

Asynchronous Spatial Image Convolutions for Event Cameras

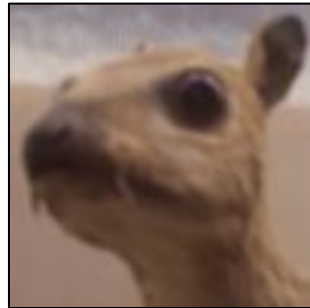
Cedric Scheerlinck, Nick Barnes, Robert Mahony

Image Convolutions

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



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



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



Image Convolutions

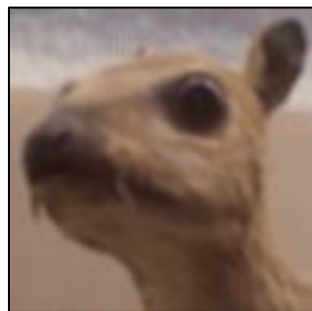
$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



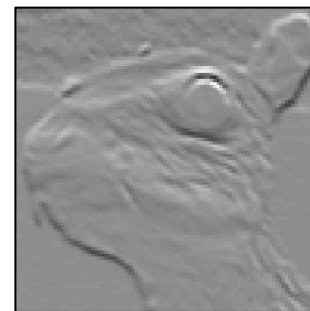
$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$



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



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



Image Convolutions

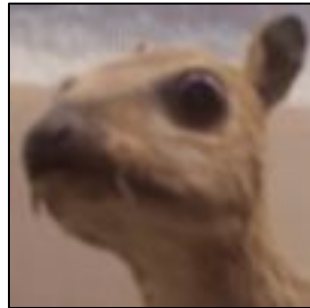
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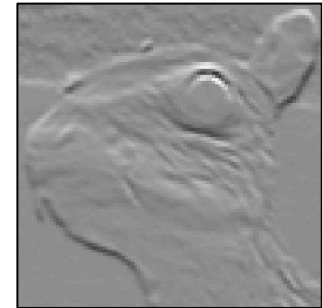
$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$



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



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



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

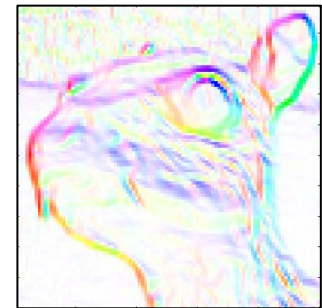
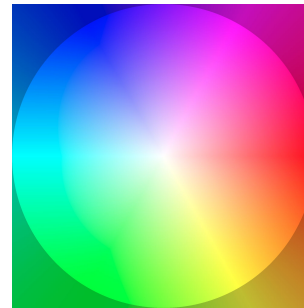


Image Convolutions for Events

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * \text{Image} = \text{Result}$$
The diagram illustrates a 2D convolution operation. On the left, a 3x3 kernel matrix is shown: $\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$. This is followed by an asterisk (*) and a color image of a squirrel's head. An equals sign (=) follows, leading to a grayscale image of the same squirrel's head. The grayscale image shows the edges of the squirrel's features, such as its eye, ear, and whiskers, in a light gray tone against a darker background, demonstrating the effect of the edge-detection kernel.

Image Convolutions for Events

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * \text{Image of a dog's head} = \text{Edge-detected image of the dog's head}$$

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * \begin{array}{c} \text{ON} \\ \uparrow \\ \text{---} t \\ \downarrow \downarrow \downarrow \\ \text{OFF OFF OFF} \end{array} = ?$$

Image Convolutions for Events

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * \text{Image of a dog's head} = \text{Edge-detected image of the dog's head}$$

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * \text{Event timeline diagram} = ?$$

The event timeline diagram shows a horizontal axis labeled t . A red arrow labeled *ON* points upwards from the axis. Three blue arrows labeled *OFF* point downwards from the axis.

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

Can we do better?

Image Convolutions for Events

Consider one event



[timestamp, x, y, ± 1]

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

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

Kernel

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

Image Convolutions for Events

Consider one event



[timestamp, x, y, ±1]

Kernel * 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

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

=

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

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

Image Convolutions for Events

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

Image Convolutions for Events

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

For example image reconstruction:

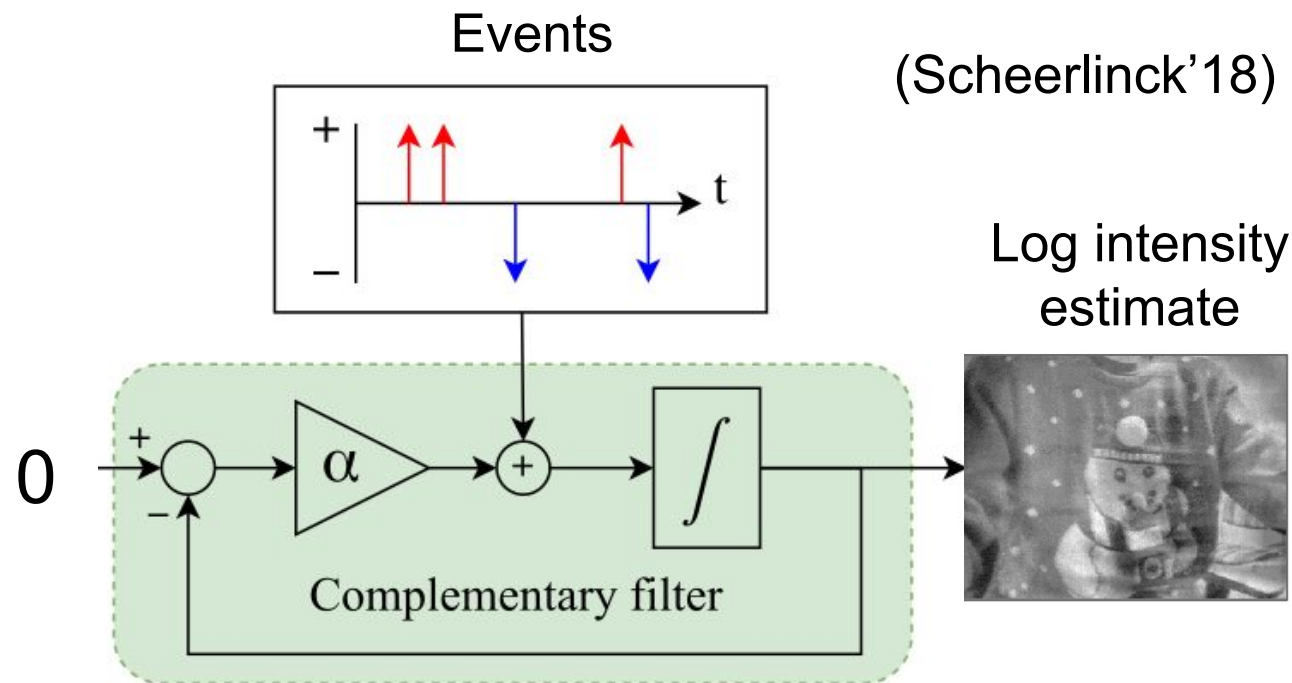
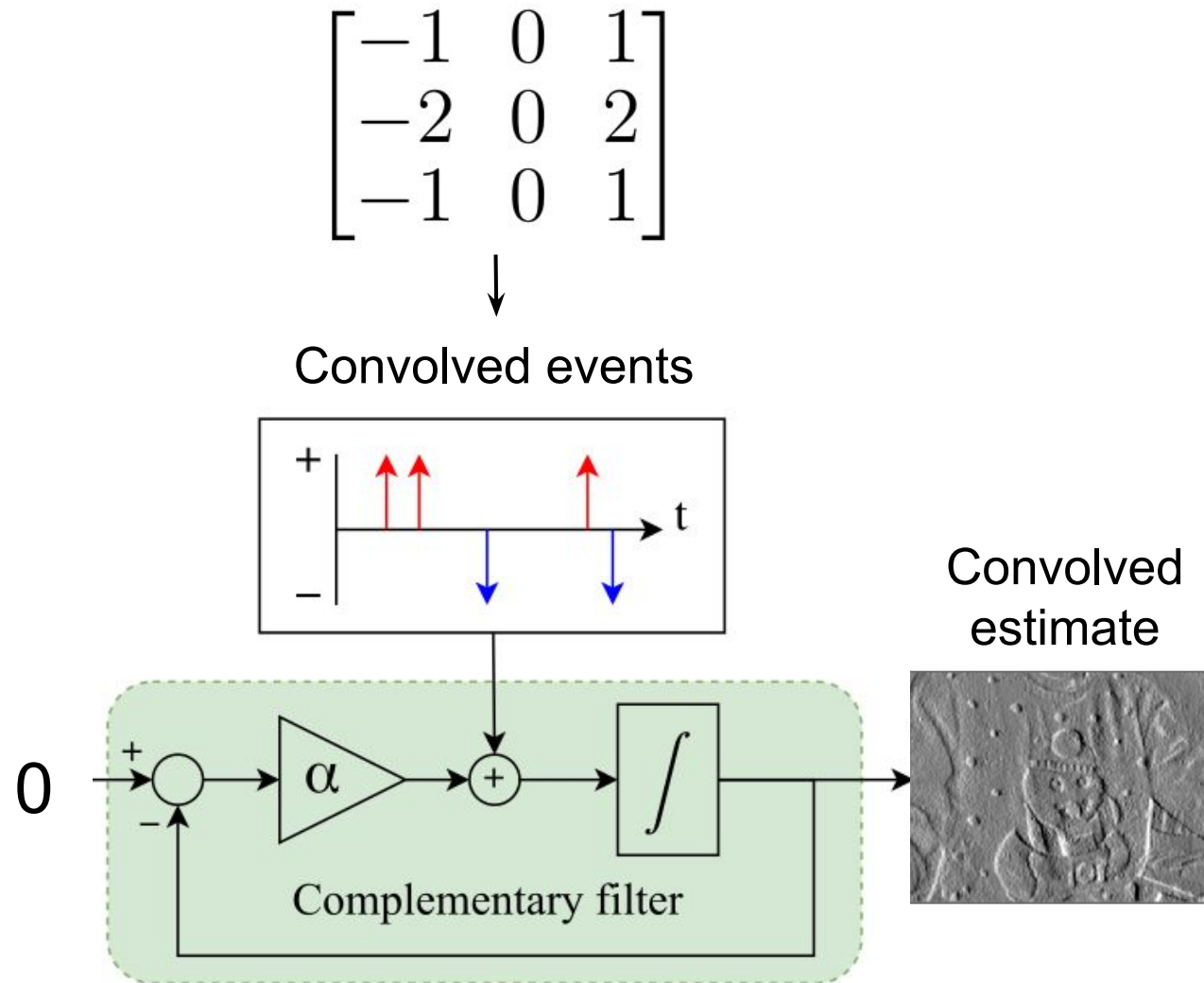


Image Convolutions for Events



Results

Identity

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



Gaussian

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



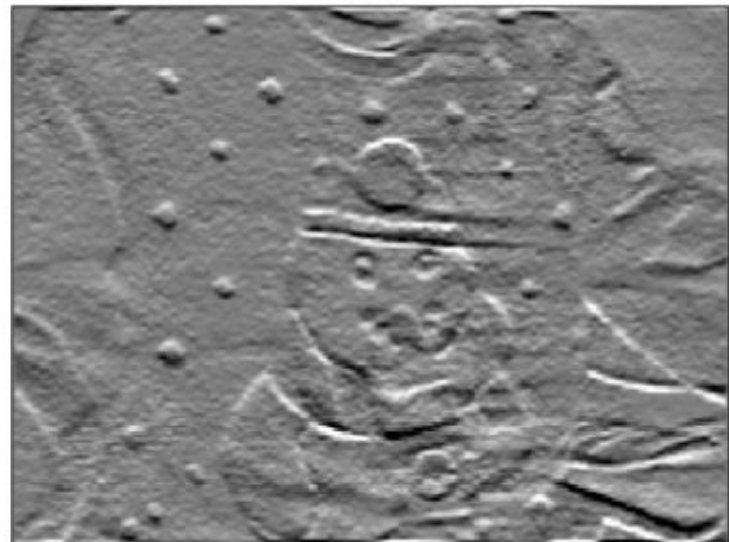
Results

Sobel

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



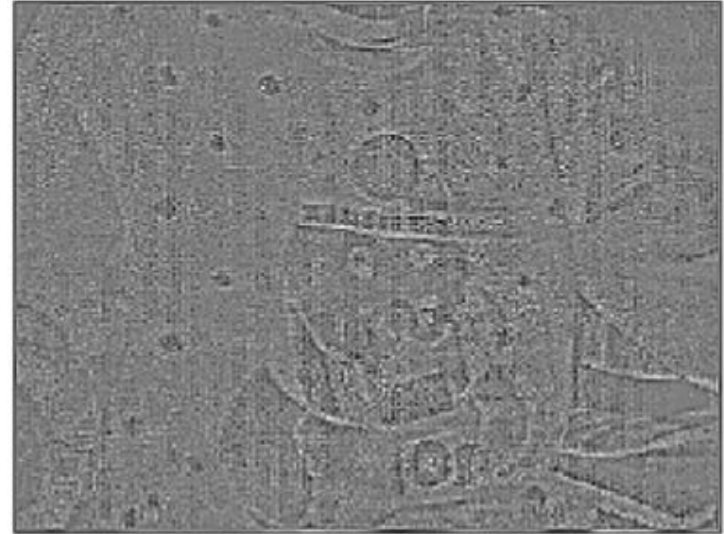
$$\begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$



Results

Laplacian

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

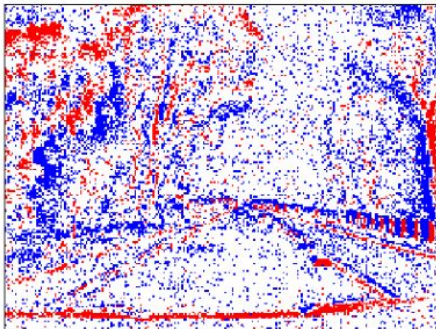
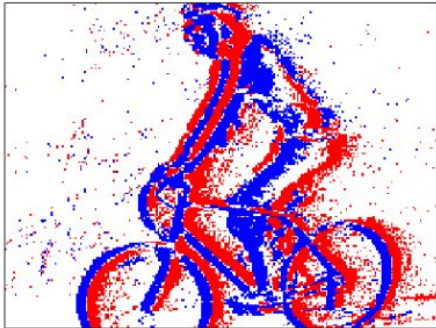
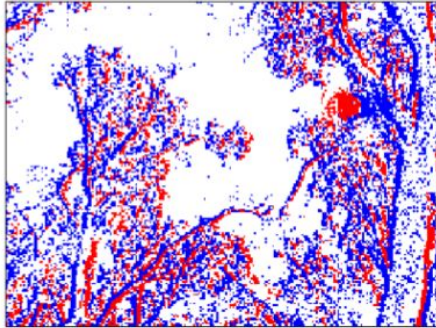


Poisson Reconstruction
from Laplacian

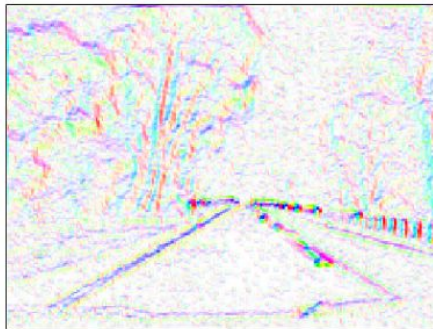
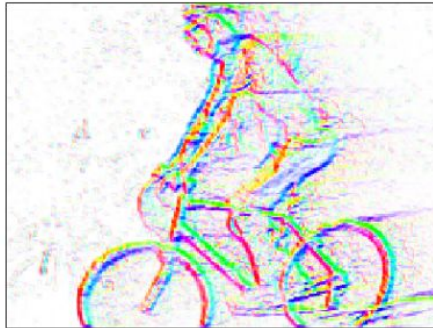
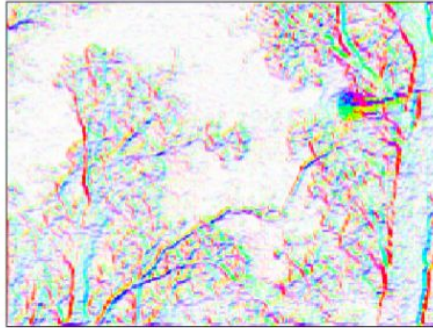


Results

Current events



Gradient estimate



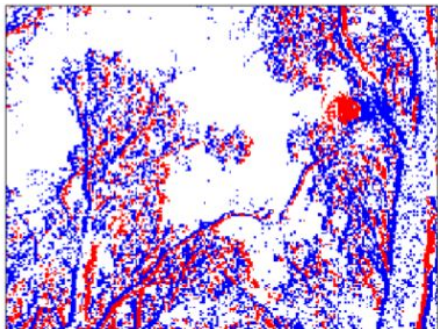
Sobel

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

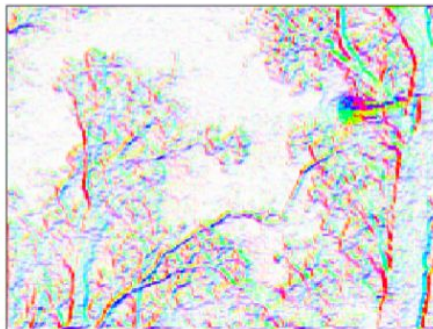
$$\begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$

Results

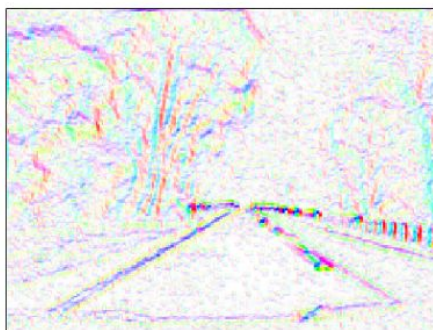
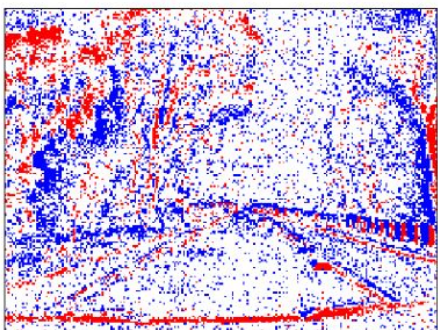
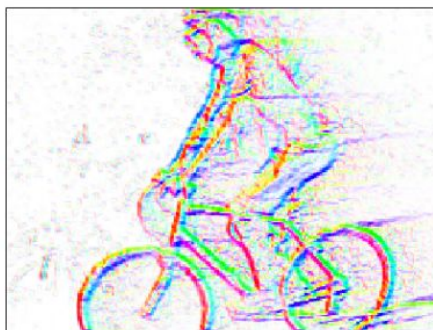
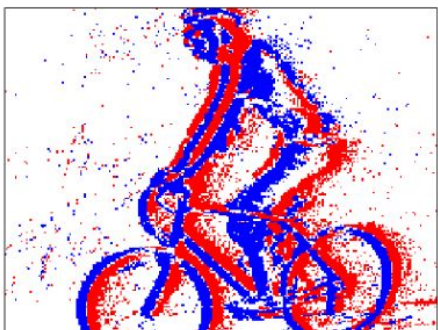
Current events



Gradient estimate

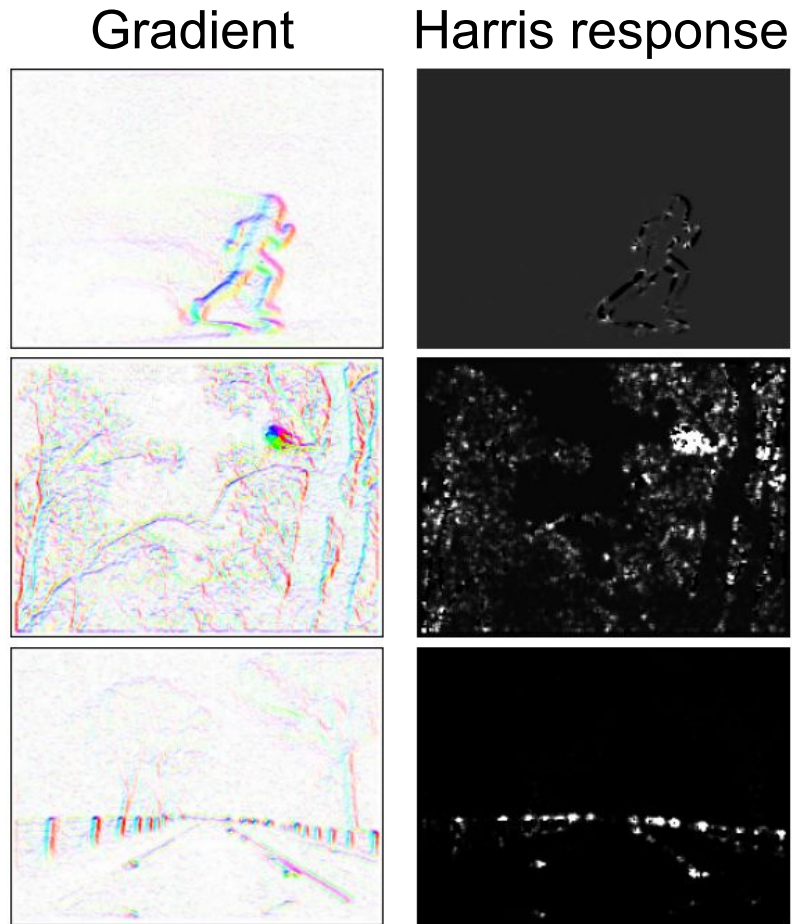


Poisson integration



Results

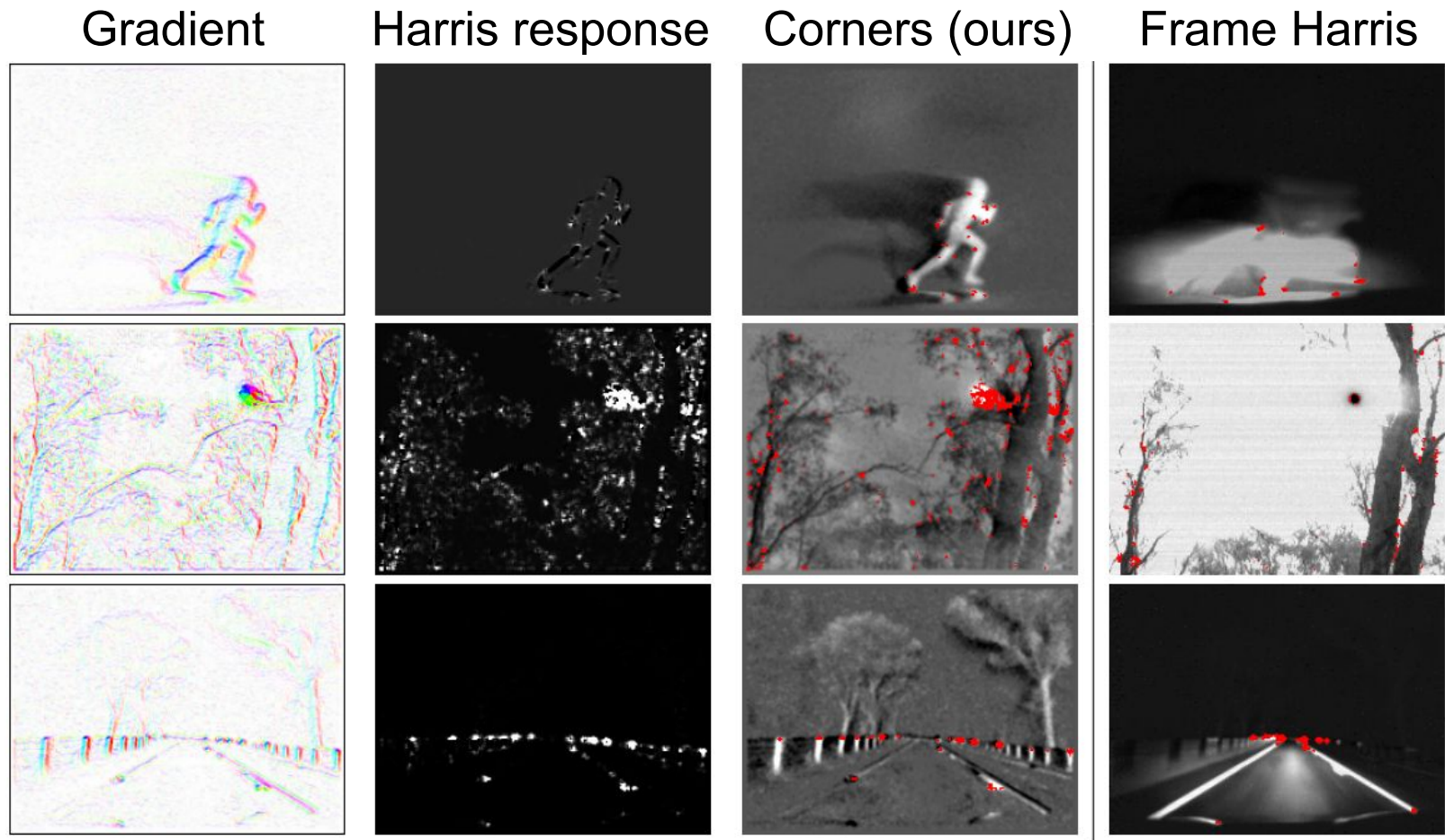
Gradient can be used as input to asynchronous Harris corner detector.



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

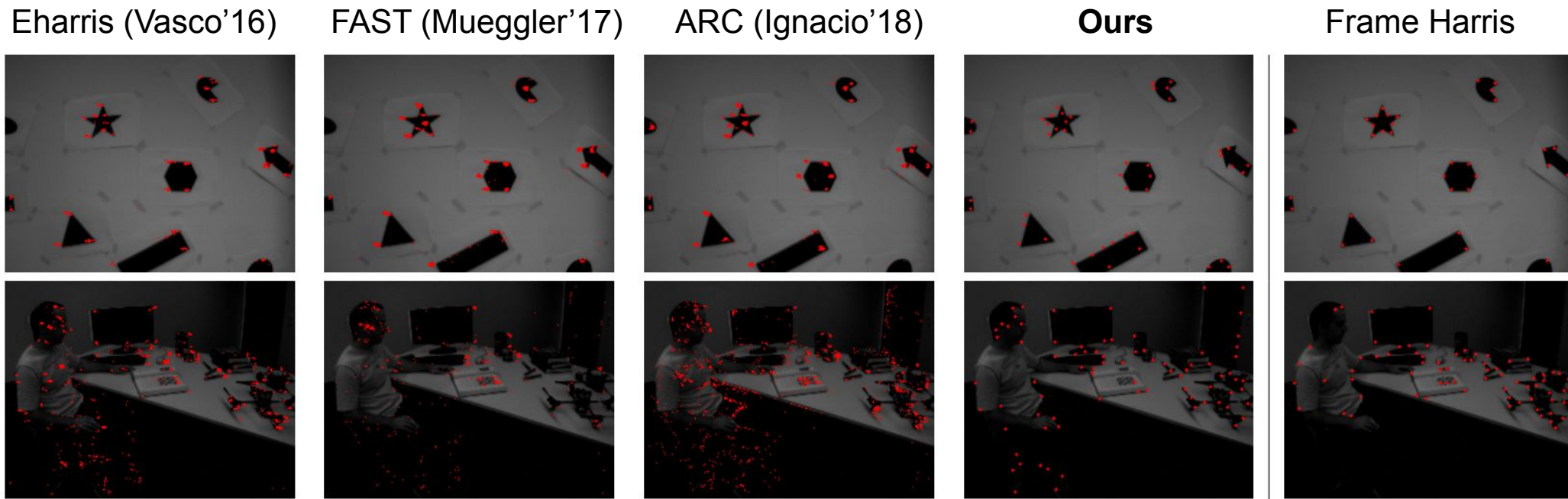
Results

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



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.

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.