Asynchronous Spatial Image Convolutions for Event Cameras

Cedric Scheerlinck, Nick Barnes, Robert Mahony

C. Scheerlinck, N. Barnes, R. Mahony, “Asynchronous Spatial Image Convolutions for Event Cameras”, IEEE Robotics and Automation Letters (RAL), 2019.

Image Convolutions

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\frac{1}{16}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & -8 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

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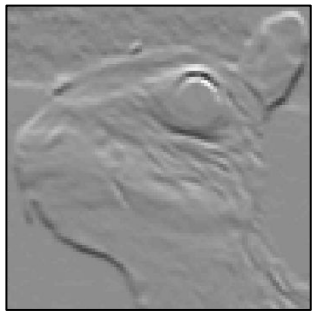

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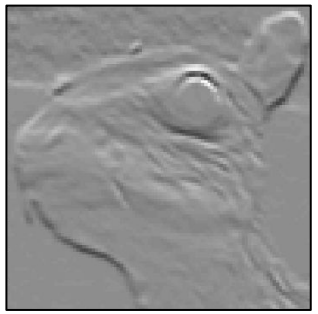

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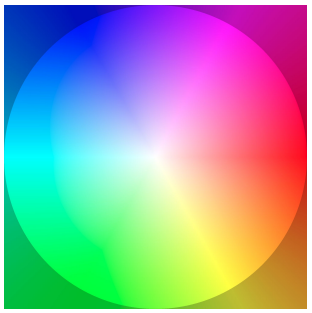

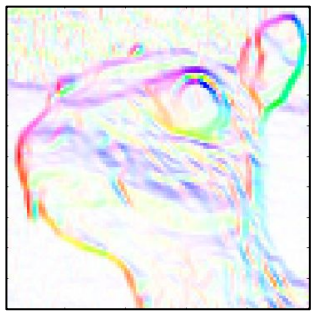

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Image Convolutions for Events

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * \quad = \quad$$

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Image Convolutions for Events

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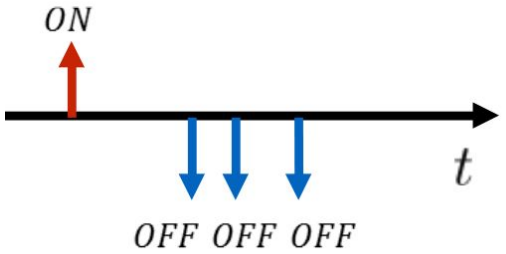

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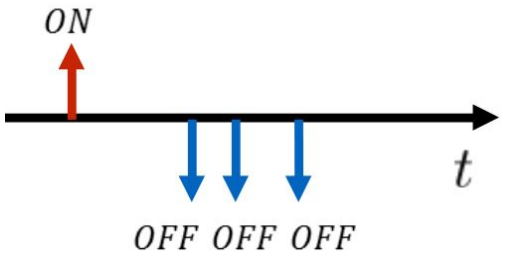

?

Naïve approach: reconstruct image frames from events then apply convolution.

Can we do better?

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Image Convolutions for Events

Consider one event 

[timestamp, x, y, ±1]

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Image Convolutions for Events

Consider one event  [timestamp, x, y, ±1]

Event image

0	0	0	0	0	0
0	0	0	0	0	0
0	0	-1	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0

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Image Convolutions for Events

Consider one event  [timestamp, x, y, ±1]

Kernel

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} *$$

Event image

0	0	0	0	0	0
0	0	0	0	0	0
0	0	-1	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0

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Image Convolutions for Events

Consider one event  [timestamp, x, y, ±1]

Kernel * Event image

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} *$$

0	0	0	0	0	0
0	0	0	0	0	0
0	0	-1	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0

=

0	0	0	0	0	0
0	1	0	-1	0	0
0	2	0	-2	0	0
0	1	0	-1	0	0
0	0	0	0	0	0
0	0	0	0	0	0

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Image Convolutions for Events

Kernel $*$ Event image

0	0	0	0	0	0
0	1	0	-1	0	0
0	2	0	-2	0	0
0	1	0	-1	0	0
0	0	0	0	0	0
0	0	0	0	0	0

Six virtual events, or a **convolved event**, can be generated

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Image Convolutions for Events

Convolved events can be used as input to an event processing algorithm.

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Image Convolutions for Events

Convolved events can be used as input to an event processing algorithm.

For example image reconstruction:

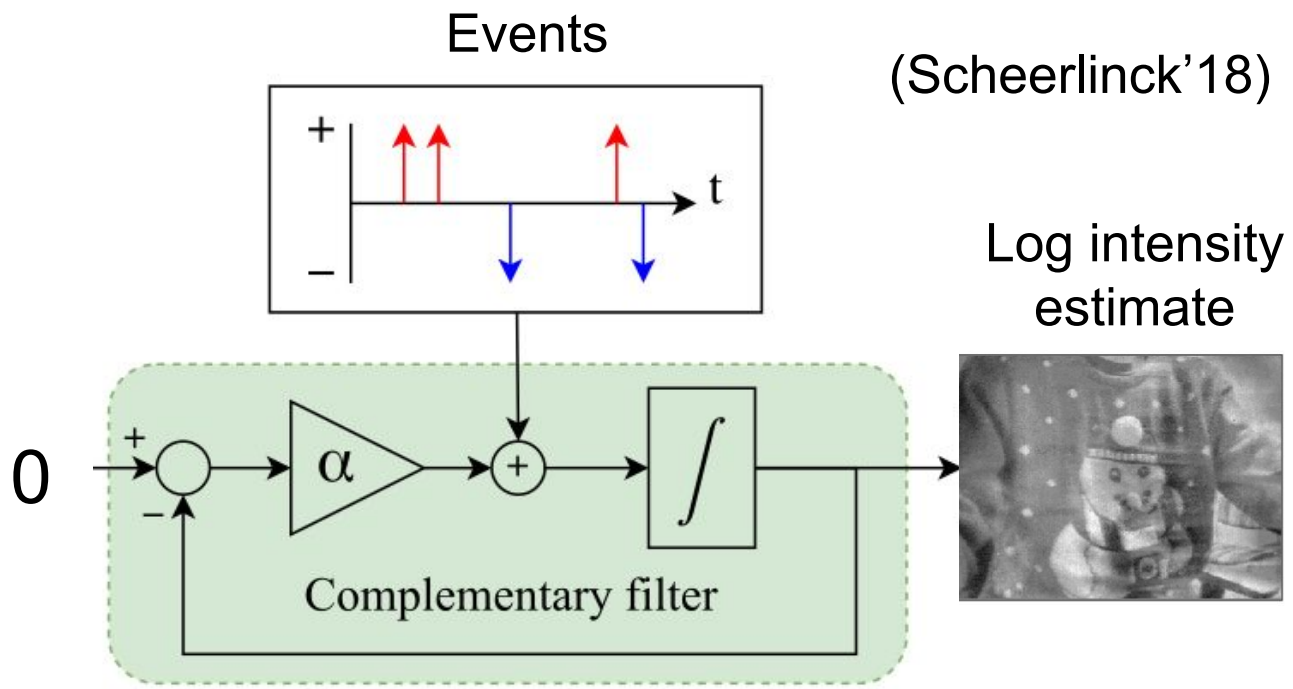

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Image Convolutions for Events

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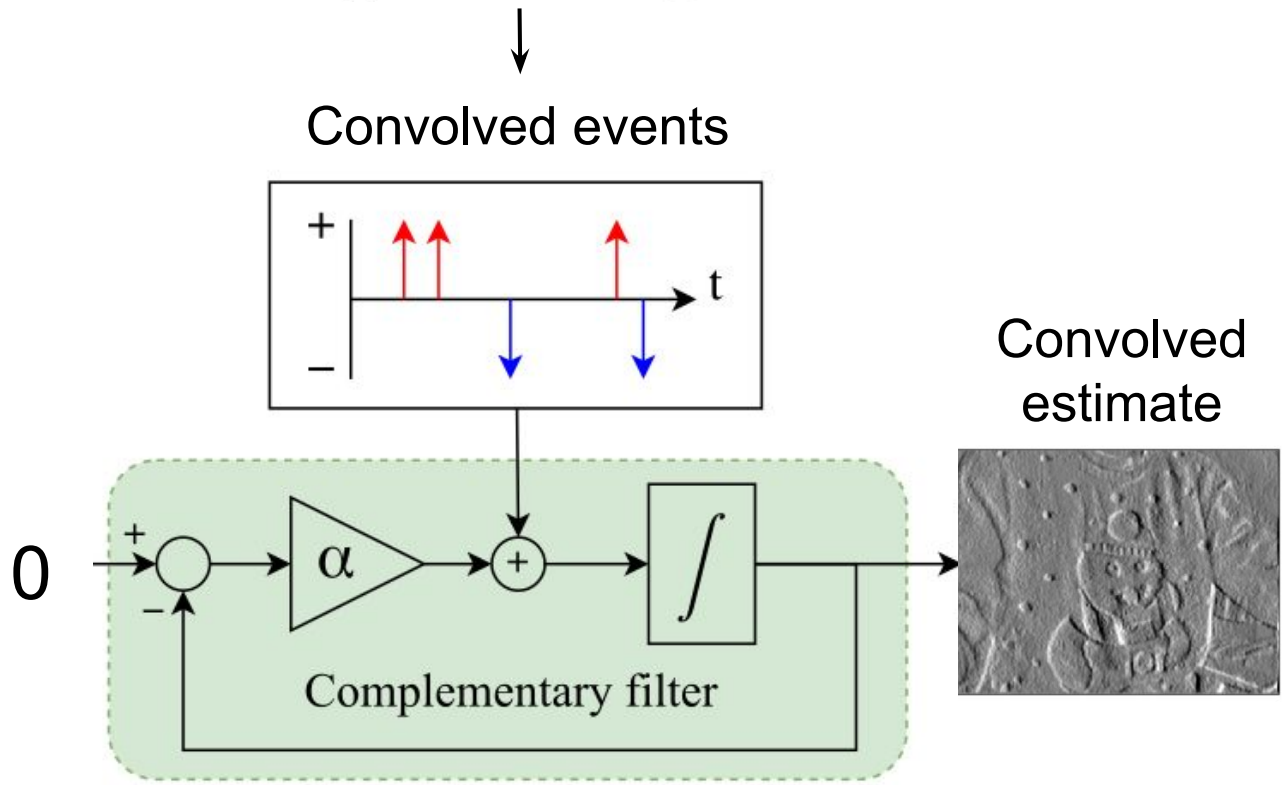

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Results

Identity

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Gaussian

$$\frac{1}{16}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

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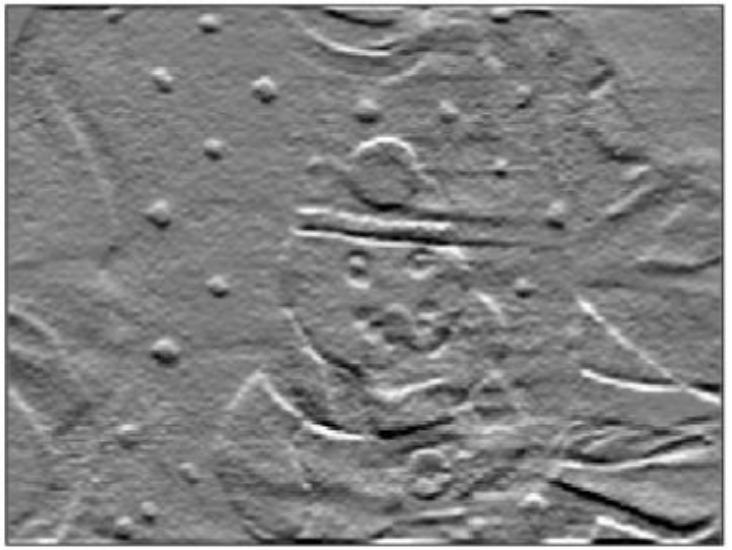
Results

Sobel

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$



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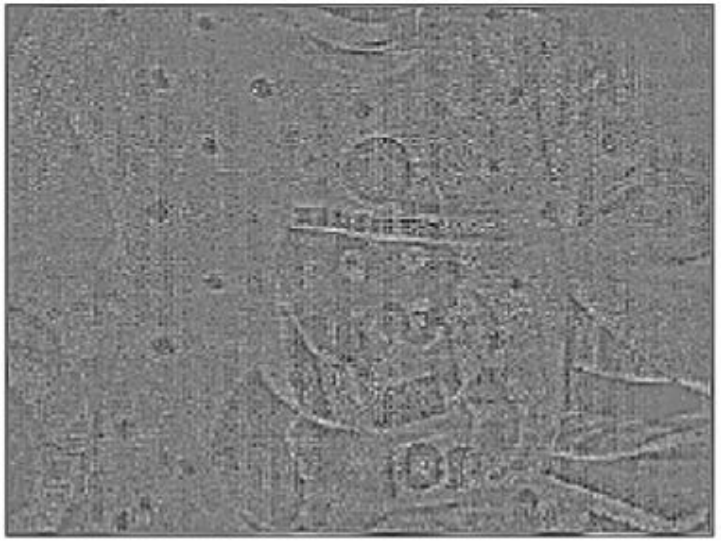
Results

Laplacian

$$\begin{bmatrix} 1 & 2 & 1 \\ 2 & -12 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$



Poisson Reconstruction from Laplacian

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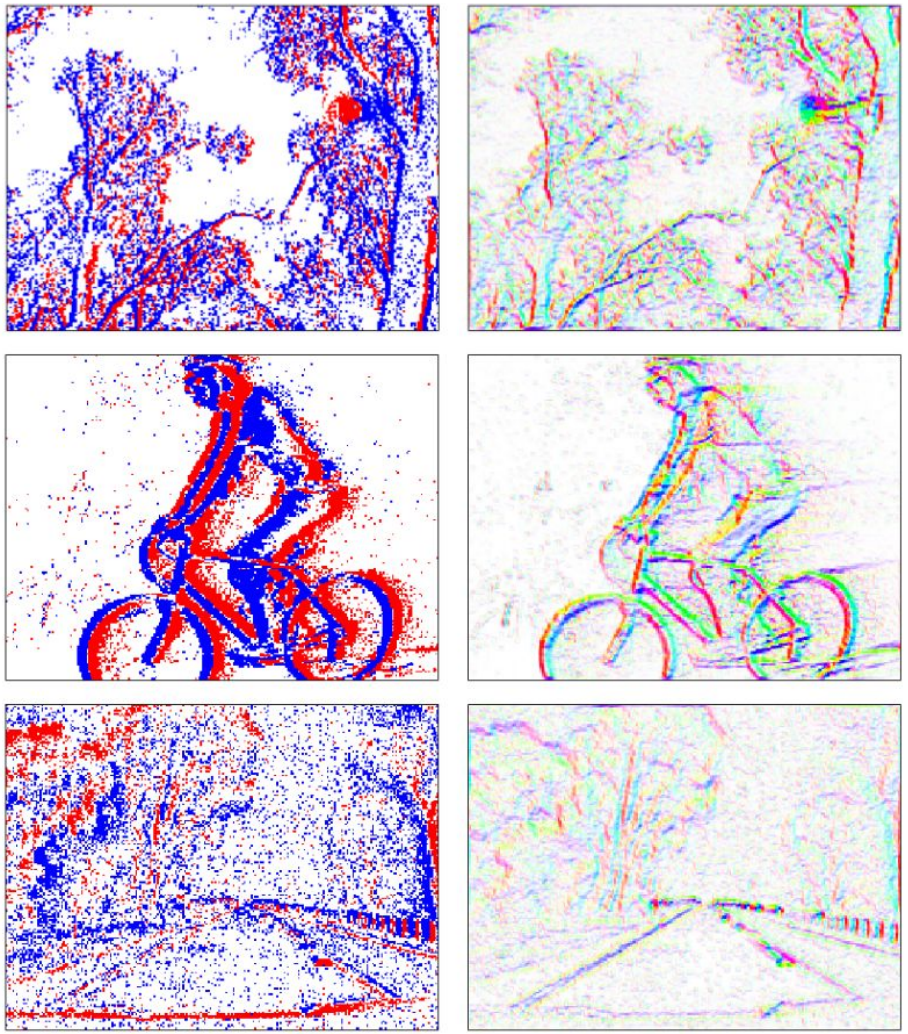
Results

Current events | Gradient estimate



Sobel

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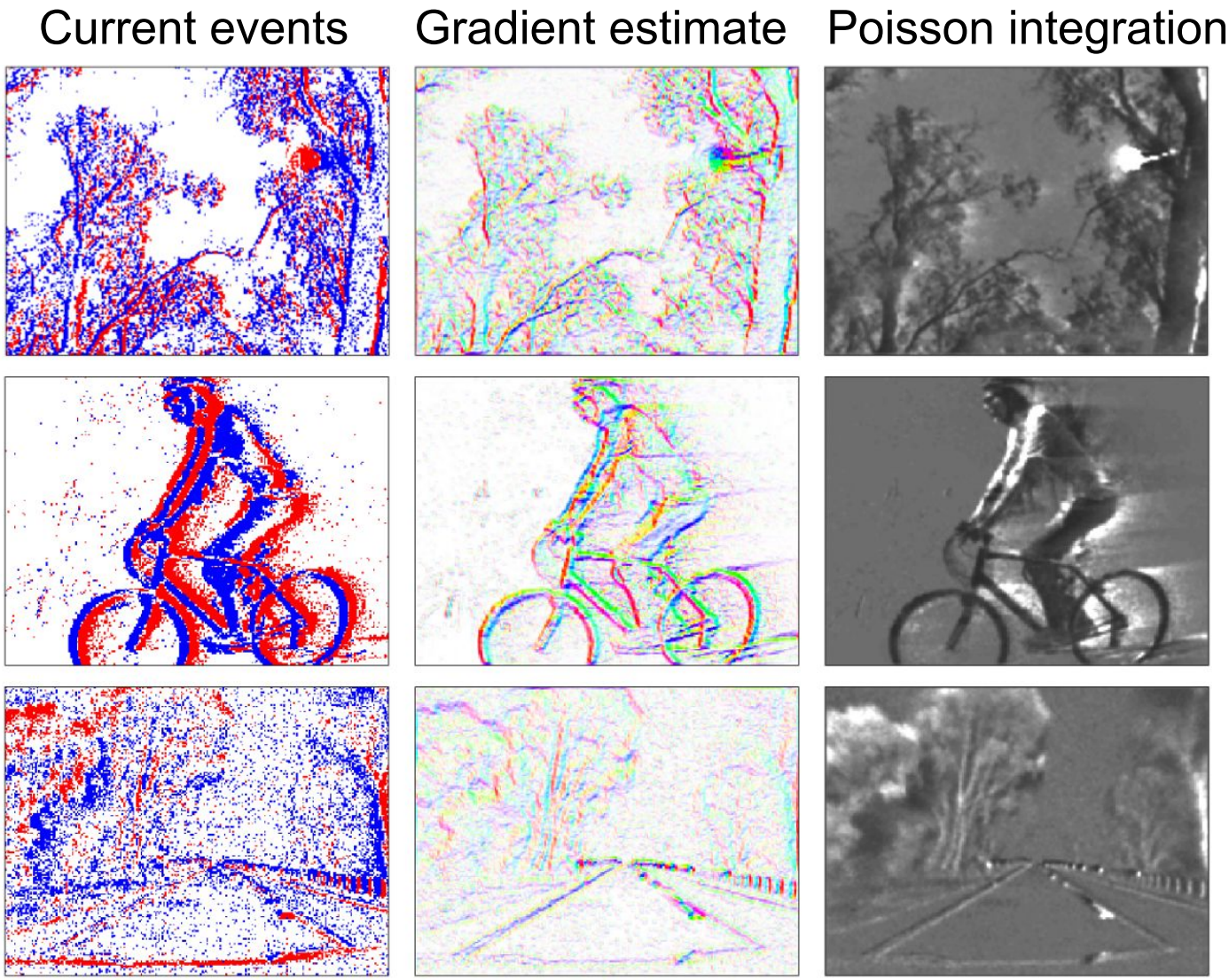

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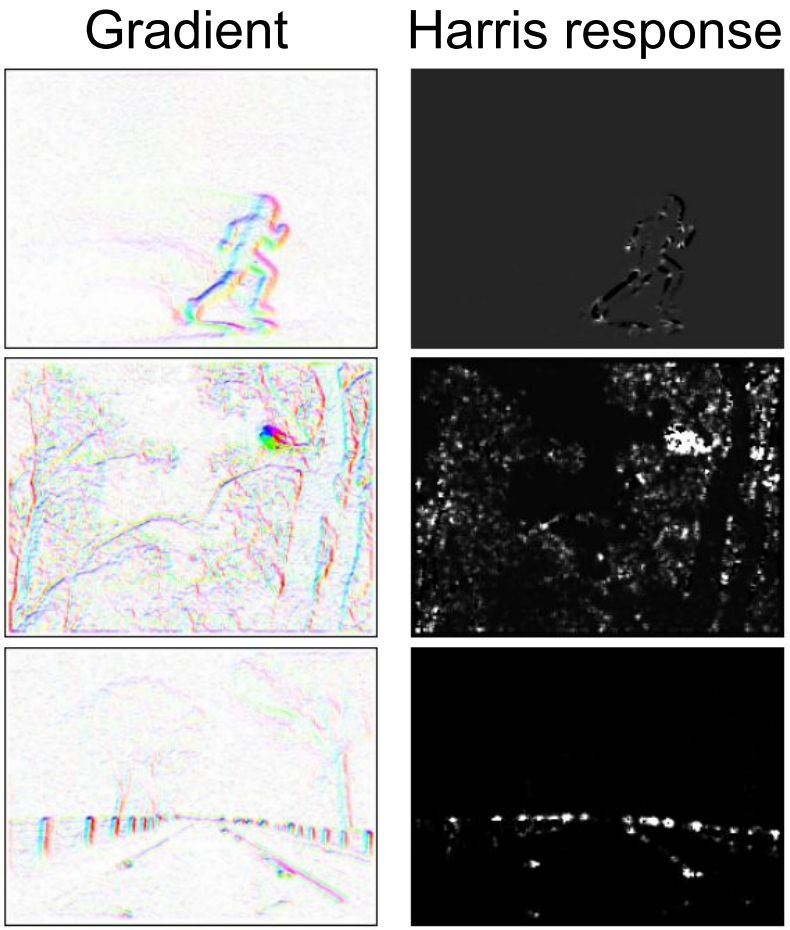
Results

Gradient can be used as input to asynchronous Harris corner detector.



When an event arrives, the Harris response is only updated in a local neighbourhood.

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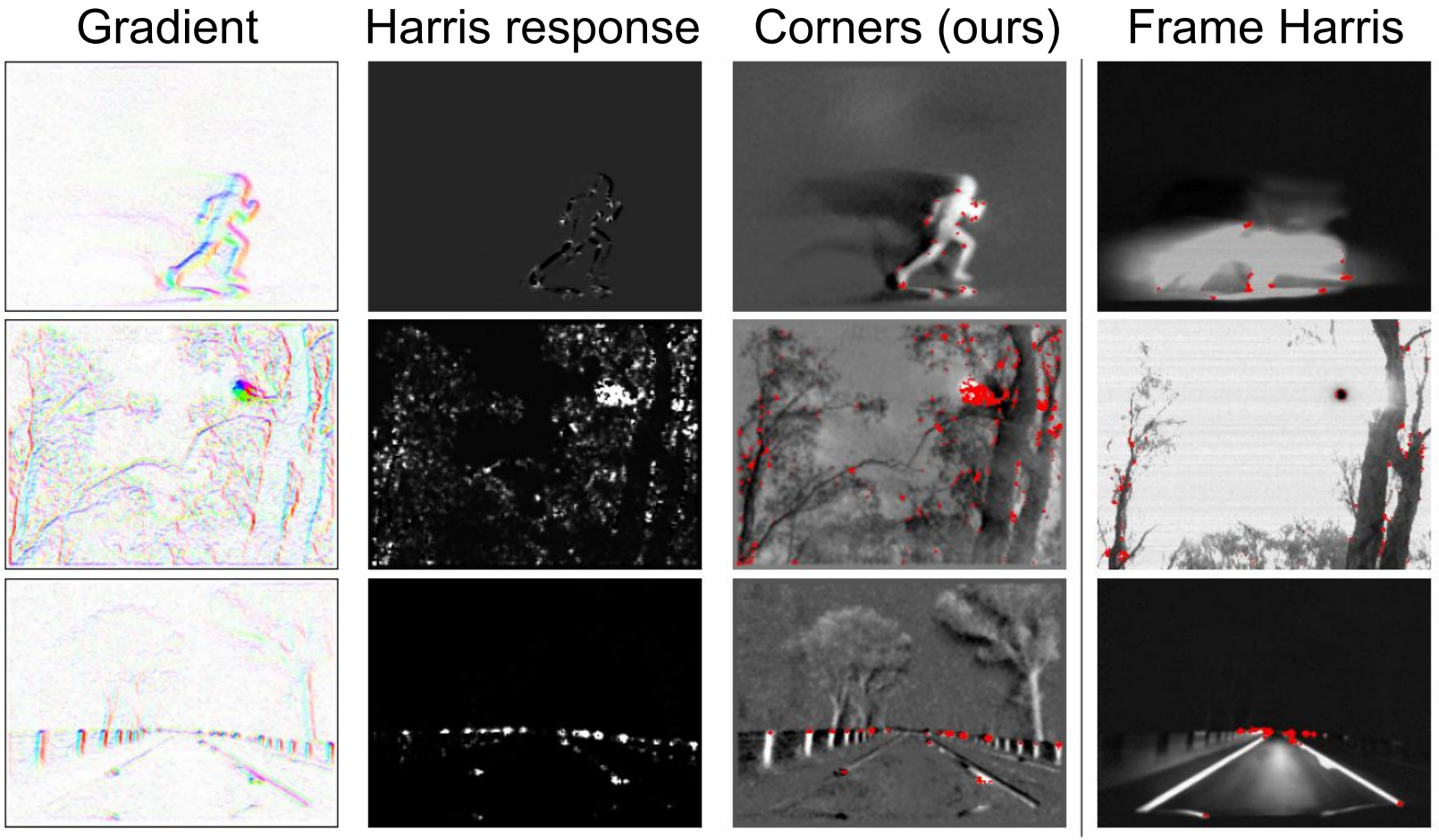

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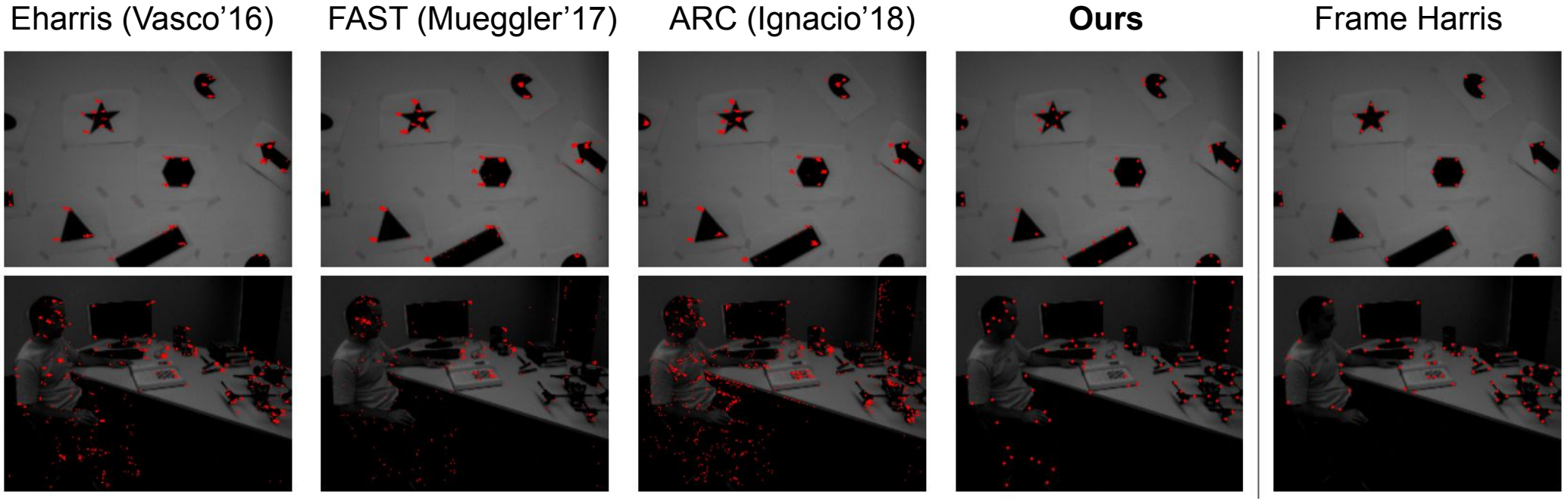
Results

Comparison to state-of-the-art event-based corner detection.



Local non-maximum suppression can be applied to our continuous-time Harris response state to get clean corners.

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Conclusion

- We have introduced a methodology for event-based convolutions.
- Each event is individually convolved, producing a cluster of convolved events.
- Convolved events are fed into an asynchronous image reconstruction algorithm to produce a continuous-time state estimate of the convolved image.
- We introduce an asynchronous Harris corner detector based on gradients produced by our method.

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