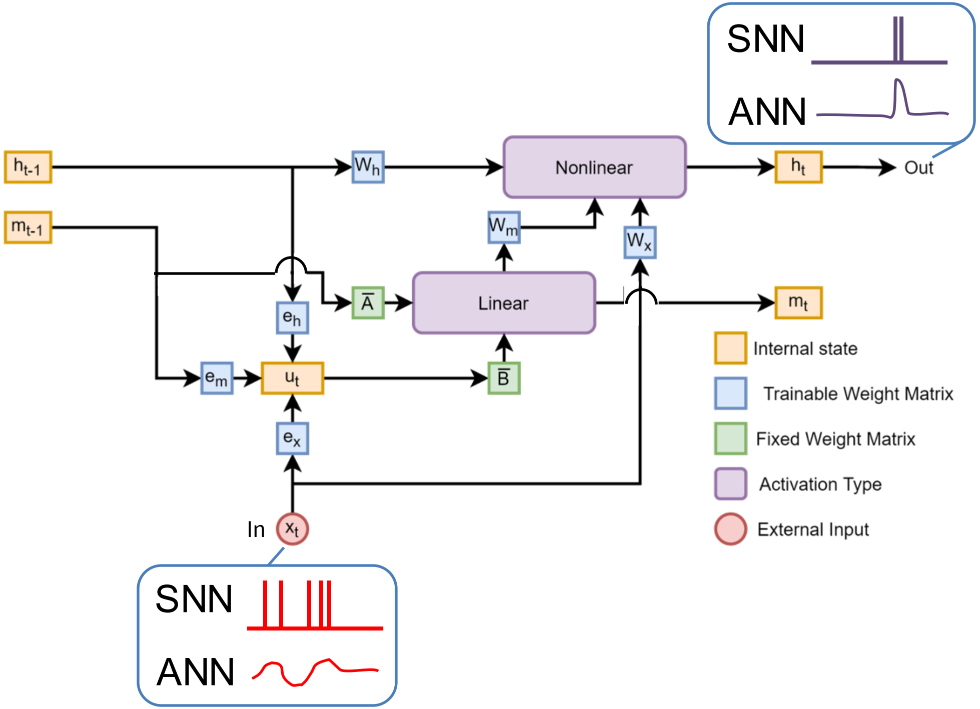
Potential advantages	Disadvantages
Fast and parallel information processing	Difficult to train
Well suited to processing event/spatiotemporal data	Incompatible with conventional hardware platforms
Low energy consumption	
Data sparsity	

SPAD events into spikes



- SPAD Events get combined via adder (e.g. [Patanwala, OJSSCS 2022]).
- Each bit line is weighted to increase the membrane potential of the LIF neuron proportional to the value it represents.

Legendre Memory Unit (LMU) Model

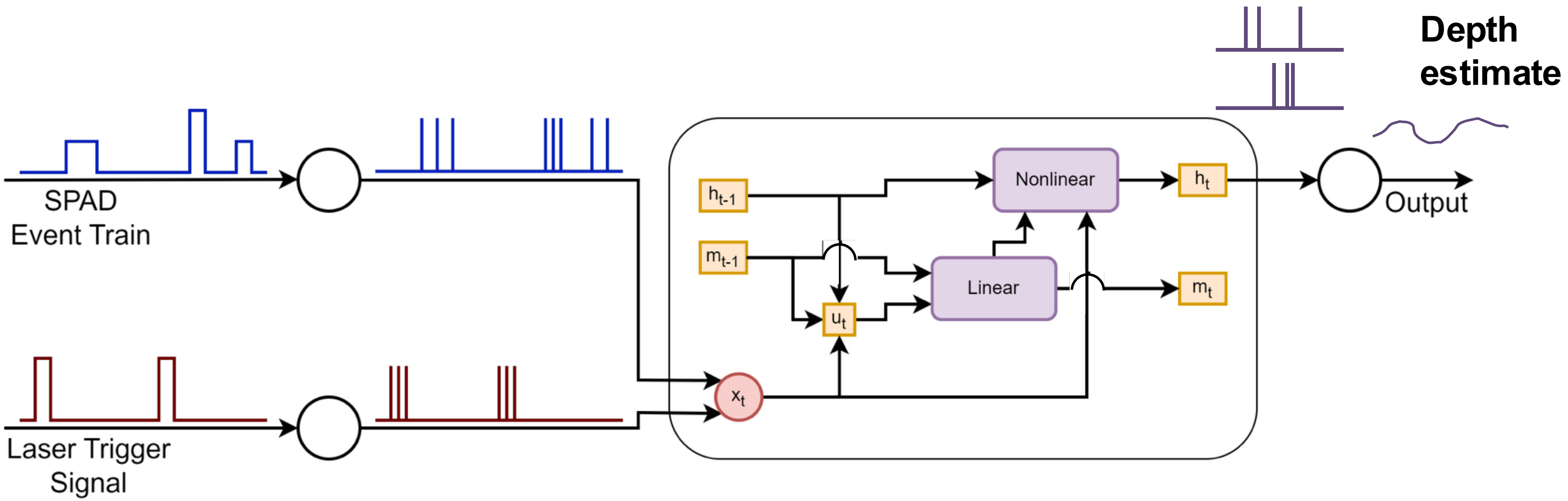


LMU:

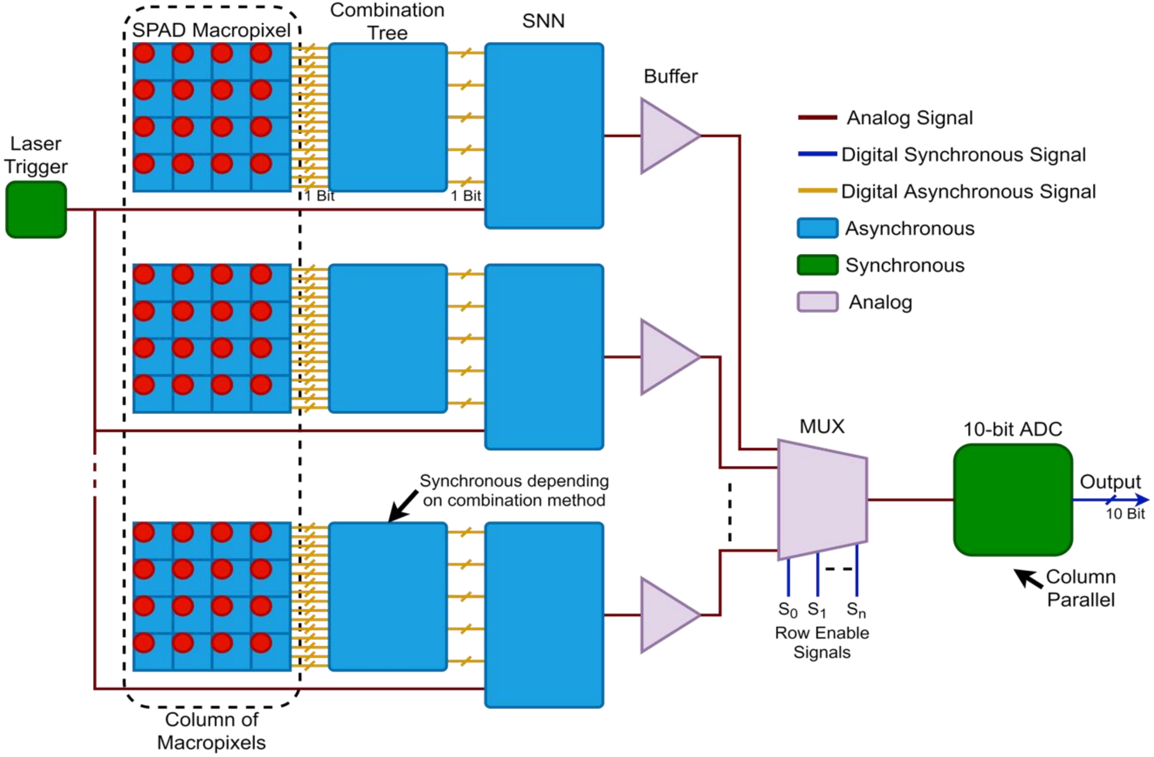
- Designed to operate for continuous time operations. i.e. $\Delta t \to 0$ and $T \to \infty$
- Requires fewer parameters than other recurrent architectures
- Governing Equations:

$$U_t = e_x^T X_t + e_h^T H_{t-1} + e_m^T M_{t-1}$$
$$M_t = \bar{A} M_{t-1} + \bar{B} U_t$$
$$H_t = f(W_x X_t + W_h H_{t-1} + W_m M_t)$$

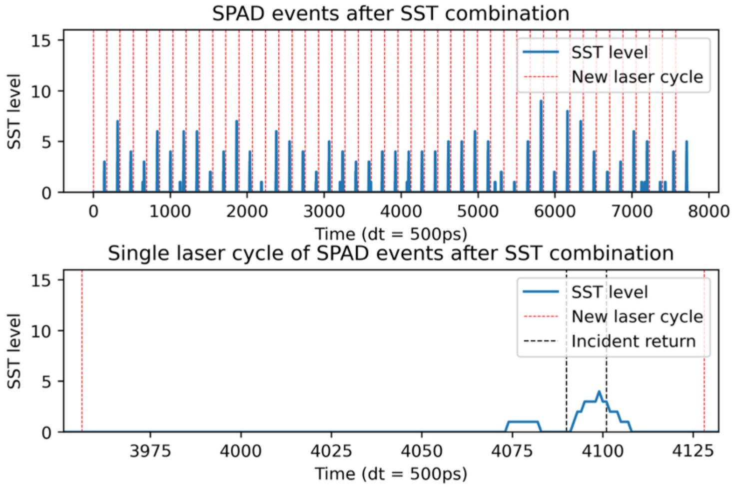
Overall single (macro)pixel network



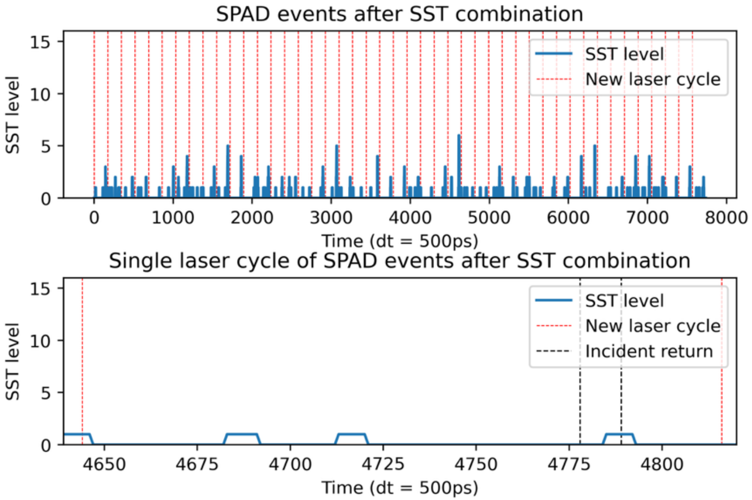
Proposed image sensor architecture



Synthetic training data



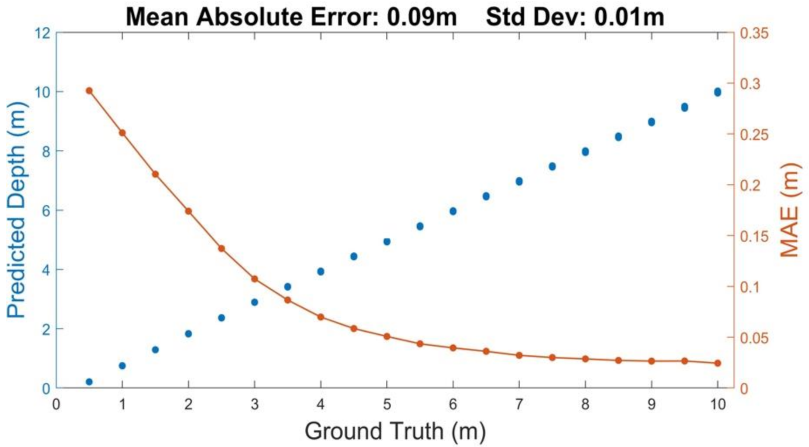
Dist. = 10 m, Reflectivity = 70%, Ambient = 1 klux



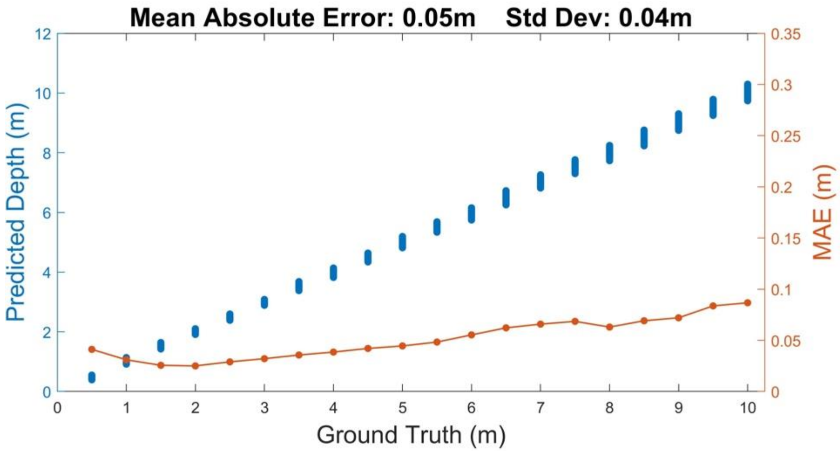
Dist. = 10 m, Reflectivity = 40%, Ambient = 25 klux

Test results on synthetic data

Histogram centre-of-mass



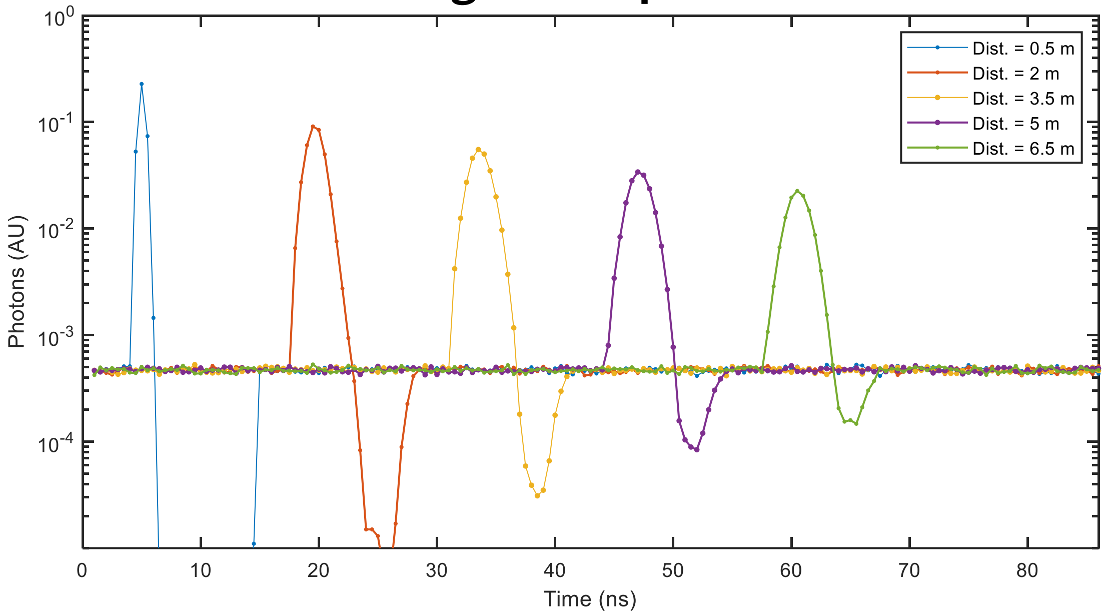
SNN



Reflectivity = 25%, Ambient = 1 klux

Test results on synthetic data – pile-up effects

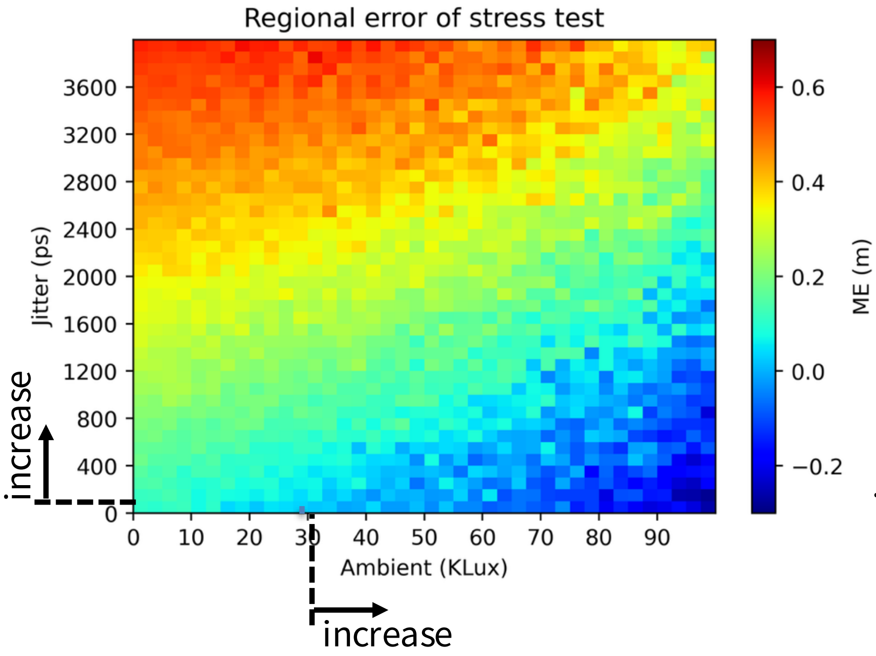
Histogram of photons

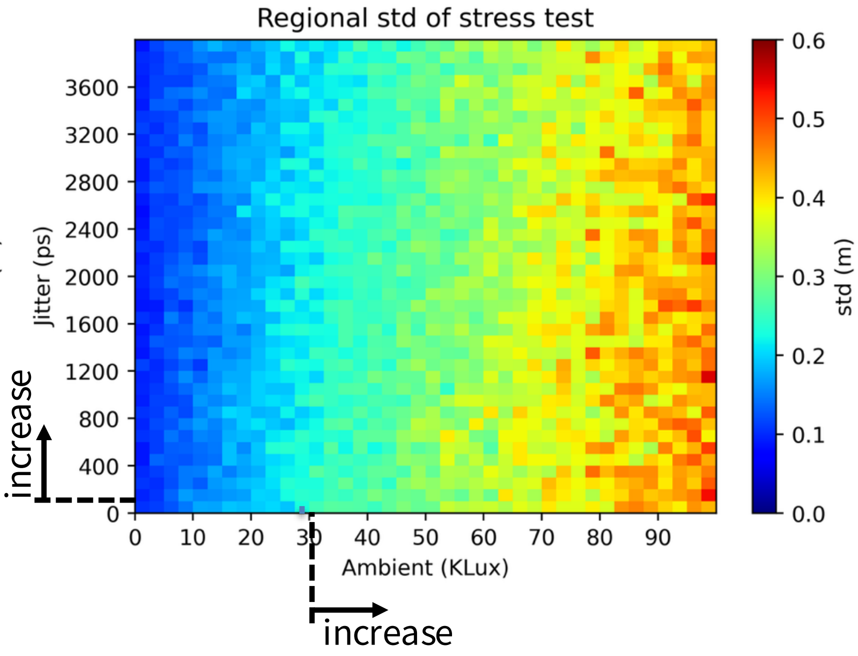


Reflectivity = 70%, Ambient = 25 klux

- Network is learning to recognise SPAD pile-up effects (compression of peak, inhibition of background counts)
- It is correcting for the resulting time skew

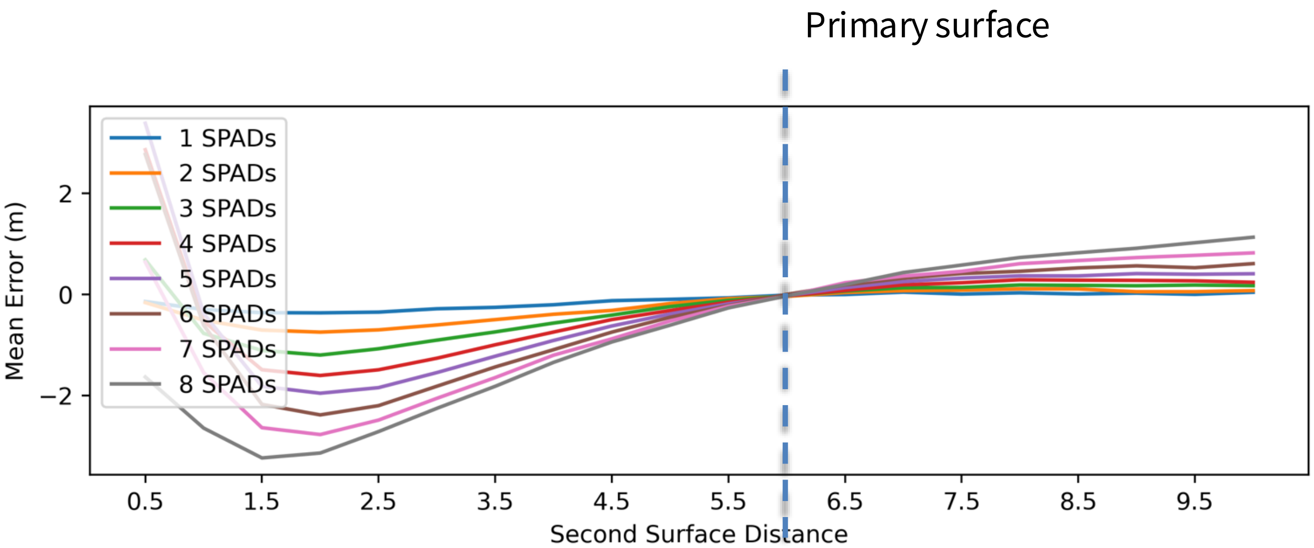
Test results on synthetic data – stress testing





Reflectivity = 40%, Target distance = 10 m

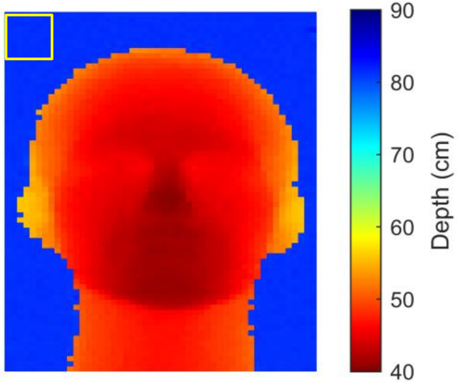
Test results on synthetic data - multipeak



Reflectivity = 40%, Ambient = 25 klux

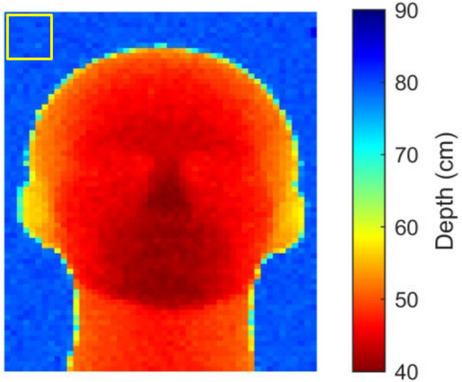
Results on real data

Histogram centre-of-mass



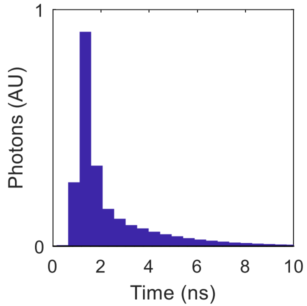
std = 0.15 cm

SNN



std = 0.59 cm

IRF



Mannequin imaged outdoors (data from [Altmann, IEEE TIP 2016])

Power and area estimates

- ~15k neural, ~916k synaptic spikes/exposure
- Analogue circuit implementation of artificial neurons/synapses exist with energy/spike in the fJ range → (SNN only) power consumption in the nW range @30FPS
- Model size: 610 neurons and 3506 synapses
- Compact (<0.1um^2) LIF neurons have been proposed in advanced technology nodes (7nm FinFET) with high (1GHz) firing rates
- In the future the model may fit under a 40×40um SPAD macropixel.

Conclusions

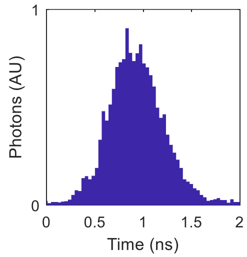
- SNN processing of SPAD dToF data was demonstrated
- Low latency (depth estimate is available at the end of exposure time)
- Low precision but good accuracy compared with conventional processing, and reasonable robustness to conditions beyond the training dataset
- Potential for low power implementation. May suit applications such as a low power object detection for robots or drones.

Acknowledgements

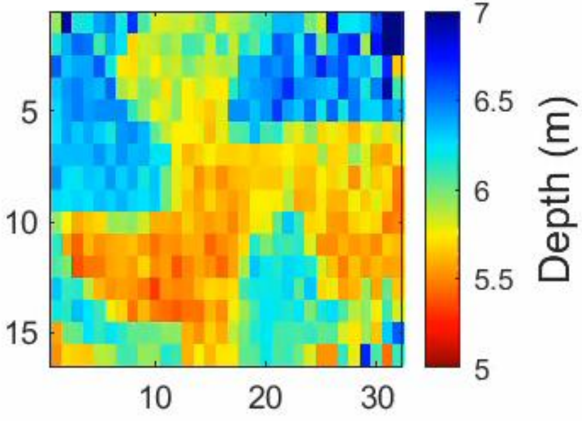
SRPe
Scottish Research Partnership
in Engineering

Results on real data (cont.)

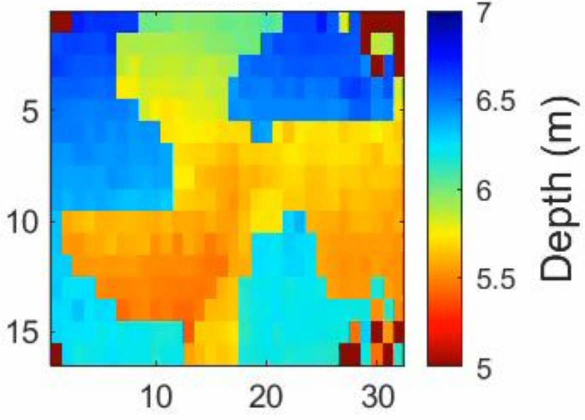
IRF



SNN



Histogram centre-of-mass



SBR ≈ 2