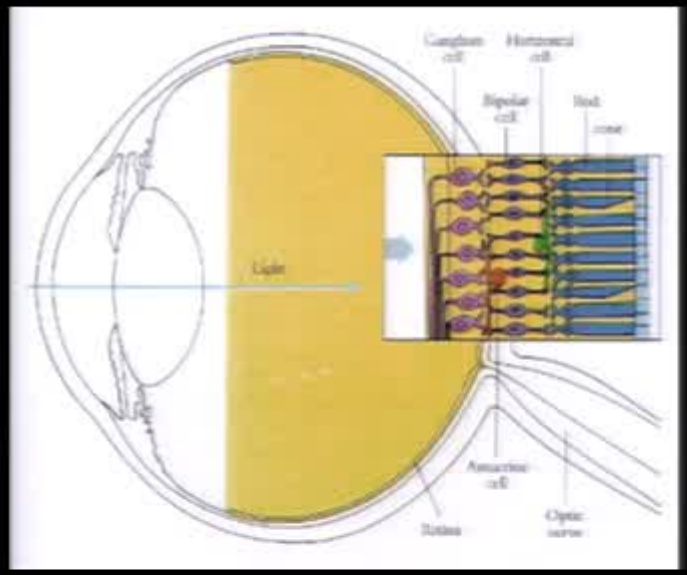
Event-Based Silicon Retina Technology

Tobi Delbruck
University of Zurich and ETH Zurich



From Rodieck 1998

Lichtsteiner & Delbruck, 2007

1. Sensor technology
2. Demo
3. Basic notions about processing output
4. State of the Art methods

SHOW TASKBAR DISPLAY SETTINGS END SLIDE SHOW

0:00:19 9:22 PM

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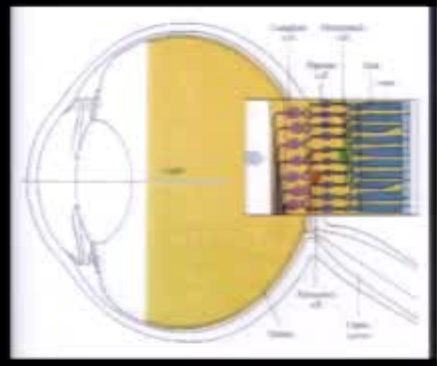

From Rodieck 1998

Lichtsteiner & Delbruck, 2007

1. Sensor technology
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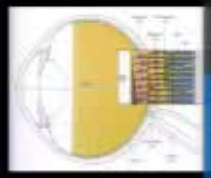
Slide 1 of 50

Next animation

Event-Based



Biology teaches
stroboscopic sec
conventional ma
the eye are asyn
in the form of di
local decisions ir
context. Our dev
asynchronous vi
same form of ev
shown that they
conventional ca
dynamic range,
especially post p
discuss these de
demonstrations
dynamic vision sensor silicon retina for

Project

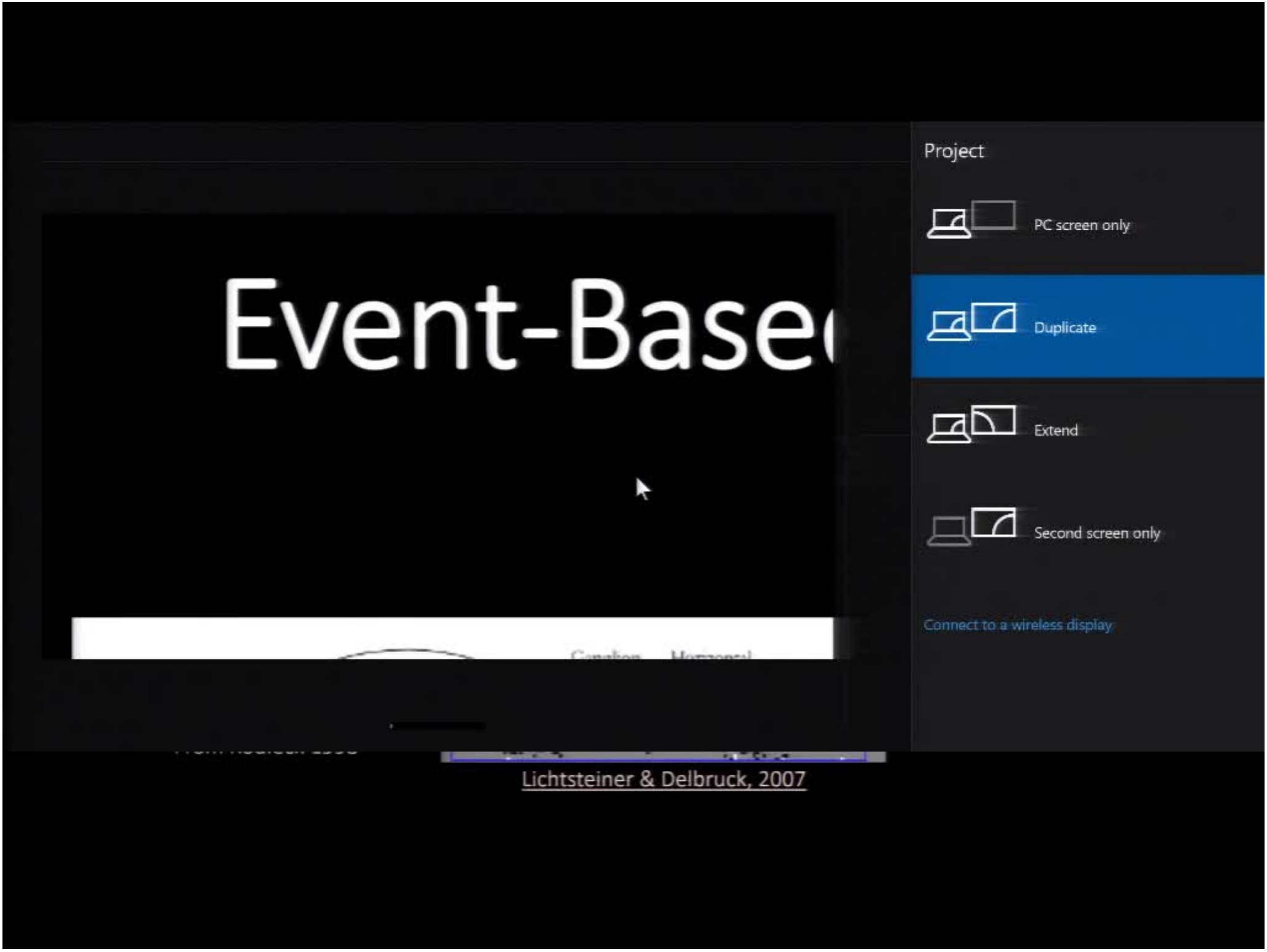
PC screen only

Duplicate

Extend

Second screen only

Connect to a wireless display



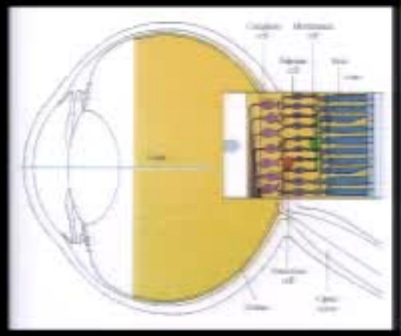
Lichtsteiner & Delbruck, 2007

SHOW TASKBAR DISPLAY SETTINGS END SLIDE SHOW

0:00:44 9:22 PM

Event-Based Silicon Retina Technology

Tobi Delbruck
University of Zurich and ETH Zurich



From Rodieck 1998

Lichtsteiner & Delbruck, 2007

1. Sensor technology
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3. Basic notions about processing output
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Slide 1 of 50

Project

screen only

Duplicate

Extend

Second screen only

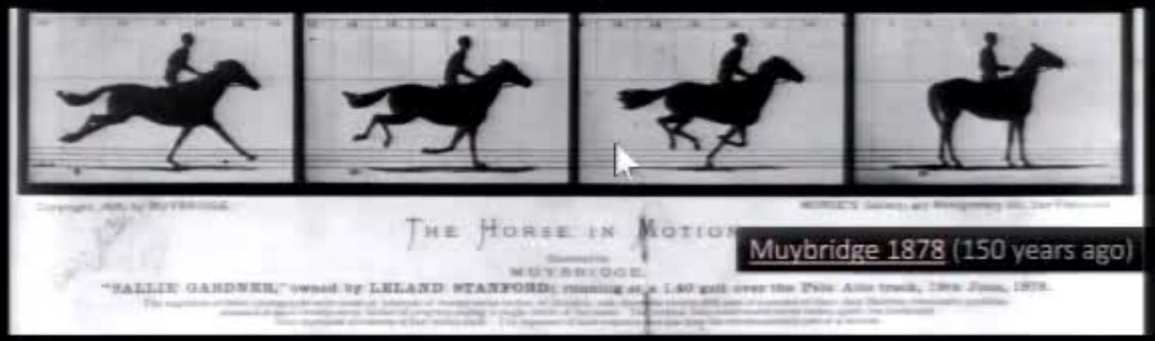
Connect to a wireless display

Lichtsteiner & Delbruck, 2007

SHOW TASKBAR DISPLAY SETTINGS END SLIDE SHOW

0:01:29 9:23 PM

Conventional cameras (aka Static vision sensors) deliver a stroboscopic sequence of frames



Slide 3 of 50

Next animation

No Notes.

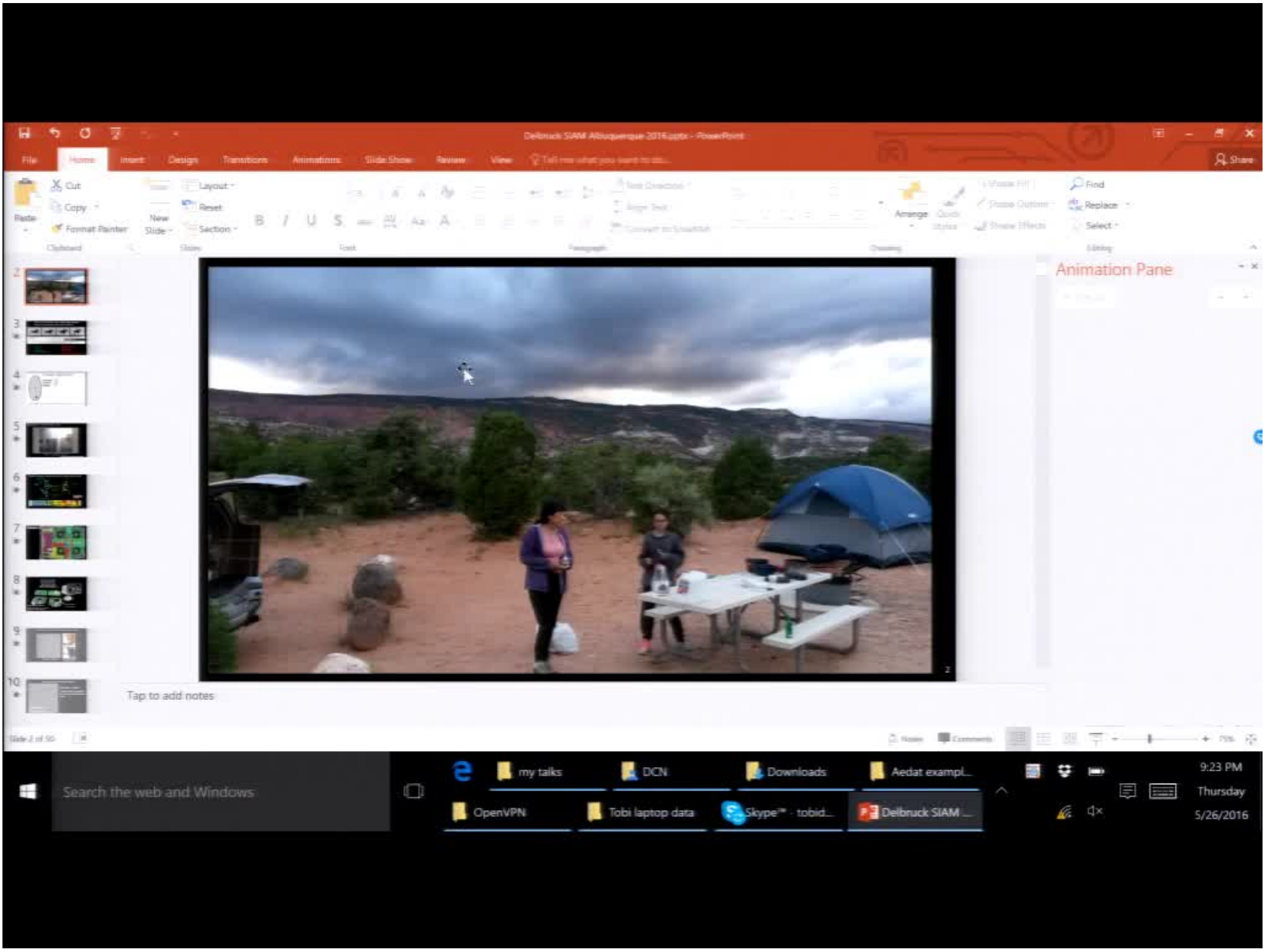
SHOW TASKBAR DISPLAY SETTINGS END SLIDE SHOW

0:01:31 9:23 PM

Slide 2 of 50

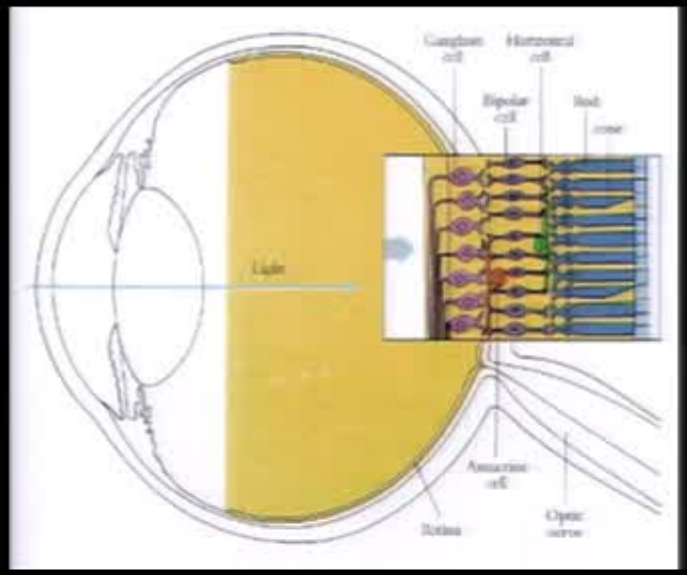
Next slide

No Notes.

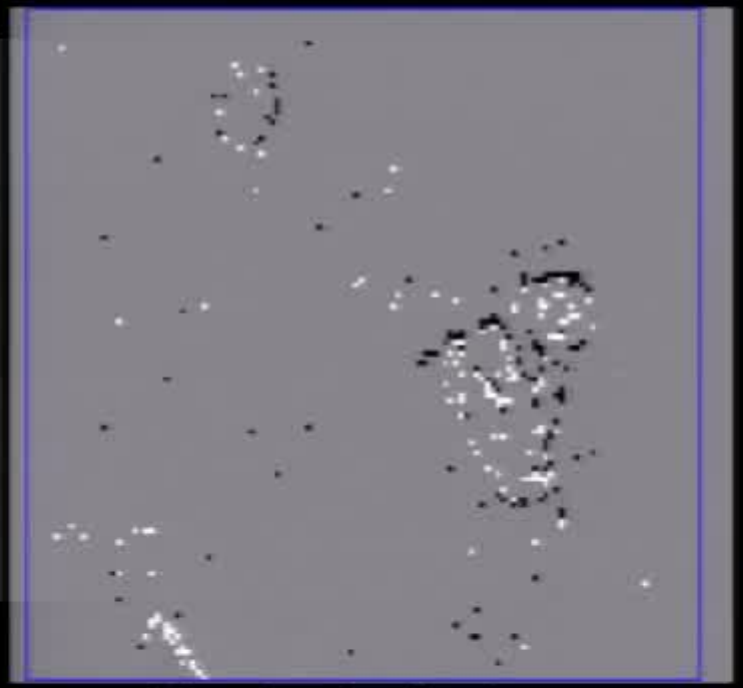

Delbruck SIAM Albuquerque 2016.pptx - PowerPoint
File
Home
Insert
Design
Transitions
Animations
Slide Show
Review
View
Share
Cut
Copy
Format Painter
Paste
New Slide
Layout
Reset
Section
Find
Replace
Select
Arrange
Animation Pane
Tap to add notes
Search the web and Windows
my talks
DCN
Downloads
Aedat exampl...
OpenVPN
Tobi laptop data
Skype™ - tobid...
Delbruck SIAM ...
9:23 PM
Thursday
5/26/2016

Event-Based Silicon Retina Technology

Tobi Delbruck
University of Zurich and ETH Zurich



From Rodieck 1998



Lichtsteiner & Delbruck, 2007

1. Sensor technology
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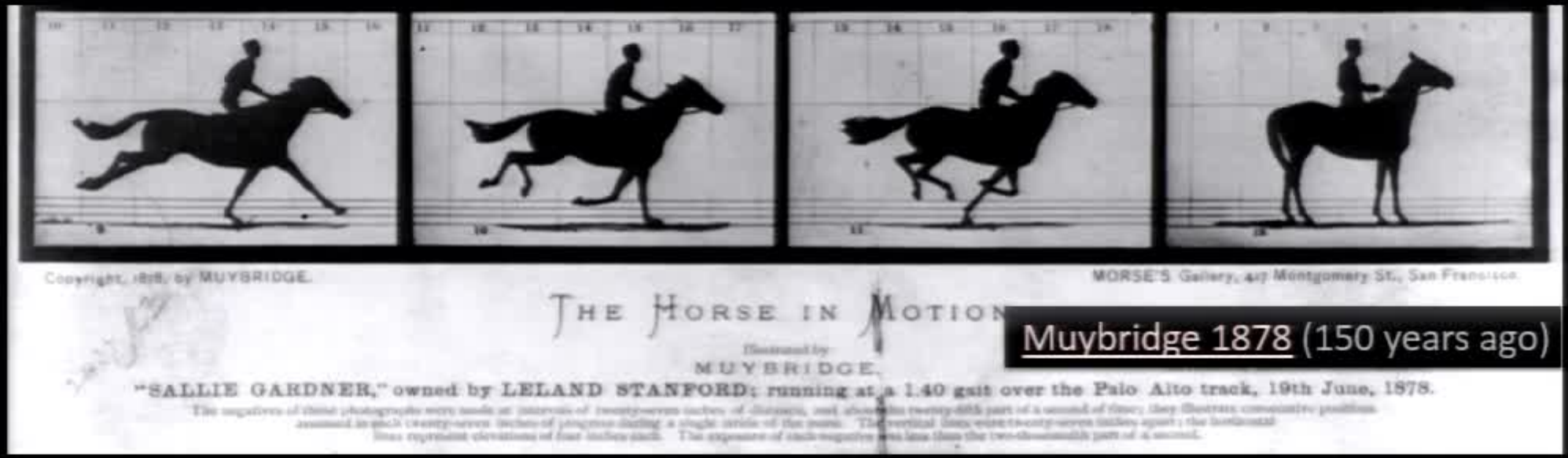
Conventional cameras (aka Static vision sensors) deliver a stroboscopic sequence of frames



Muybridge 1878 (150 years ago)

Good

Small pixels

Beautiful pictures

Compatible frame output

Bad

Limited dynamic range

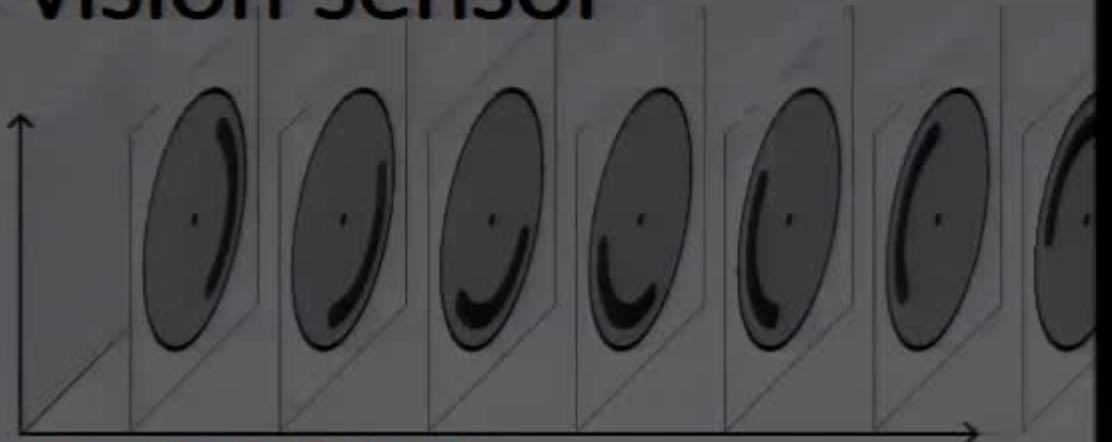
Temporal aliasing

Redundant output

Fundamental latency-power tradeoff

Dynamic vision sensor

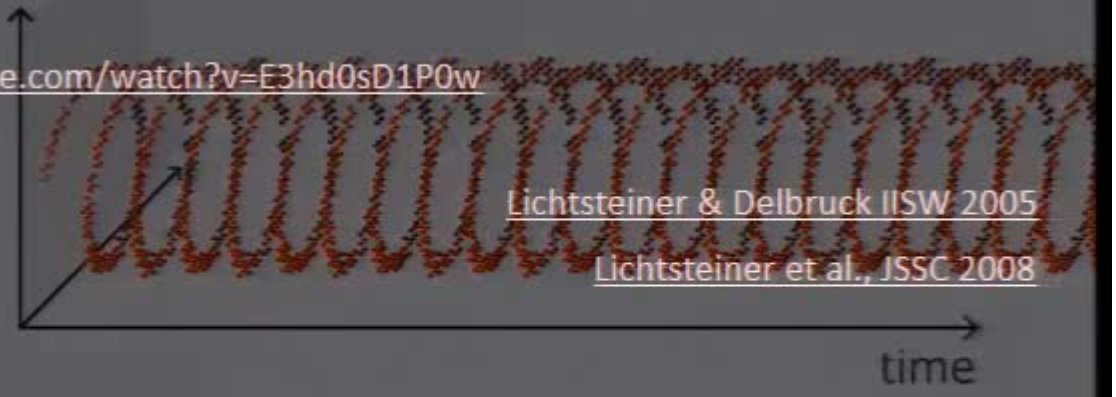
standard camera output:



motion blur!

DVS output:

https://www.youtube.com/watch?v=E3hd0sD1P0w



Lichtsteiner & Delbruck IISW 2005

Lichtsteiner et al., JSSC 2008

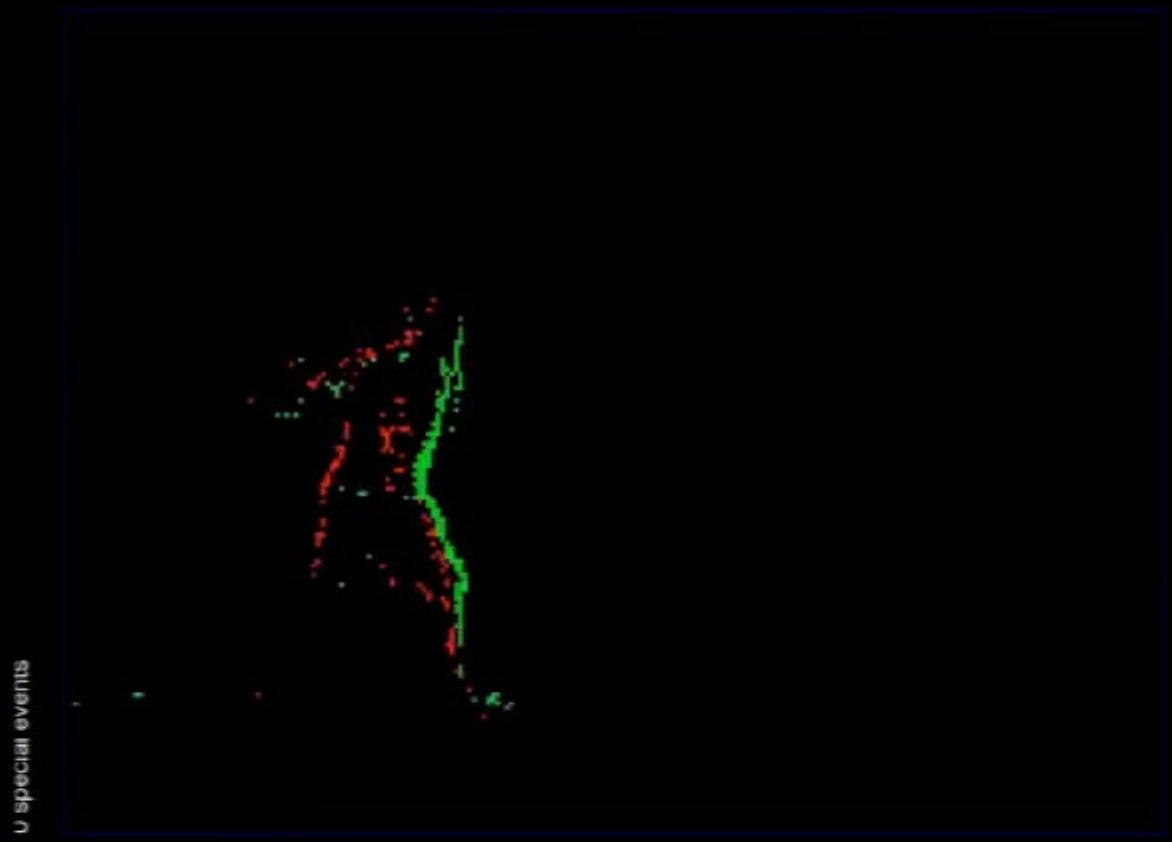
DAVIS (DVS + APS) Example data

https://www.youtube.com/watch?v=2wxH73wlvKE

DAVIS (DVS + APS) Example data

https://www.youtube.com/watch?v=2wxH73wlvKE

DAVIS (DVS + APS) Example data



https://www.youtube.com/watch?v=2wxH73wlvKE

DAVIS (DVS + APS) Example data

DAVIS: mountain biking in Telluride

https://www.youtube.com/watch?v=2wxH73wlvKE

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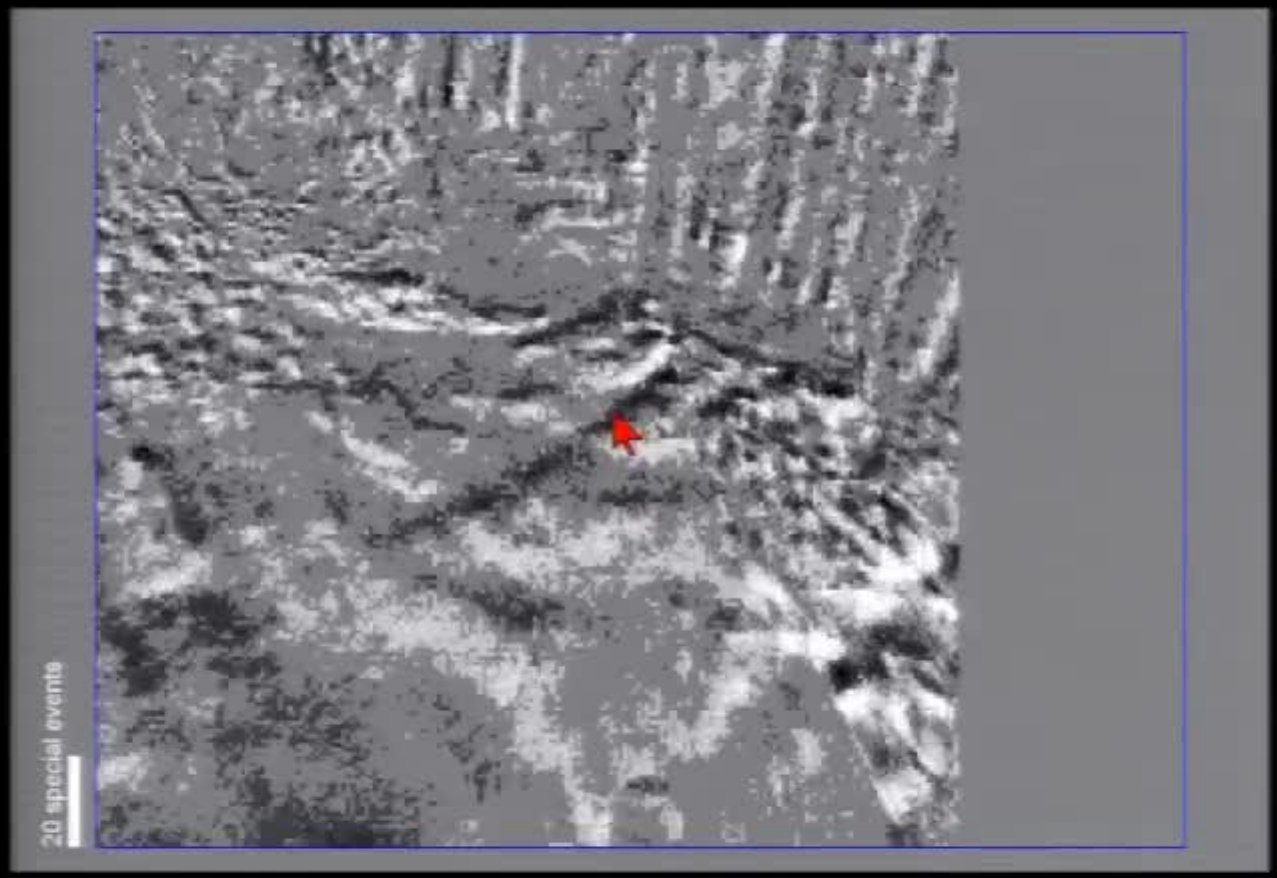
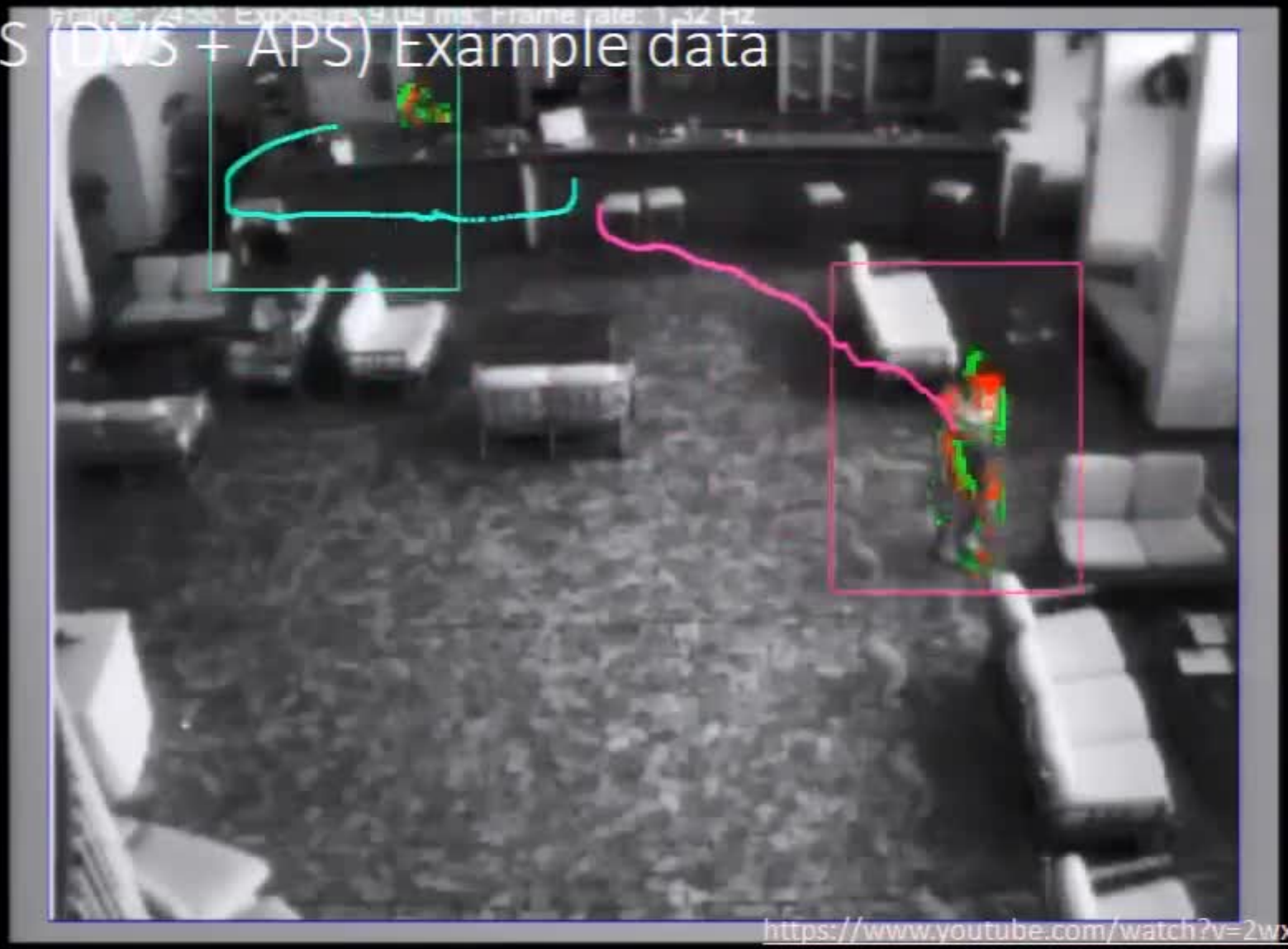
DAVIS (DVS + APS) Example data



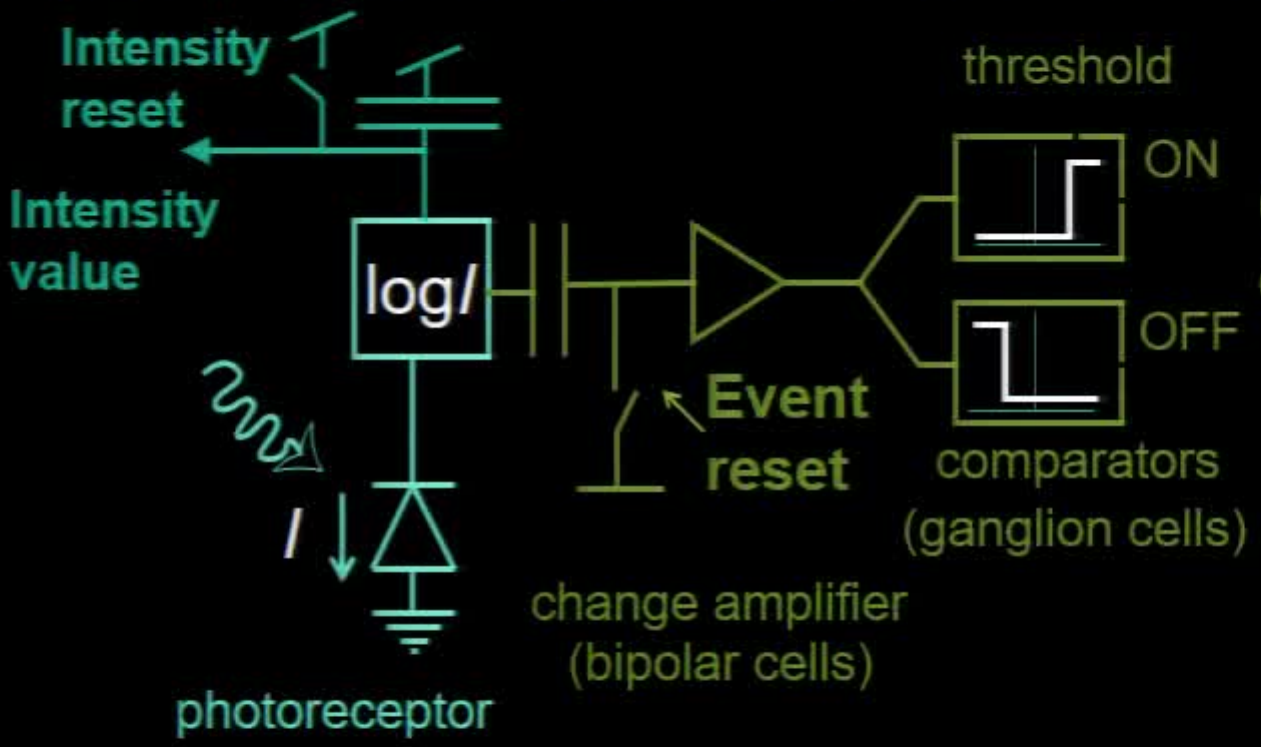
https://www.youtube.com/watch?v=2wxH73wlvKE

DAVIS (DVS + APS) Example data



https://www.youtube.com/watch?v=2wxH73wlvKE

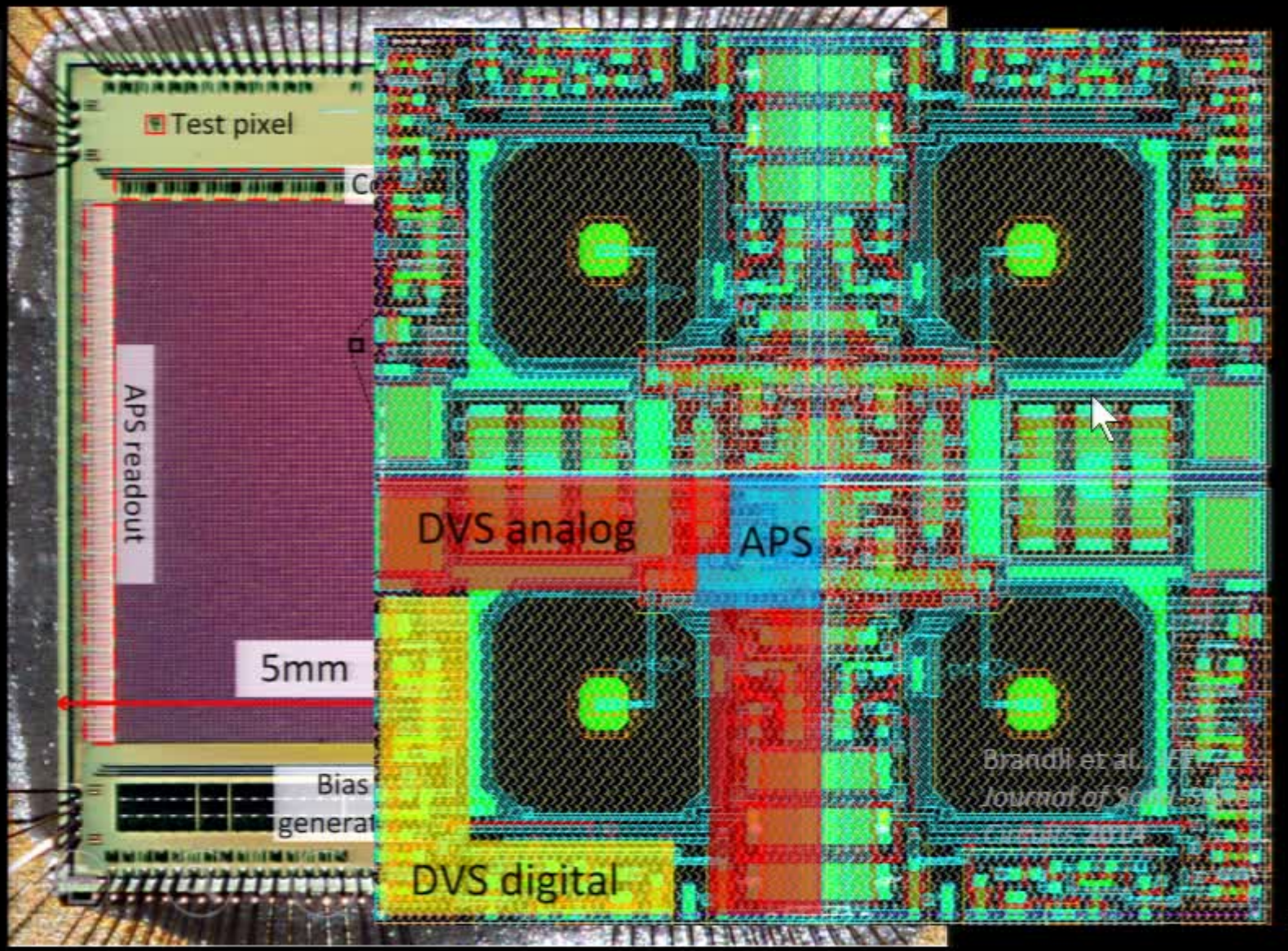
DAVIS (Dynamic and Active Pixel Vision Sensor) Pixel

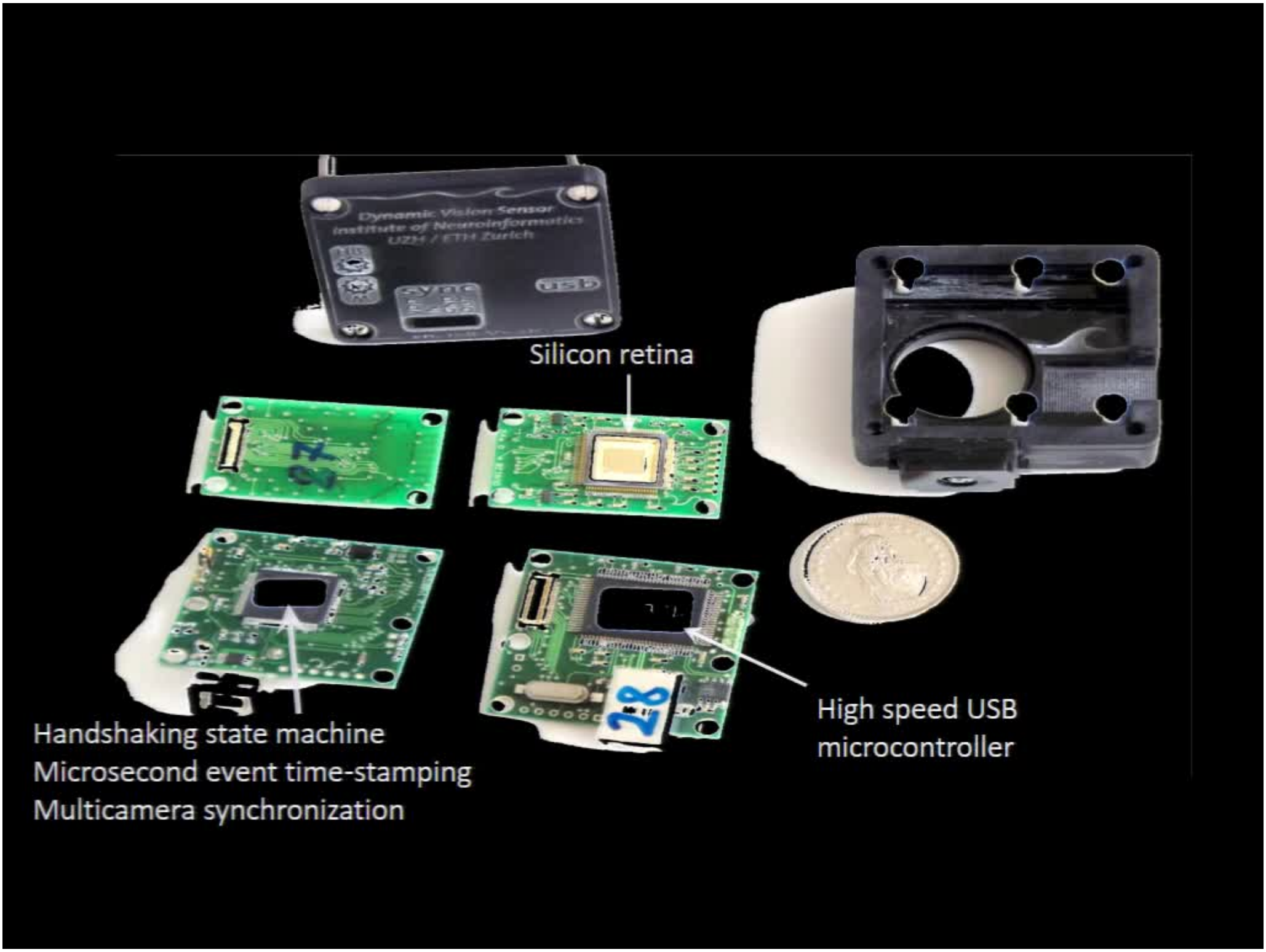


Brandli et al., *IEEE Journal of Solid-State Circuits* **2014**

From Rodieck 1998

A DAVIS chip




Dynamic Vision Sensor
Institute of Neuroinformatics
UZH / ETH Zurich
Silicon retina
Handshaking state machine
Microsecond event time-stamping
Multicamera synchronization
High speed USB
microcontroller

Working with event sensors

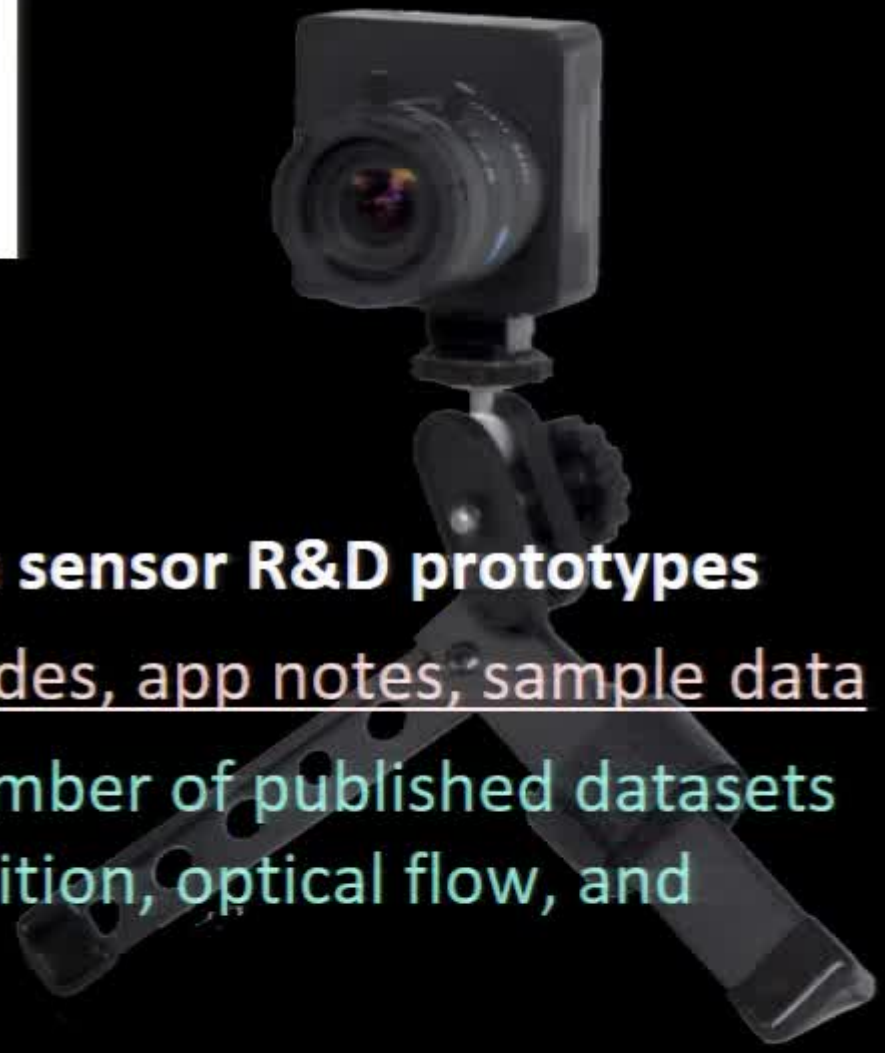
jAER & cAER are open-source software projects (at jaerproject.net) for real time processing with event-based sensors on PCs (Win/Mac/Linux), including embedded Linux APs. A ROS module is also available.

jAER/cAER and the event-based sensors work together.

iniLabs

Founded 2009

www.iniLabs.com



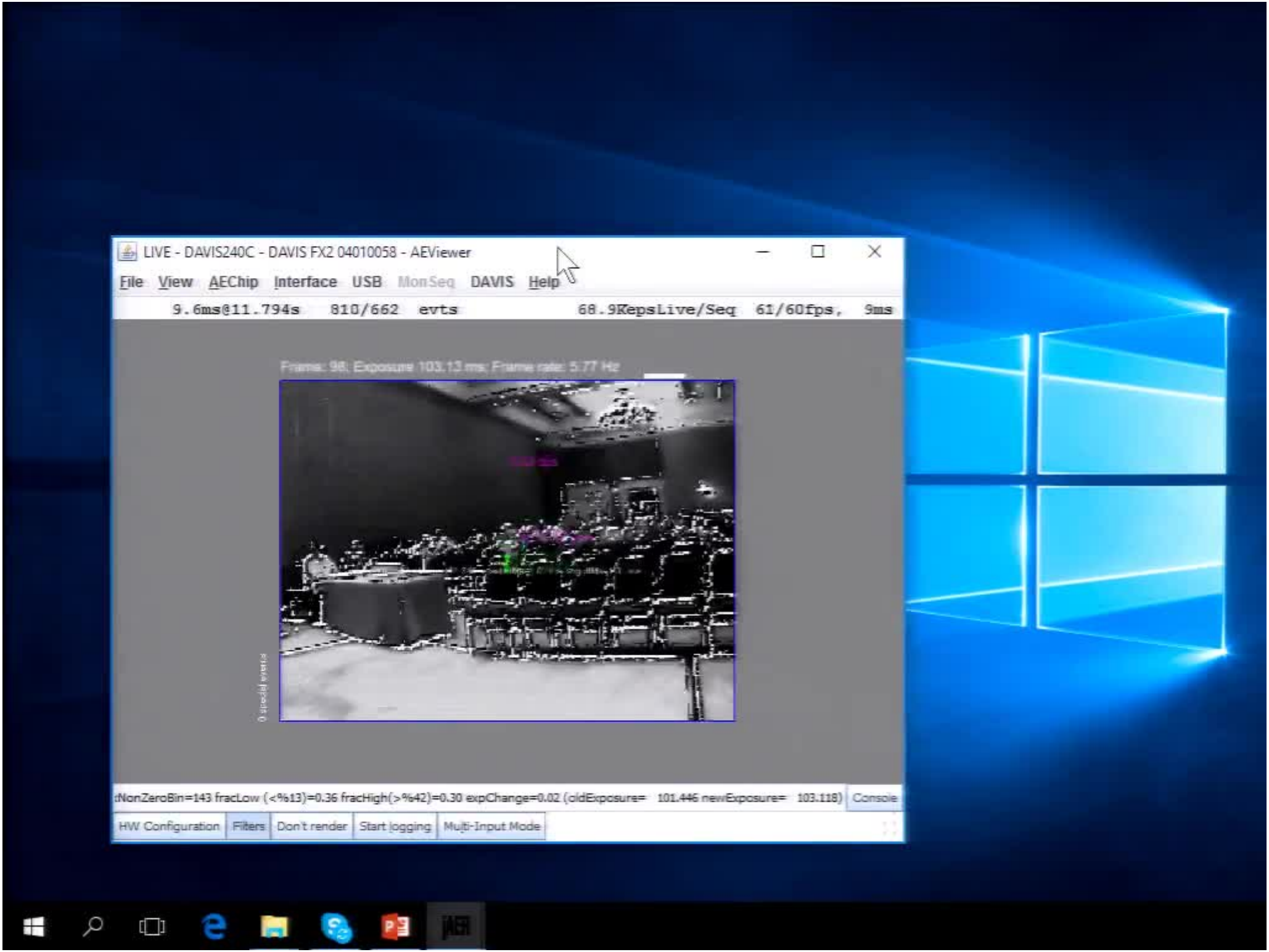
Neuromorphic retina / cochlea sensor R&D prototypes

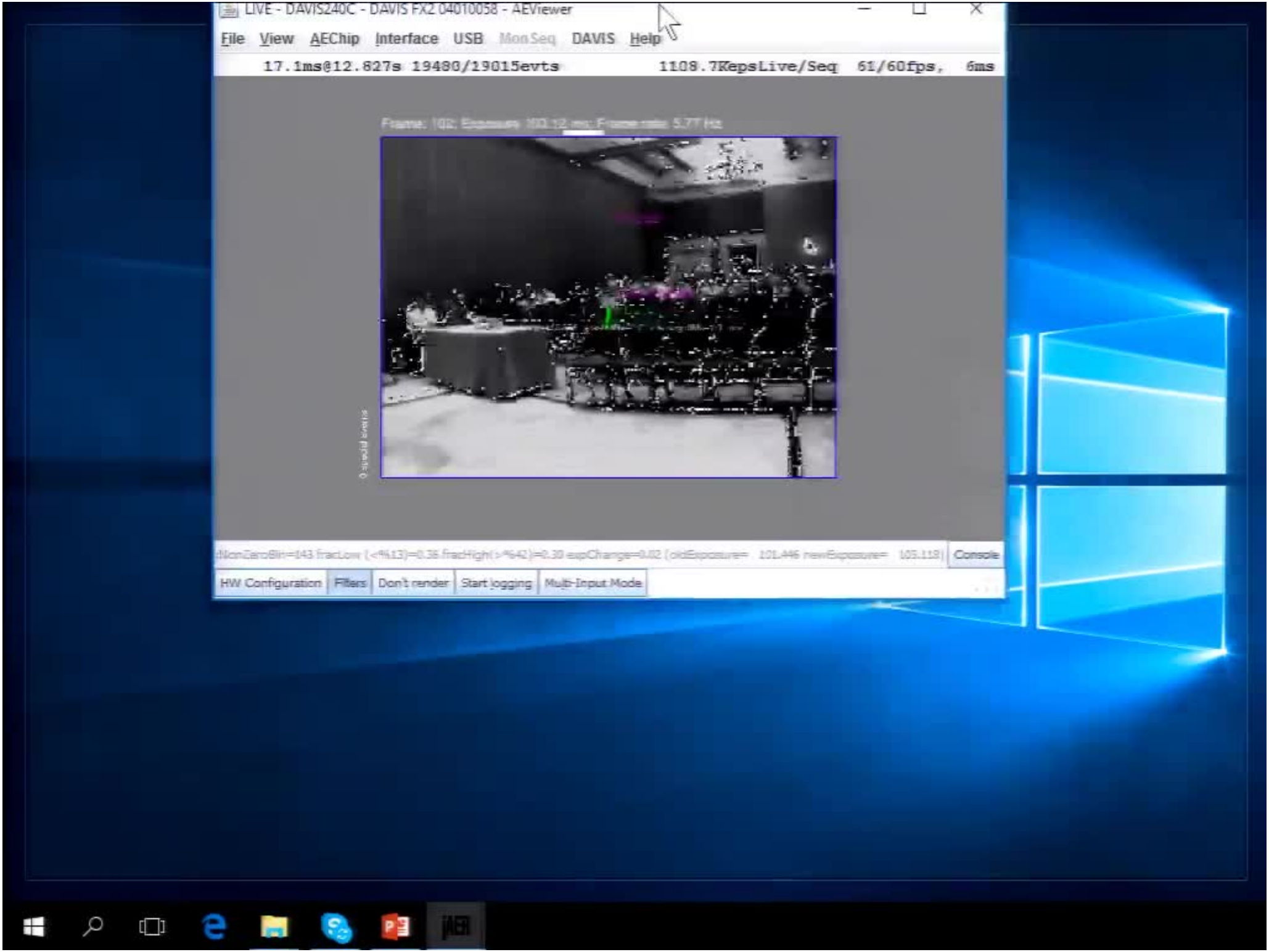
Open source software, user guides, app notes, sample data

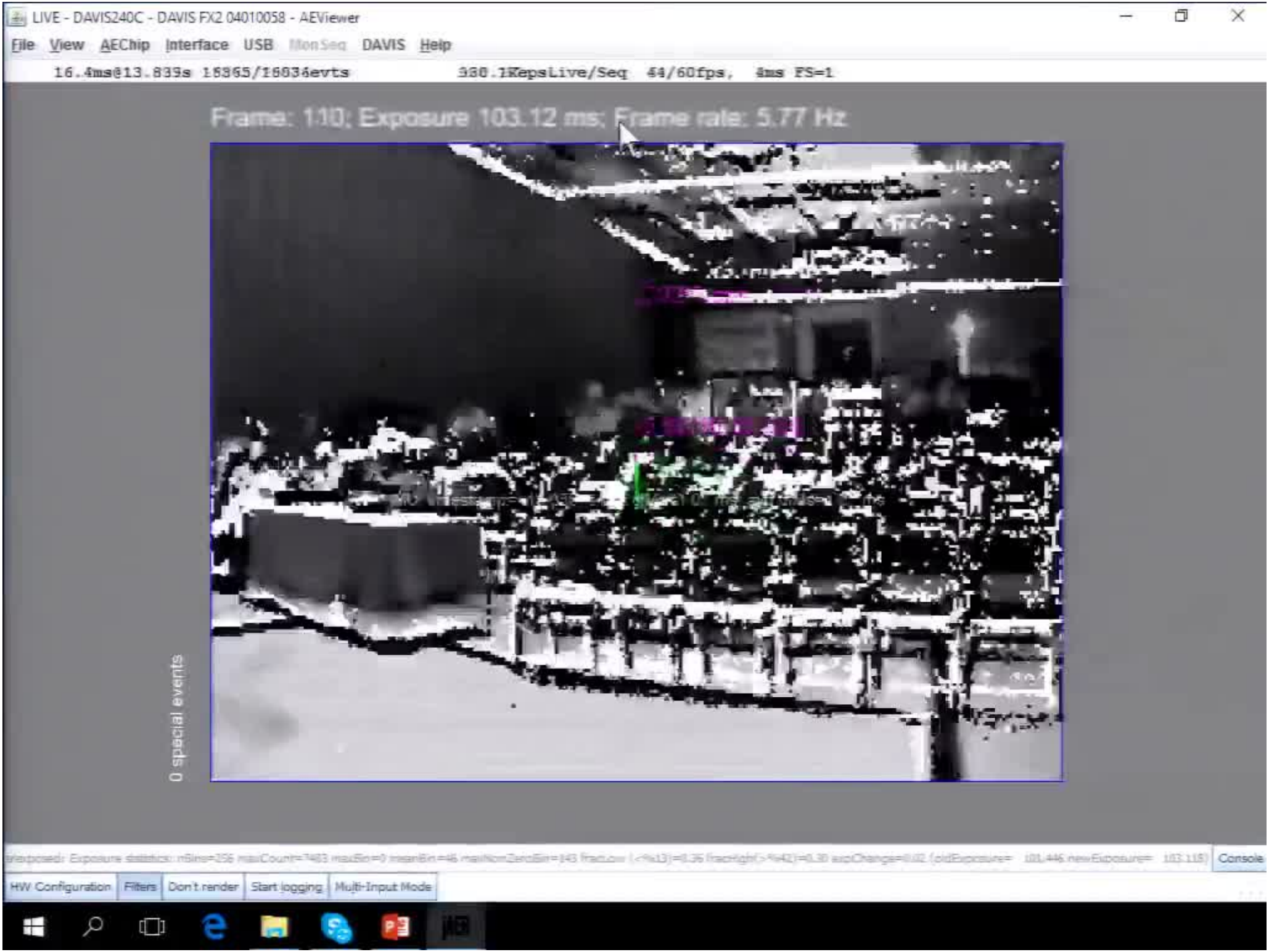
There are also an increasing number of published datasets available, e.g. for object recognition, optical flow, and odometry

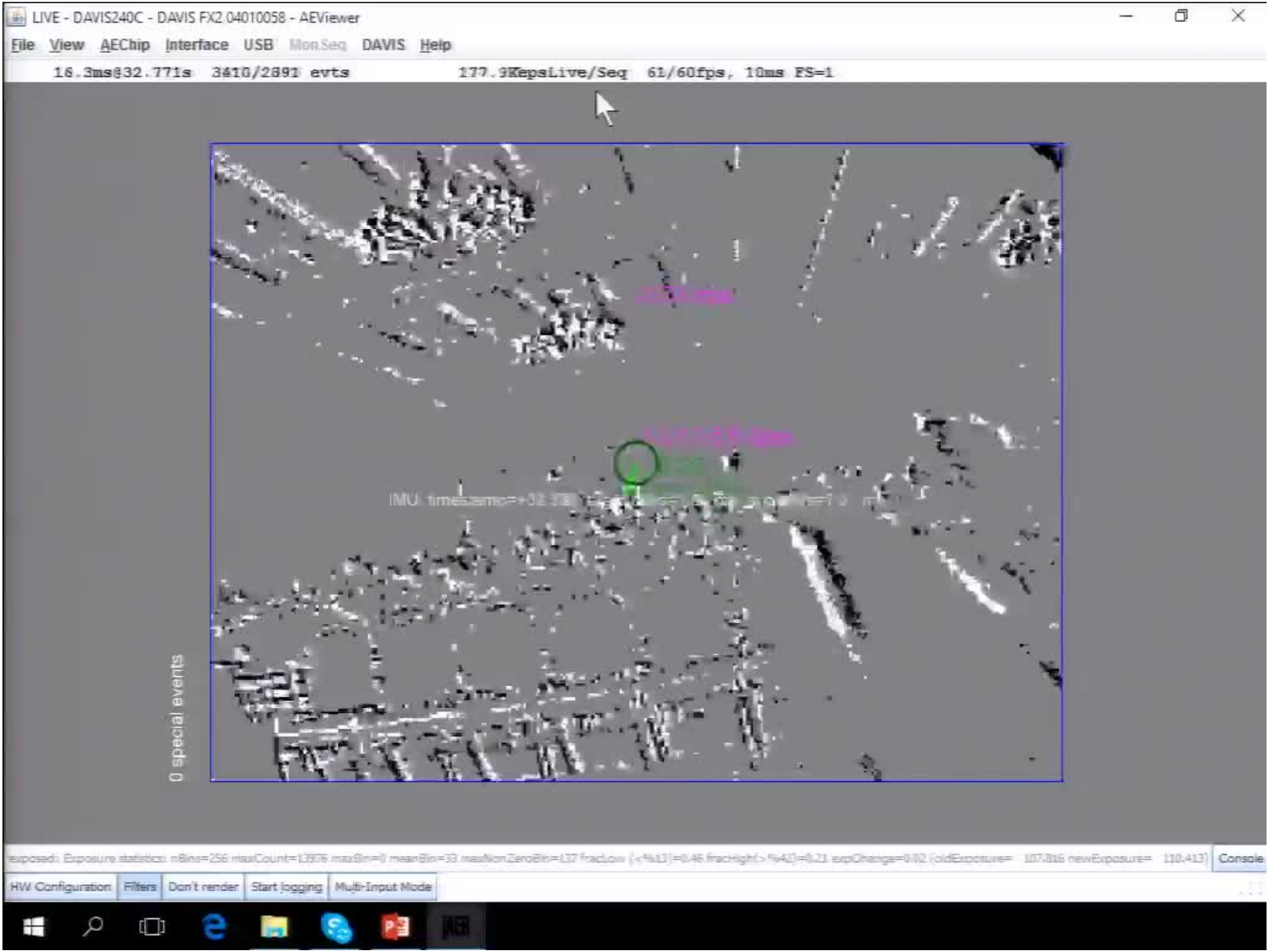
Demo: Dynamic Vision Sensor (DVS) + DAVIS

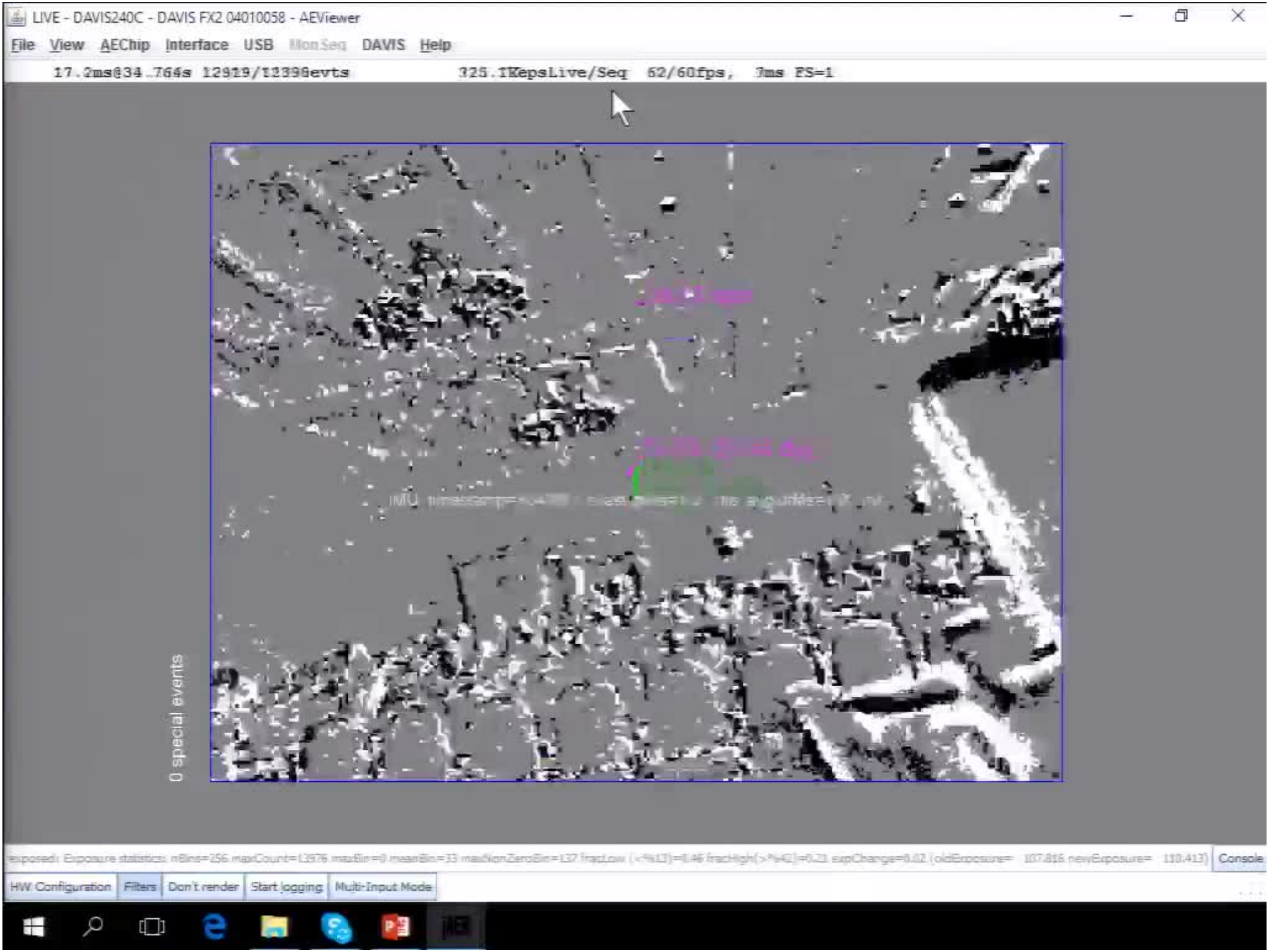
Brandli, C., Berner, R., Yang, M., Liu, S.-C. & Delbruck, T. A 240x180 130 dB 3us Latency Global Shutter Spatiotemporal Vision Sensor. *IEEE Journal of Solid-State Circuits* **(2015)**.

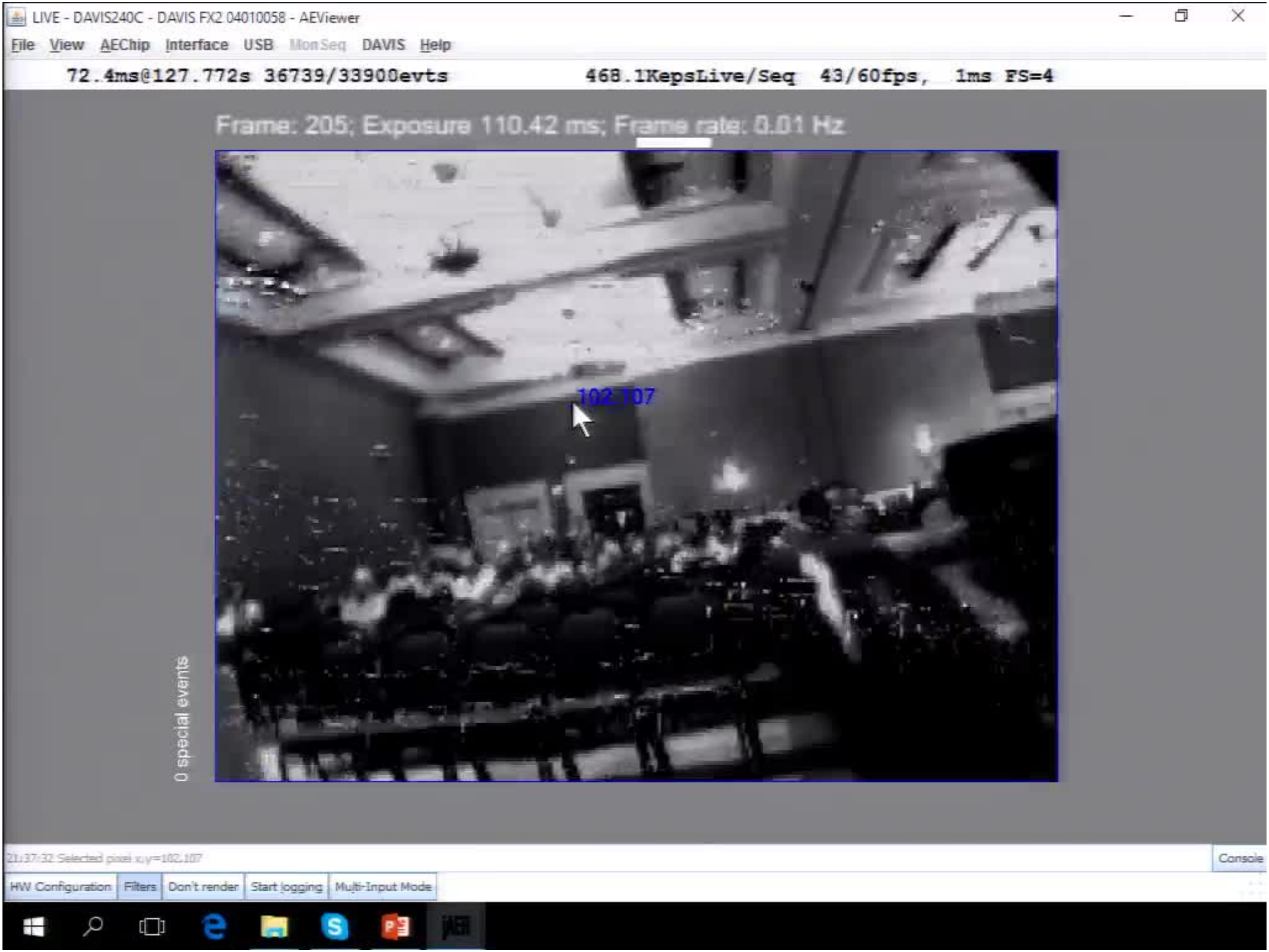

LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
9.6ms@11.794s 810/662 evts 68.9KepsLive/Seq 61/60fps, 9ms
Frame: 98; Exposure 103.13 ms; Frame rate: 5.77 Hz
0 special events
:NonZeroBin=143 fracLow (<%13)=0.36 fracHigh(>%42)=0.30 expChange=0.02 (oldExposure= 101.446 newExposure= 103.118)
Console
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode

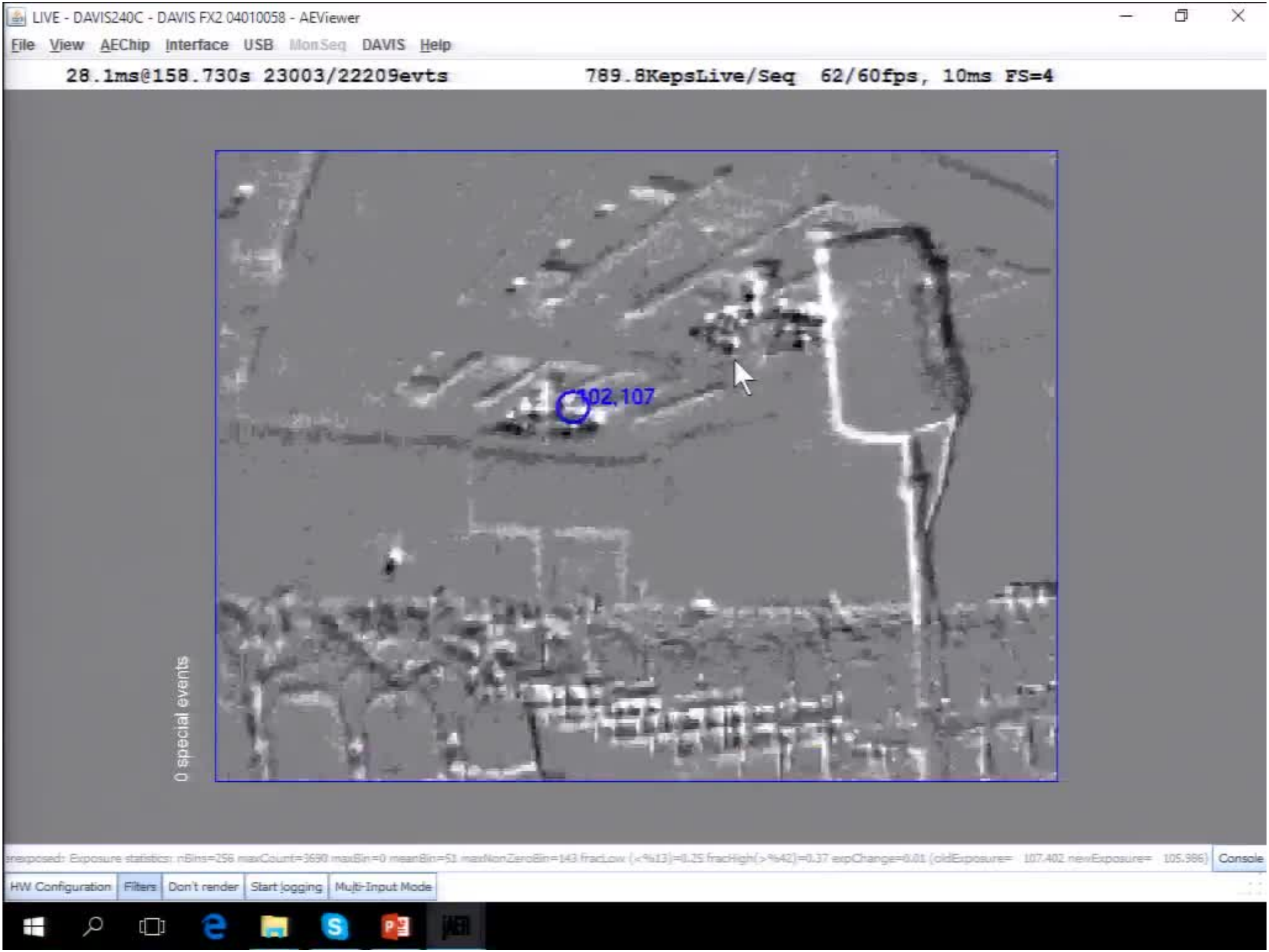

LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
17.1ms@12.827s 19480/19015evts 1108.7KepsLive/Seq 61/60fps, 6ms
Console
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode

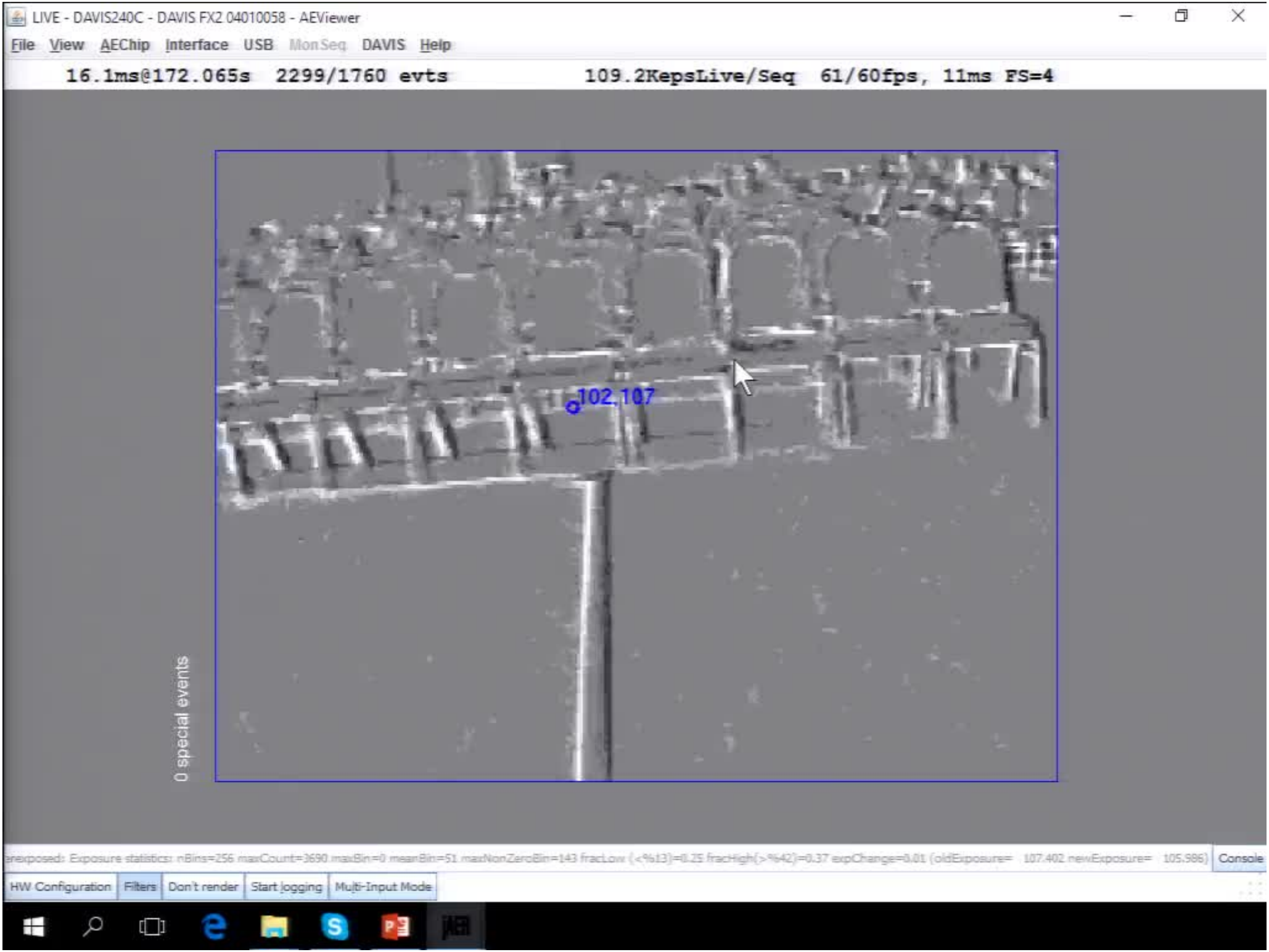

LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
16.4ms@13.839s 16365/16036evts 330.1KepsLive/Seq 54/60fps, 4ms FS=1
Frame: 110; Exposure 103.12 ms; Frame rate: 5.77 Hz
0 special events
Console
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode


LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
16.3ms@32.771s 3410/2891 evts 177.3KepsLive/Seq 61/60fps, 10ms FS=1
0 special events
Console
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode


LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
17.2ms@34.764s 12919/13398evts 325.1KepsLive/Seq 62/60fps, 7ms FS=1
0 special events
Console
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode


LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
72.4ms@127.772s 36739/33900evts 468.1KepsLive/Seq 43/60fps, 1ms FS=4
Frame: 205; Exposure 110.42 ms; Frame rate: 0.01 Hz
102,107
0 special events
21:37:32 Selected pixel x,y=102,107
Console
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode


LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
28.1ms@158.730s 23003/22209evts
789.8KepsLive/Seq 62/60fps, 10ms FS=4
102,107
0 special events
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode
Console


LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
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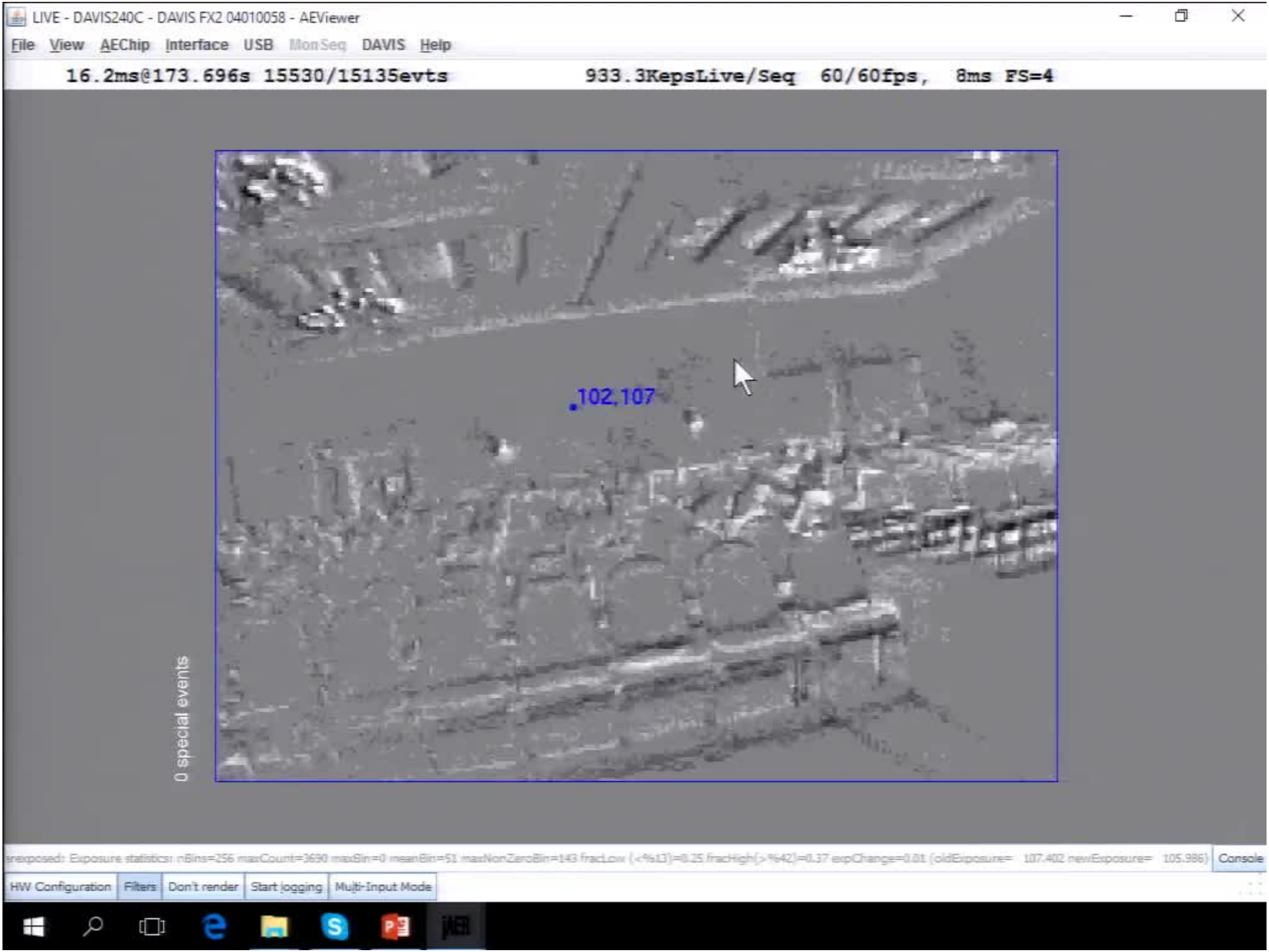
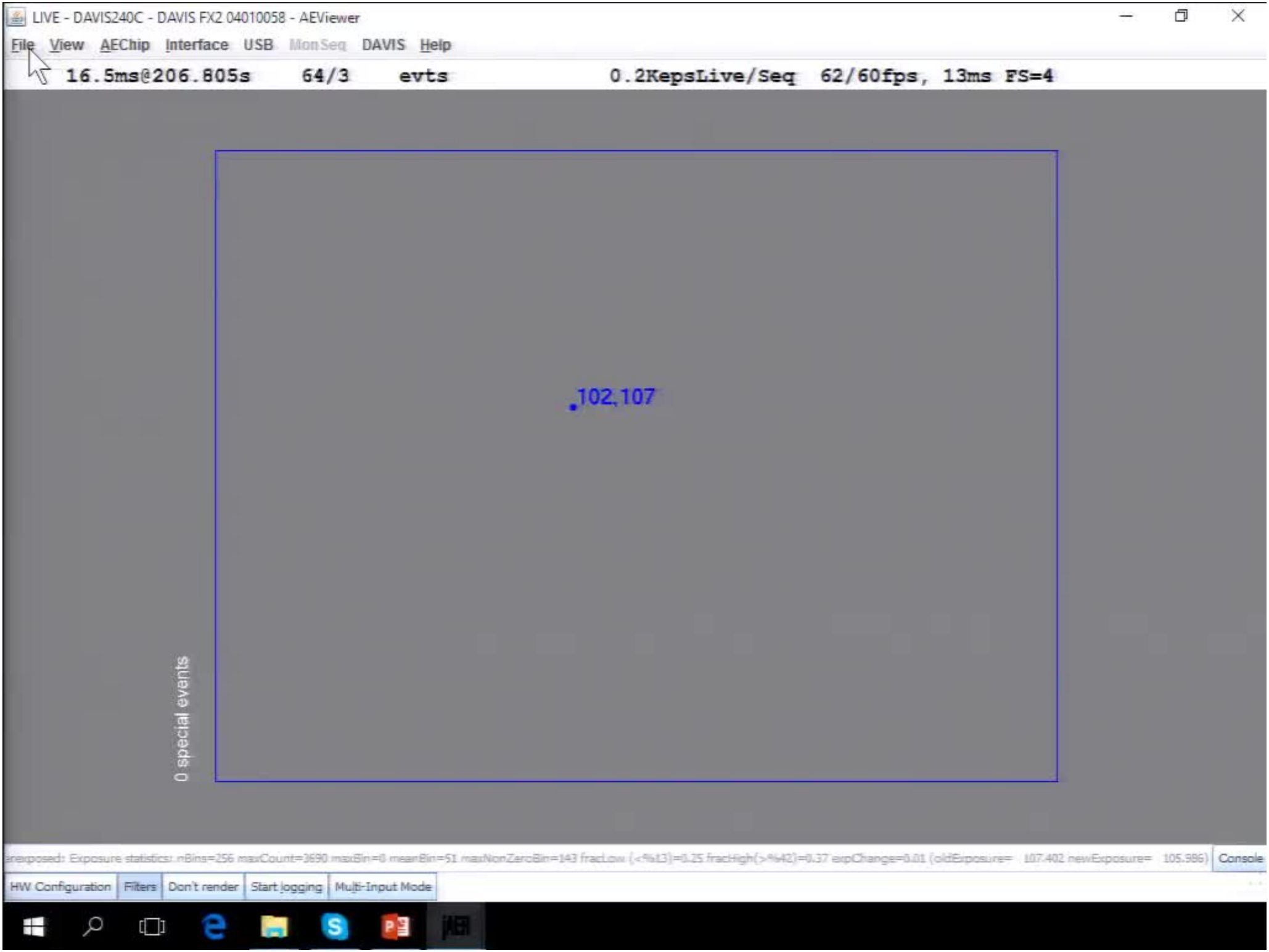
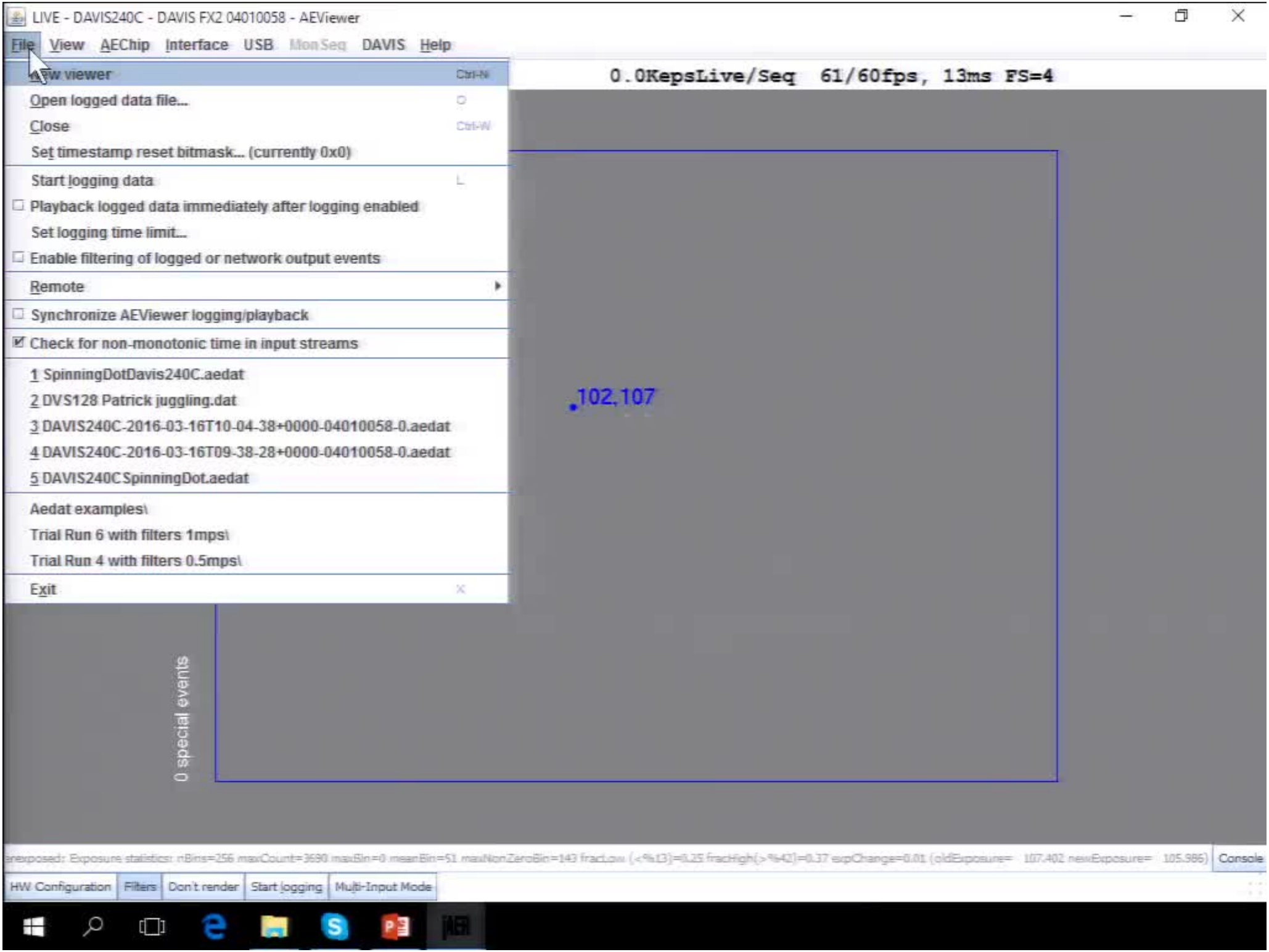
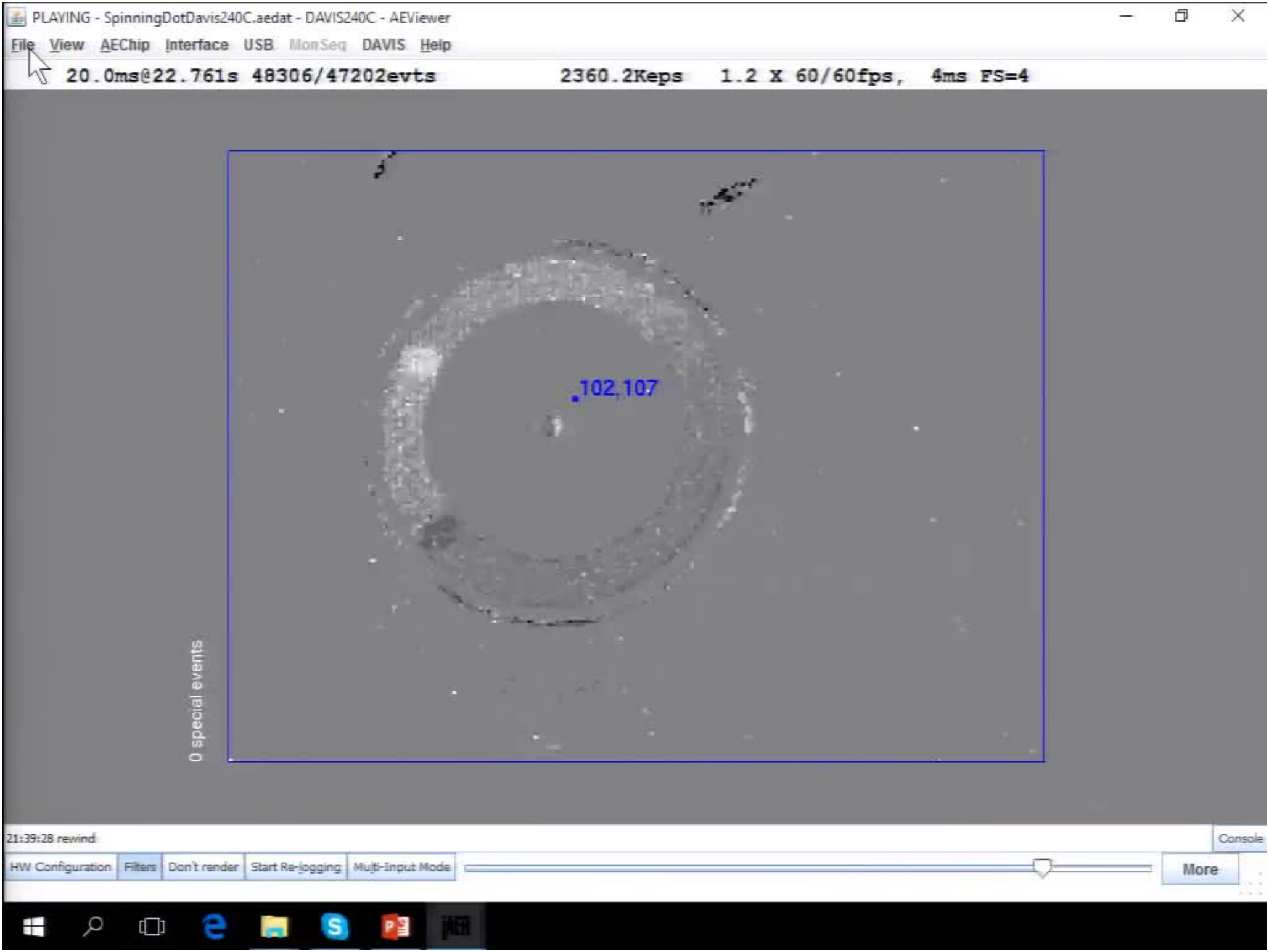
109.2KepsLive/Seq 61/60fps, 11ms FS=4
102,107
0 special events
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode
Console

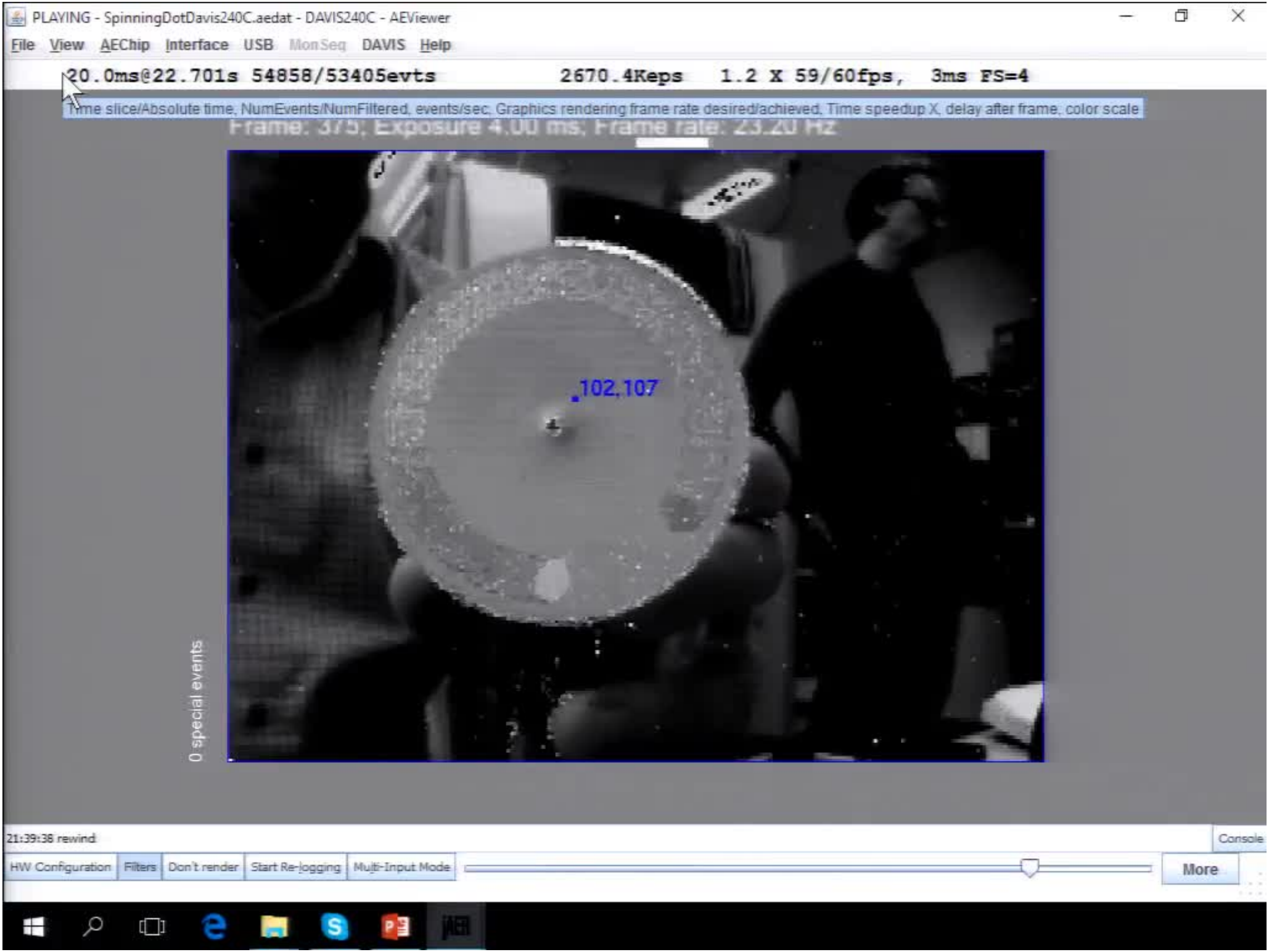

LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
16.2ms@173.696s 15530/15135evts
933.3KepsLive/Seq 60/60fps, 8ms FS=4
102,107
0 special events
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode
Console

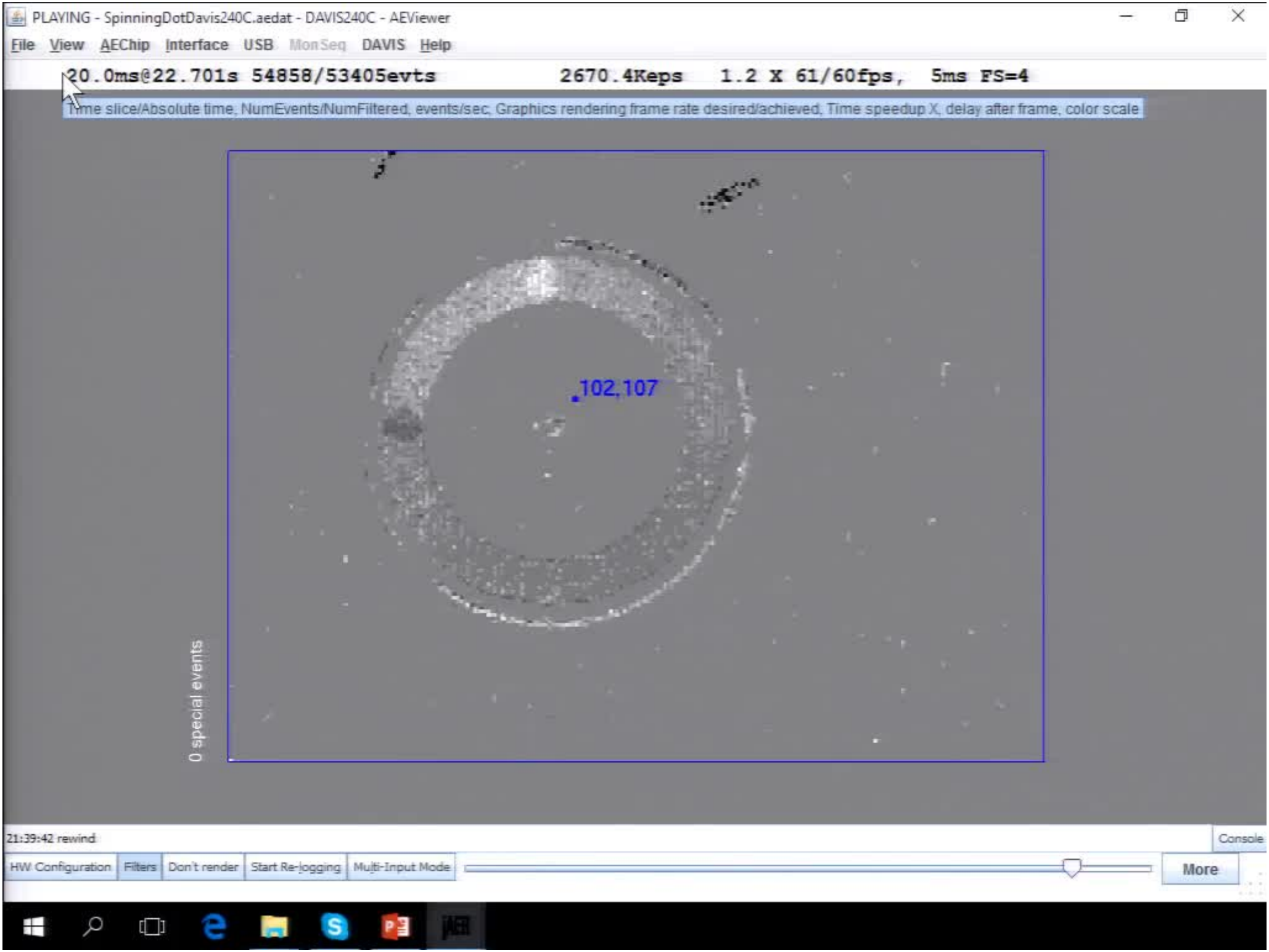

LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
17.2ms@195.909s 11635/10548evts 612.4KepsLive/Seq 61/60fps, 12ms FS=4
102,107
0 special events
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode
Console

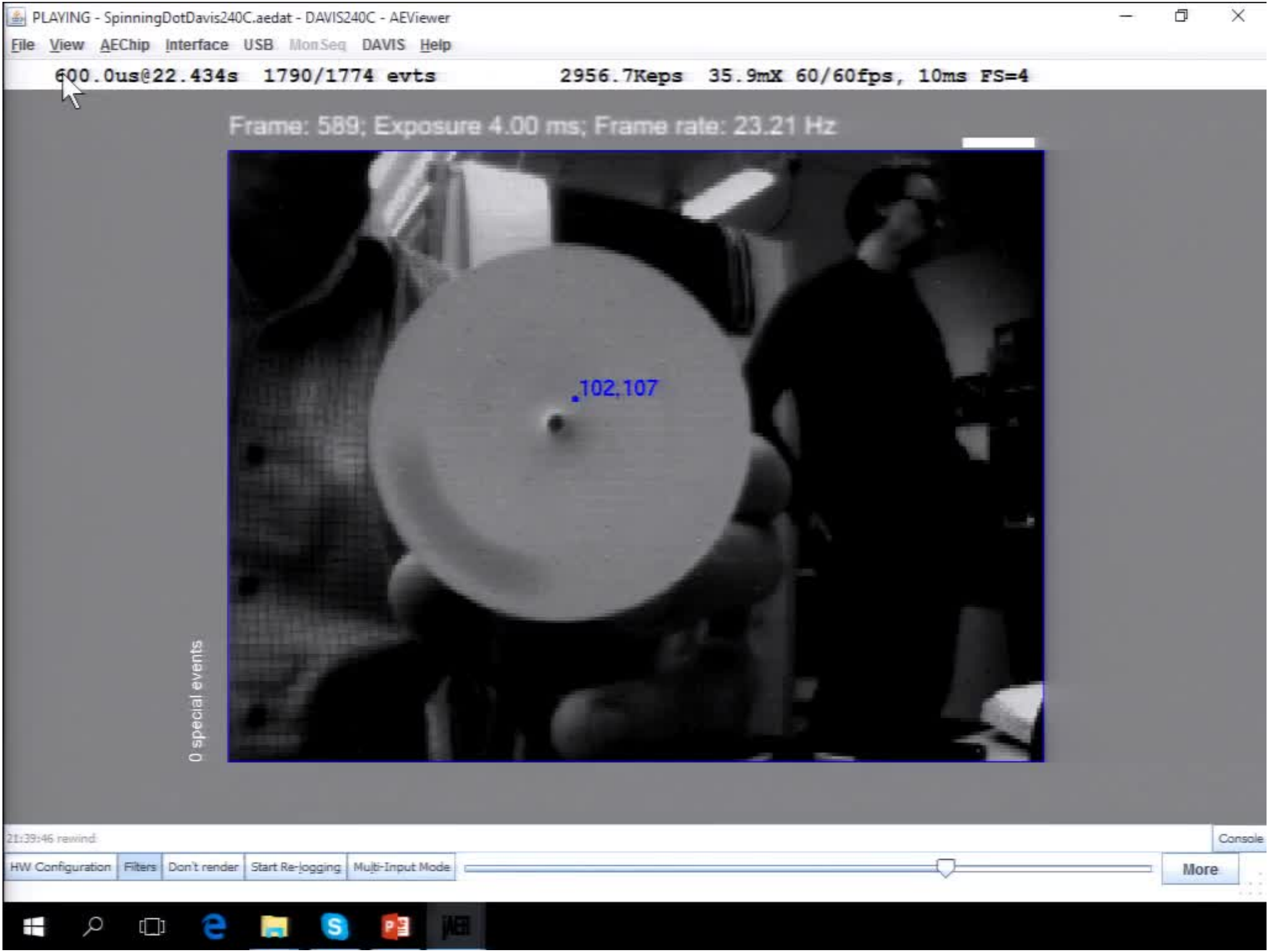

LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
16.5ms@206.805s 64/3 evts 0.2KepsLive/Seq 62/60fps, 13ms FS=4
102,107
0 special events
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode
Console

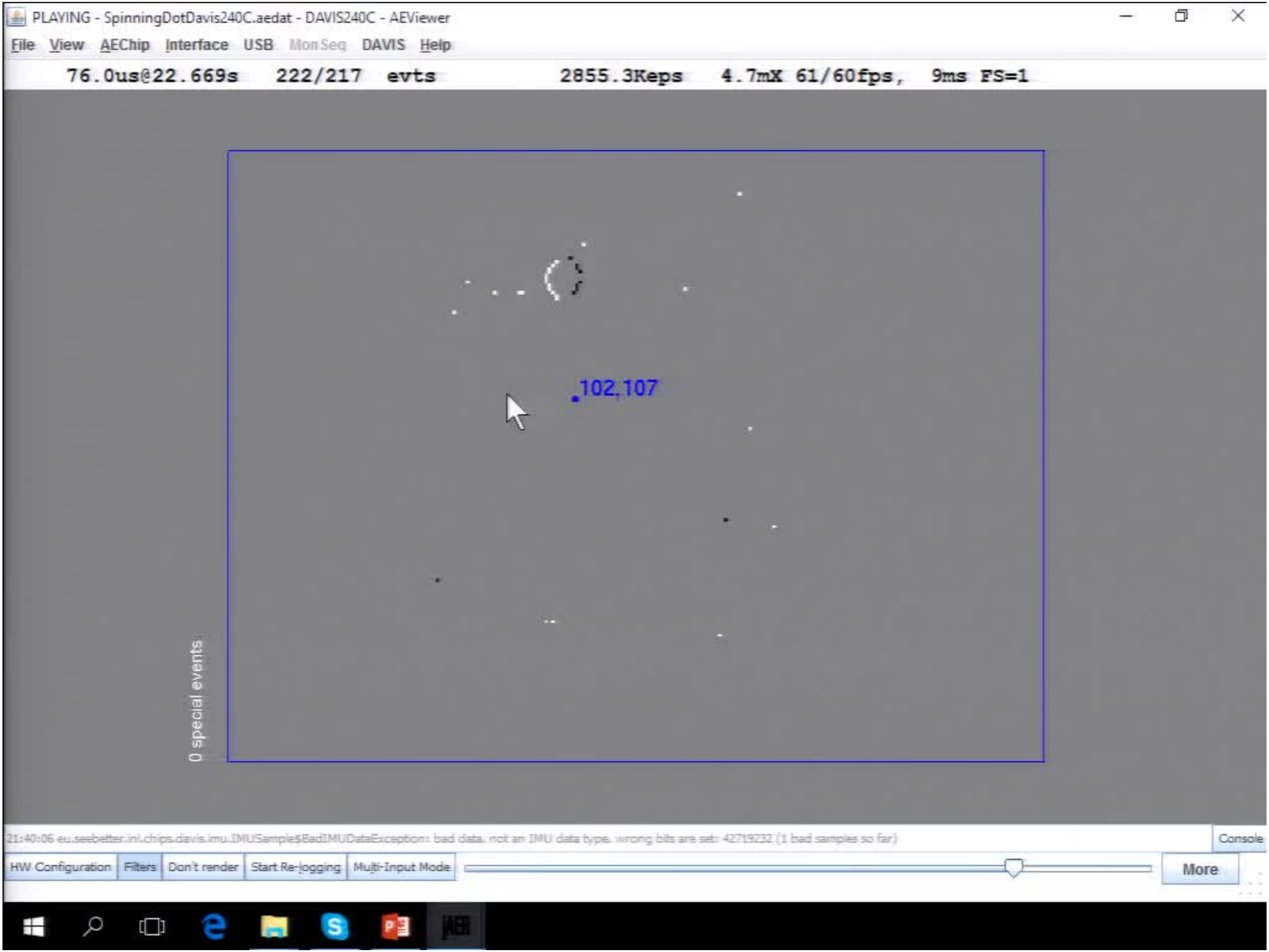

LIVE - DAVIS240C - DAVIS FX2 04010058 - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
New viewer Ctrl-N
Open logged data file... O
Close Ctrl-W
Set timestamp reset bitmask... (currently 0x0)
Start logging data L
Playback logged data immediately after logging enabled
Set logging time limit...
Enable filtering of logged or network output events
Remote
Synchronize AEViewer logging/playback
Check for non-monotonic time in input streams
1 SpinningDotDavis240C.aedat
2 DVS128 Patrick juggling.dat
3 DAVIS240C-2016-03-16T10-04-38+0000-04010058-0.aedat
4 DAVIS240C-2016-03-16T09-38-28+0000-04010058-0.aedat
5 DAVIS240C SpinningDot.aedat
Aedat examples\
Trial Run 6 with filters 1mps\
Trial Run 4 with filters 0.5mps\
Exit X
0.0KepsLive/Seq 61/60fps, 13ms FS=4
102,107
0 special events
Console
HW Configuration
Filters
Don't render
Start logging
Multi-Input Mode

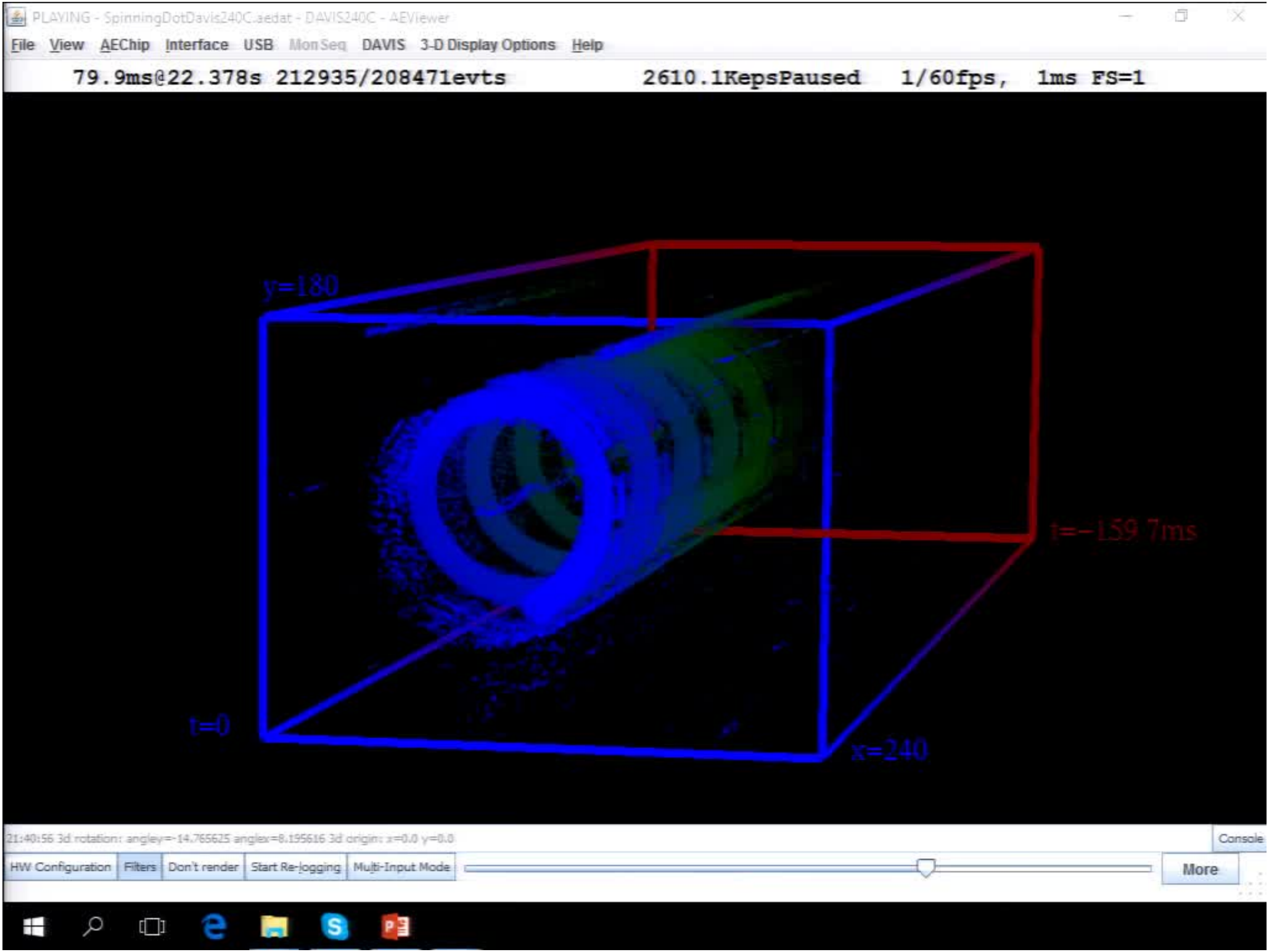

PLAYING - SpinningDotDavis240C.aedat - DAVIS240C - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
20.0ms@22.761s 48306/47202evts 2360.2Keps 1.2 X 60/60fps, 4ms FS=4
102,107
0 special events
21:39:28 rewind
Console
HW Configuration
Filters
Don't render
Start Re-logging
Multi-Input Mode
More

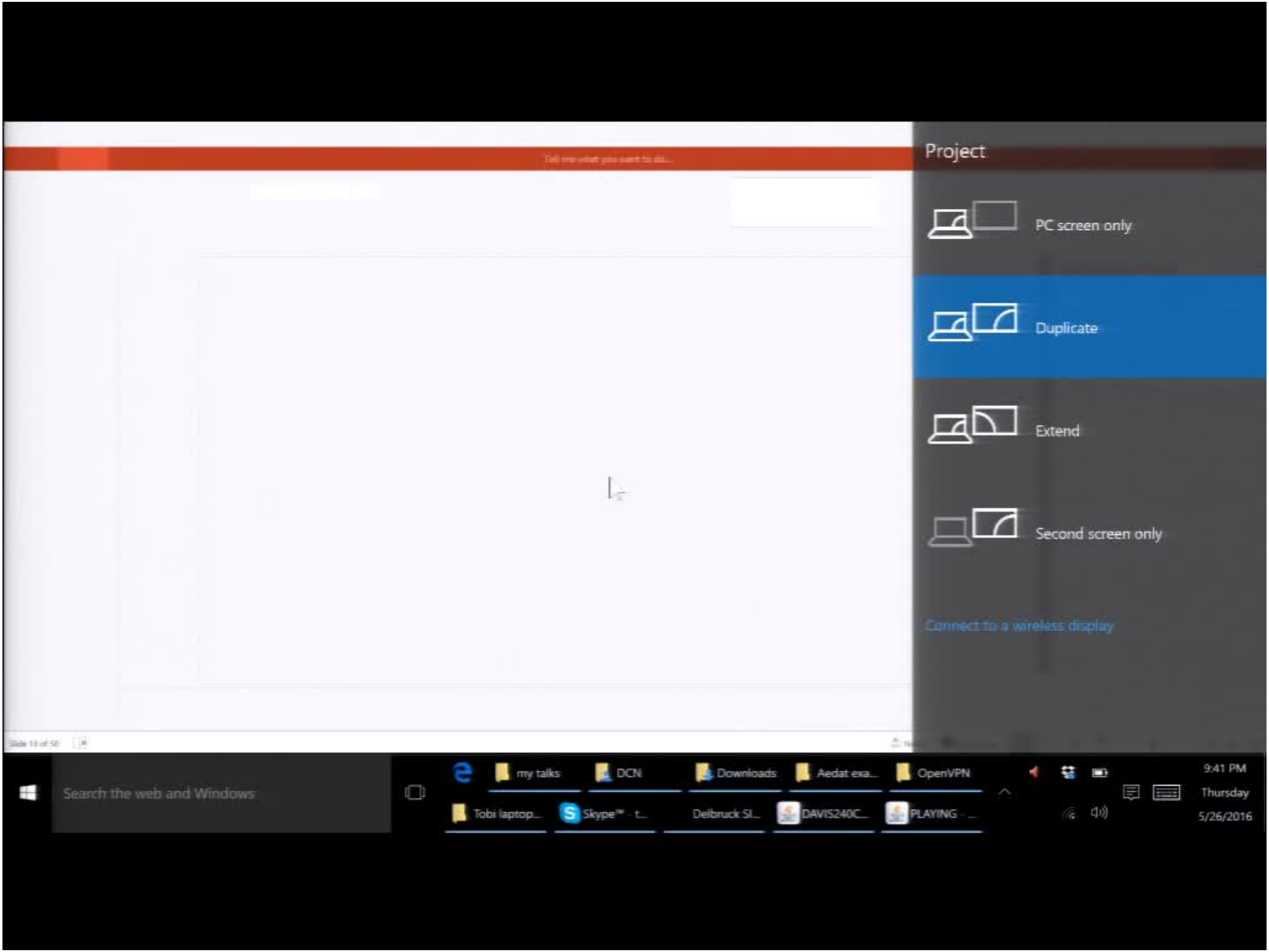

PLAYING - SpinningDotDavis240C.aedat - DAVIS240C - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
20.0ms@22.701s 54858/53405evts 2670.4Keps 1.2 X 59/60fps, 3ms FS=4
Time slice/Absolute time, NumEvents/NumFiltered, events/sec, Graphics rendering frame rate desired/achieved, Time speedup X, delay after frame, color scale
Frame: 375, Exposure 4.00 ms, Frame rate: 23.20 Hz
102,107
0 special events
21:39:38 rewind
Console
HW Configuration
Filters
Don't render
Start Re-logging
Multi-Input Mode
More


PLAYING - SpinningDotDavis240C.aedat - DAVIS240C - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
20.0ms@22.701s 54858/53405evts 2670.4Keps 1.2 X 61/60fps, 5ms FS=4
Time slice/Absolute time, NumEvents/NumFiltered, events/sec, Graphics rendering frame rate desired/achieved, Time speedup X, delay after frame, color scale
102,107
0 special events
21:39:42 rewind
Console
HW Configuration
Filters
Don't render
Start Re-logging
Multi-Input Mode
More


PLAYING - SpinningDotDavis240C.aedat - DAVIS240C - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
600.0us@22.434s 1790/1774 evts 2956.7Keps 35.9mX 60/60fps, 10ms FS=4
Frame: 589; Exposure 4.00 ms; Frame rate: 23.21 Hz
102,107
0 special events
21:39:46 rewind
Console
HW Configuration
Filters
Don't render
Start Re-logging
Multi-Input Mode
More


PLAYING - SpinningDotDavis240C.aedat - DAVIS240C - AEViewer
File View AEChip Interface USB MonSeq DAVIS Help
76.0us@22.669s 222/217 evts 2855.3Keps 4.7mX 61/60fps, 9ms FS=1
102,107
0 special events
21:40:06 eu.seebetter.ini.chips.davis.imu.IMUSample$BadIMUDataException: bad data, not an IMU data type. wrong bits are set: 42719232 (1 bad samples so far)
Console
HW Configuration
Filters
Don't render
Start Re-logging
Multi-Input Mode
More


PLAYING - SpinningDotDavis240C.aedat - DAVIS240C - AEViewer
File View AEChip Interface USB MonSeq DAVIS 3-D Display Options Help
79.9ms@22.378s 212935/208471evts 2610.1KepsPaused 1/60fps, 1ms FS=1
y=180
t=-159.7ms
t=0
x=240
21:40:56 3d rotation: angley=-14.765625 anglex=8.195616 3d origin: x=0.0 y=0.0
Console
HW Configuration
Filters
Don't render
Start Re-logging
Multi-Input Mode
More


Project
PC screen only
Duplicate
Extend
Second screen only
Connect to a wireless display
Search the web and Windows
my talks
DCN
Downloads
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OpenVPN
Tobi laptop...
Skype™ - t...
Delbruck SI...
DAVIS240C...
PLAYING - ...
9:41 PM
Thursday
5/26/2016

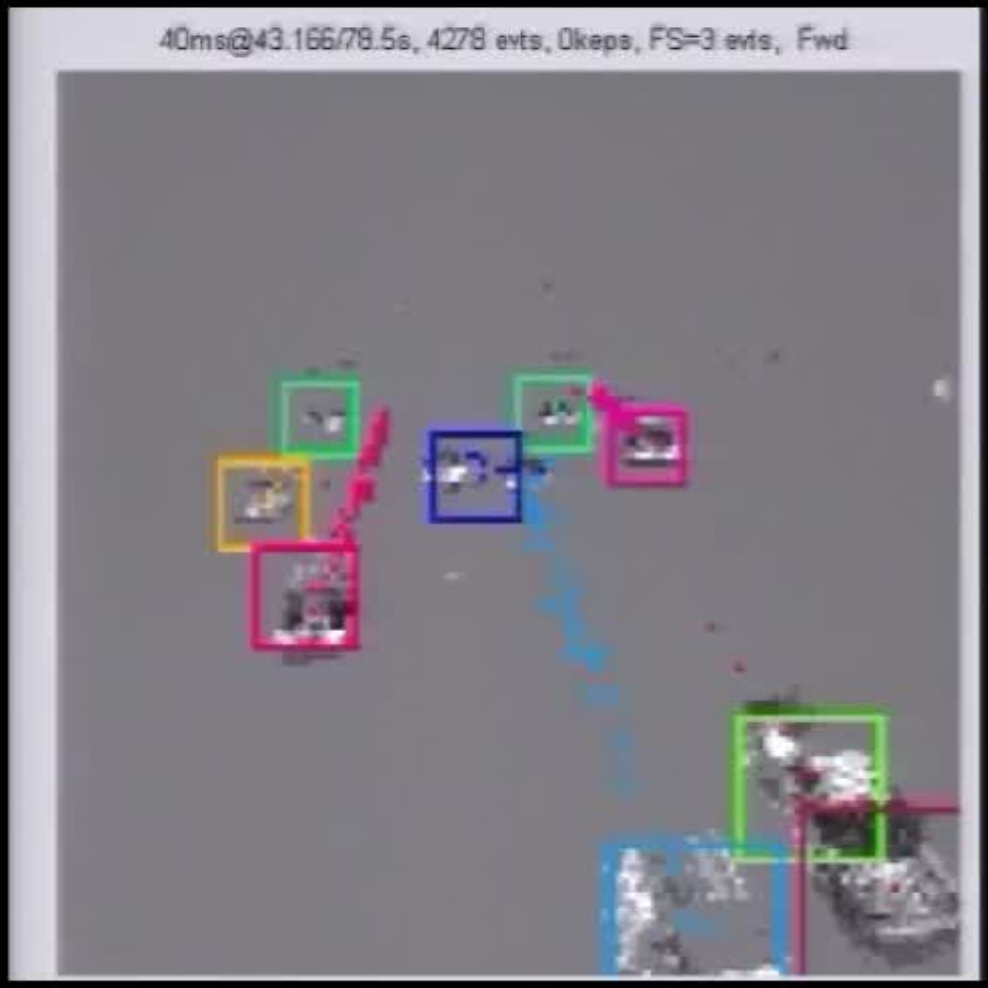
Demo: Dynamic Vision Sensor (DVS) + DAVIS

Brandli, C., Berner, R., Yang, M., Liu, S.-C. & Delbruck, T. A 240x180 130 dB 3us Latency Global Shutter Spatiotemporal Vision Sensor. *IEEE Journal of Solid-State Circuits* **(2015)**.

Basic notions of event-driven DVS processing

Key idea: Use the spatio-temporal coherence of the events

Tracking objects from DVS events using spatio-temporal coherence



For each packet of events

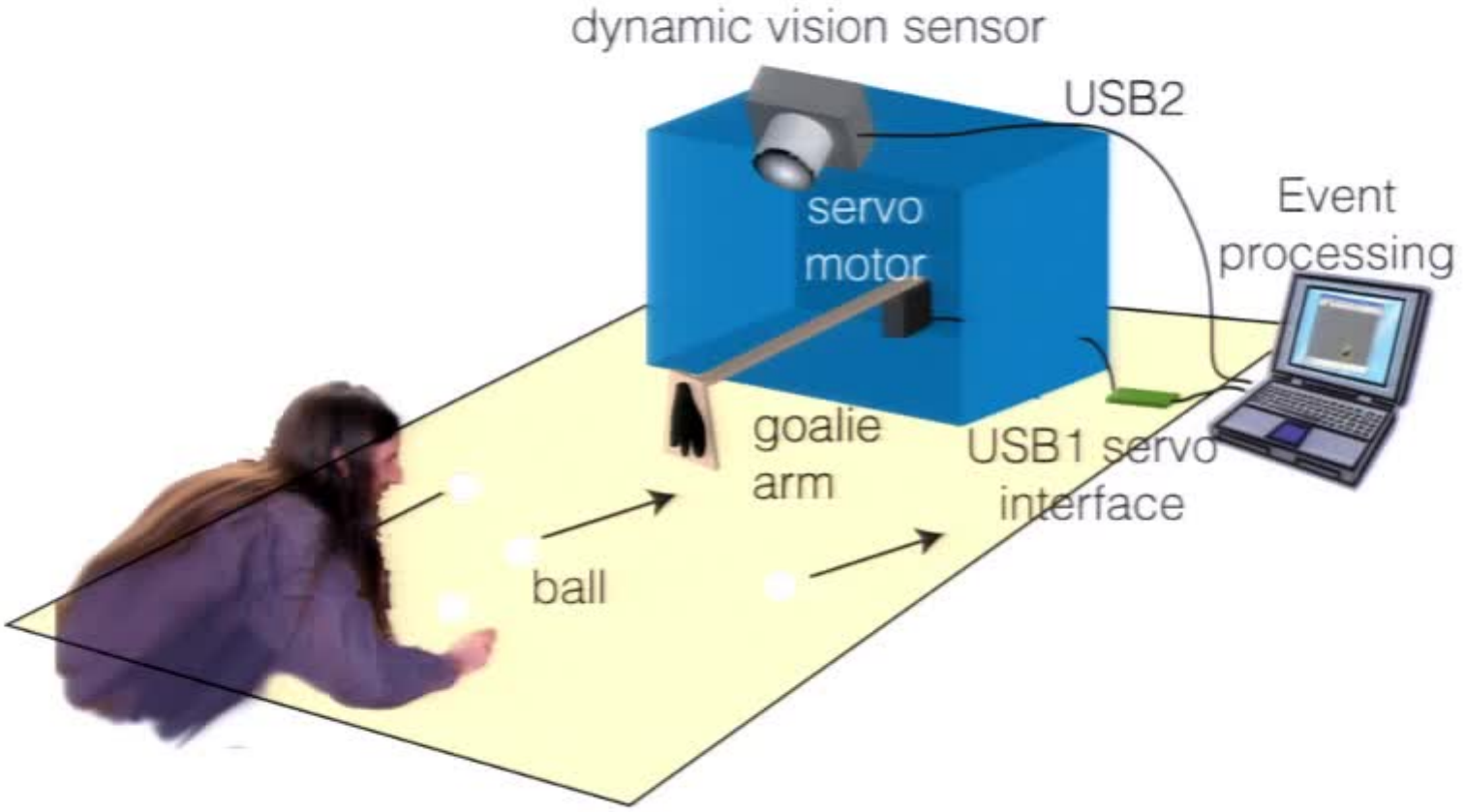
1. For each event

1. Find nearest cluster
   - If event within a cluster, move cluster
   - If event not within cluster, seed new cluster
2. Prune starved clusters, merge clusters, etc (lifetime mgmt)

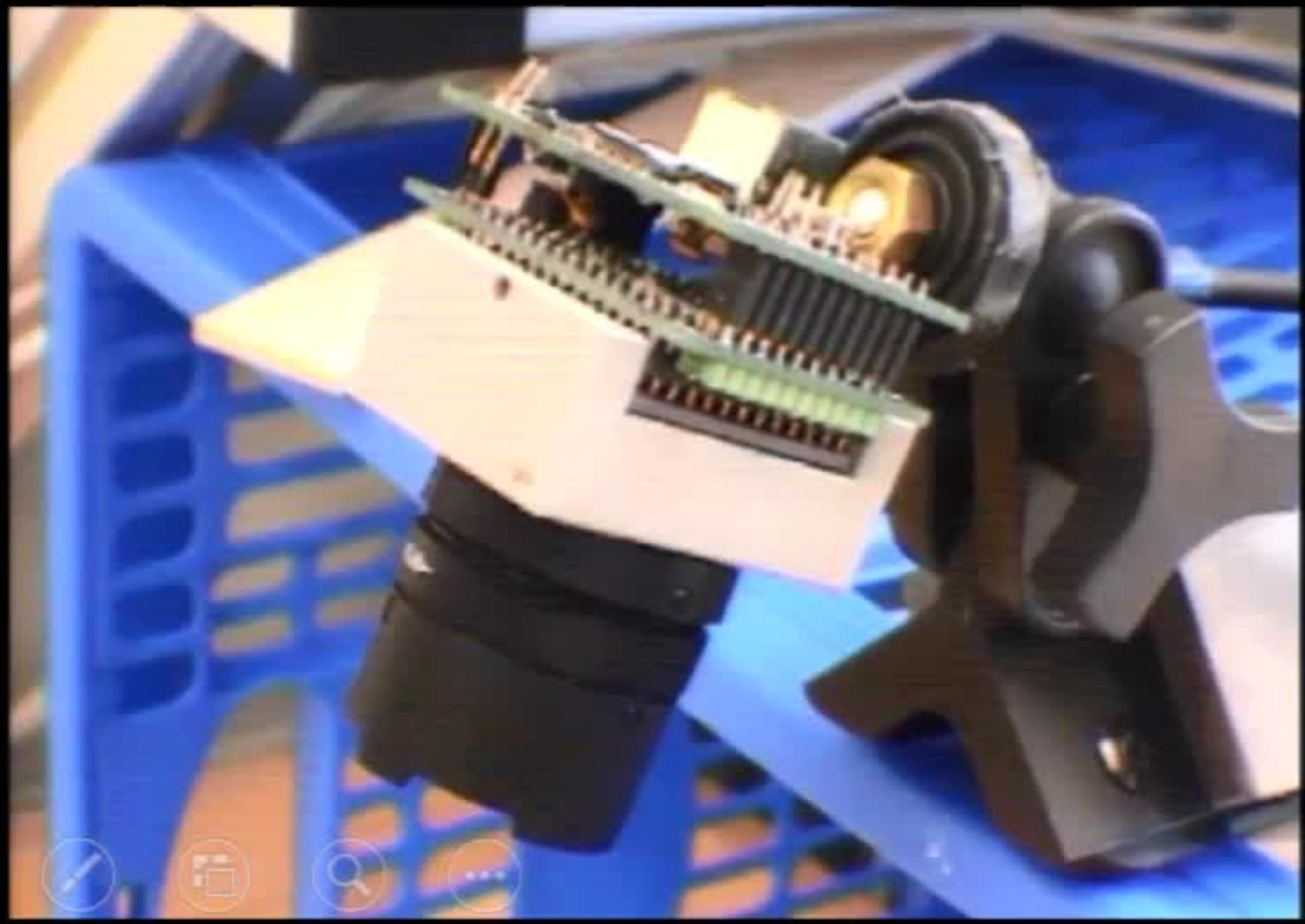
Advantages

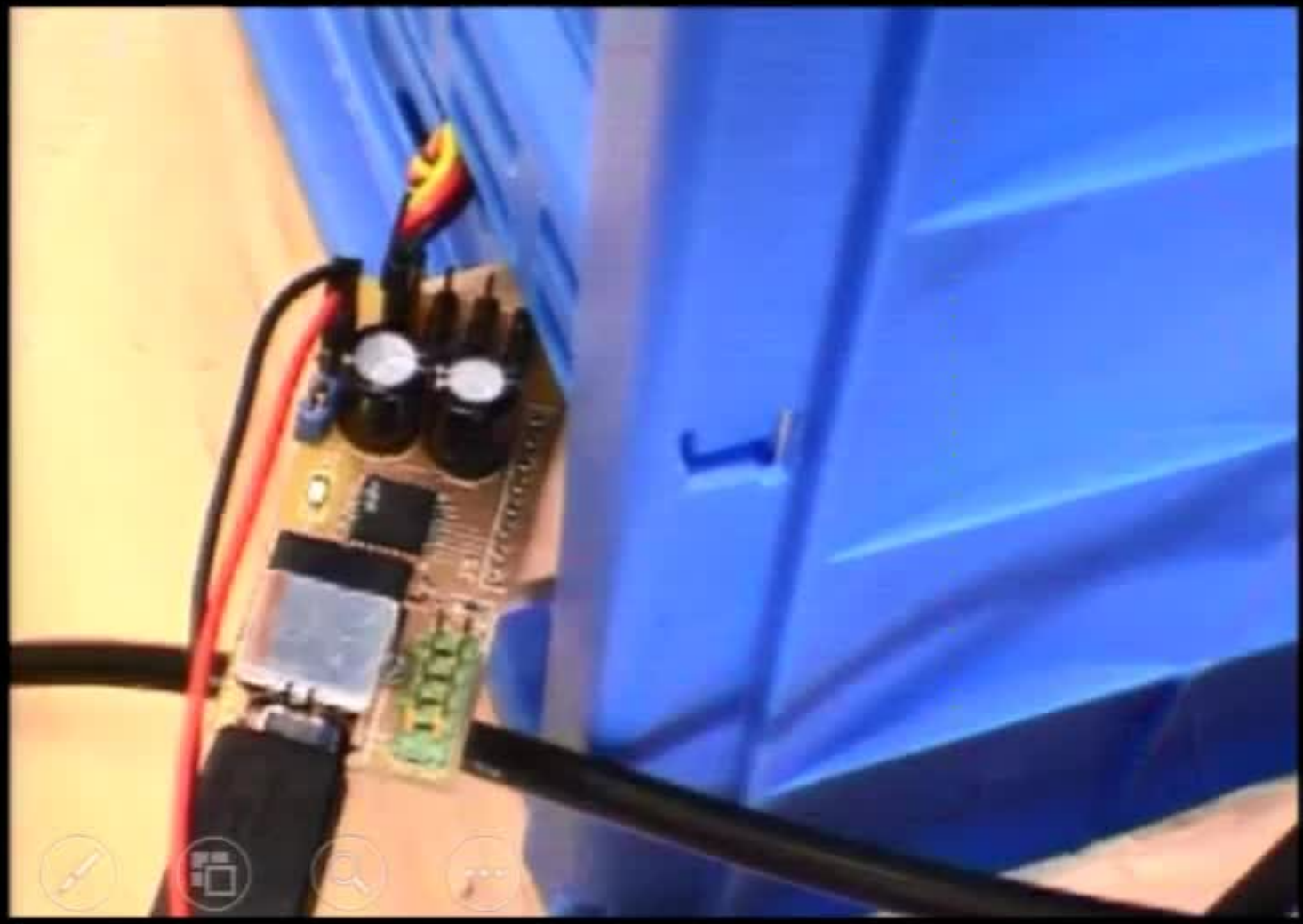
1. Low computational cost (e.g. <5% CPU)
2. No frame memory (~100 bytes/object).
3. No frame correspondence problem

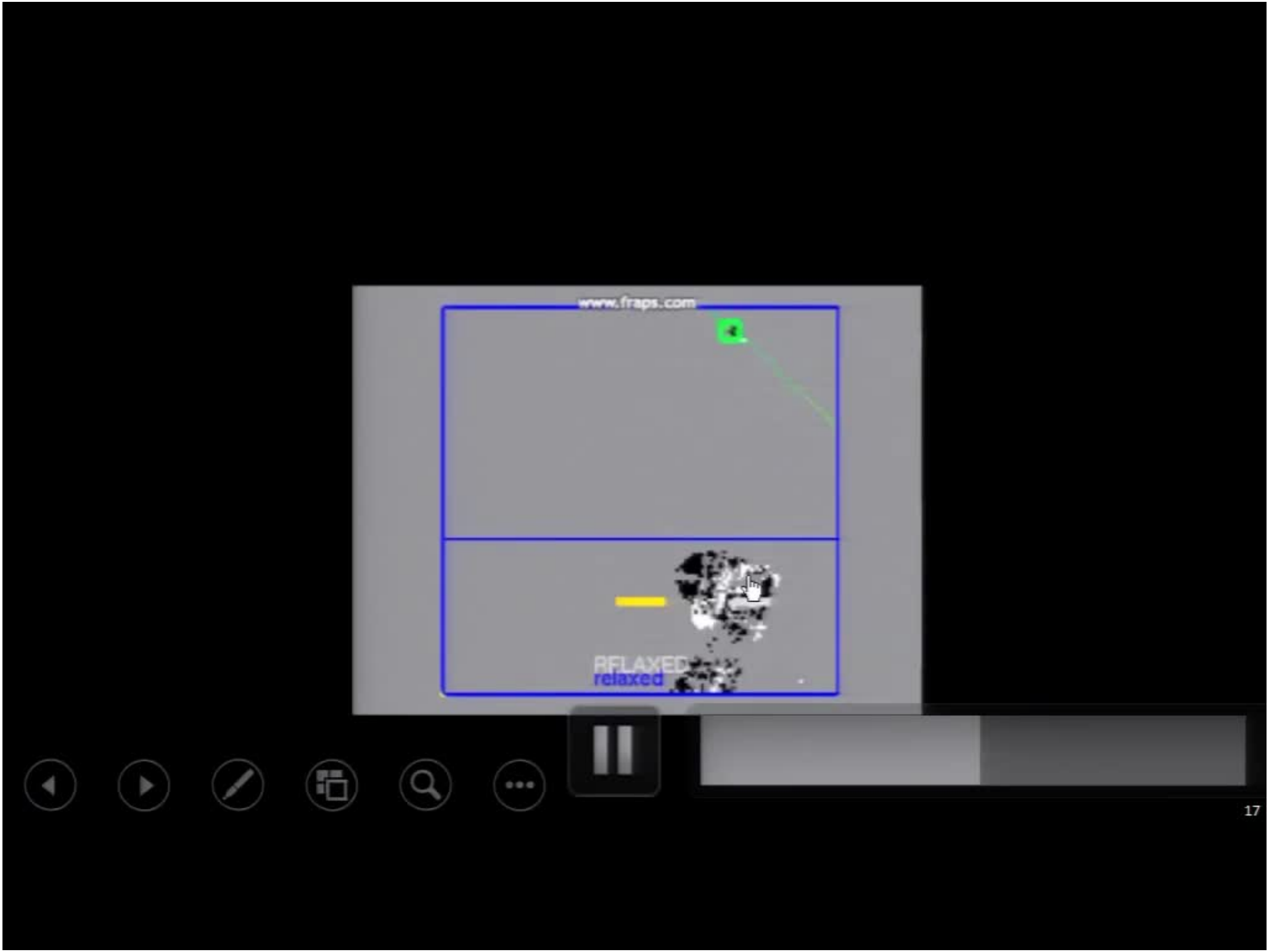
Robot Goalie




11159
Hardware






www.fraps.com
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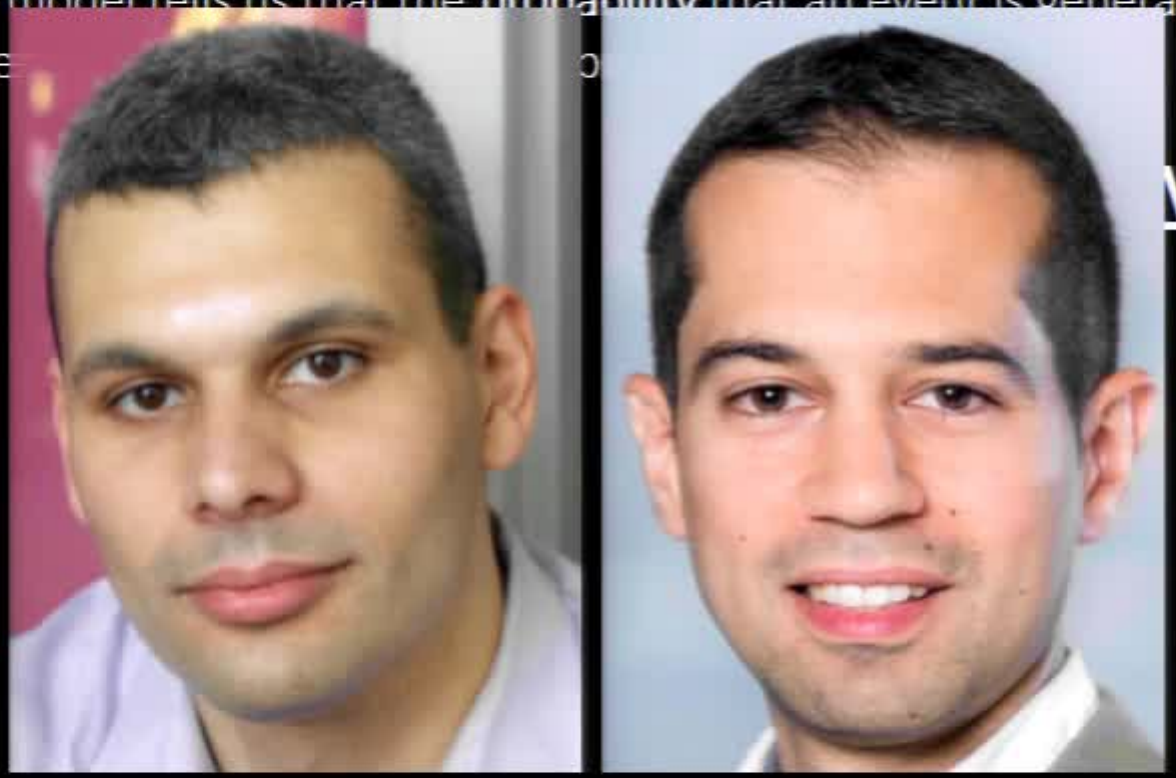
Generative Model [Censi & Scaramuzza, ICRA'14]

The generative model tells us that the **probability** that an event is generated depends on the **scalar product** betwee



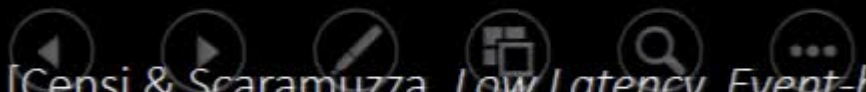
$\Delta t\rangle|$

[Censi & Scaramuzza, *Low Latency, Event-based Visual Odometry*, ICRA'14]

Generative Model [Censi & Scaramuzza, ICRA'14]

The generative model tells us that the **probability** that an event is generated depends on the **scalar product** between the gradient ∇I and the apparent motion $\dot{\mathbf{u}}\Delta t$

$$P(e) \propto |\langle \nabla I, \dot{\mathbf{u}}\Delta t \rangle|$$



[Censi & Scaramuzza, *Low Latency, Event-based Visual Odometry*, ICRA'14]

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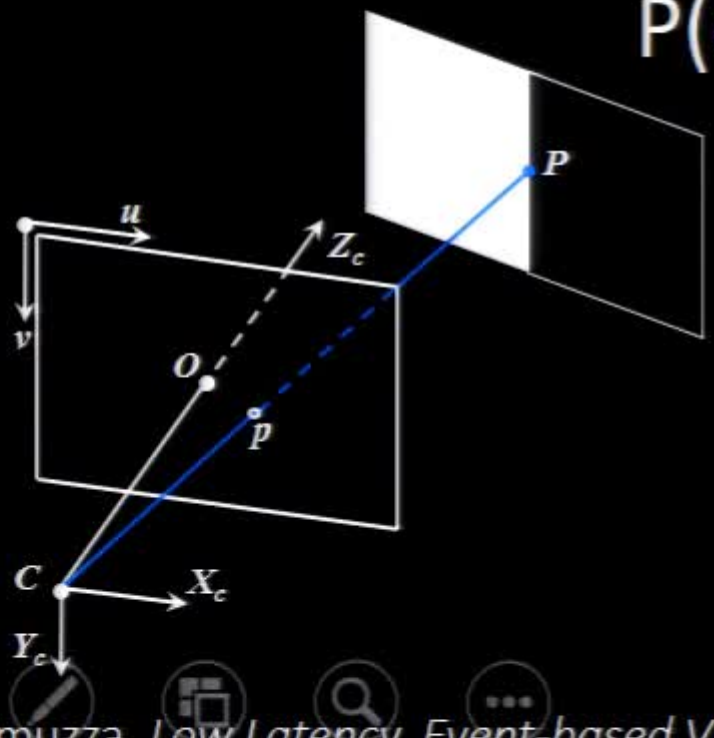

[Censi & Scaramuzza, *Low Latency, Event-based Visual Odometry*, ICRA'14]

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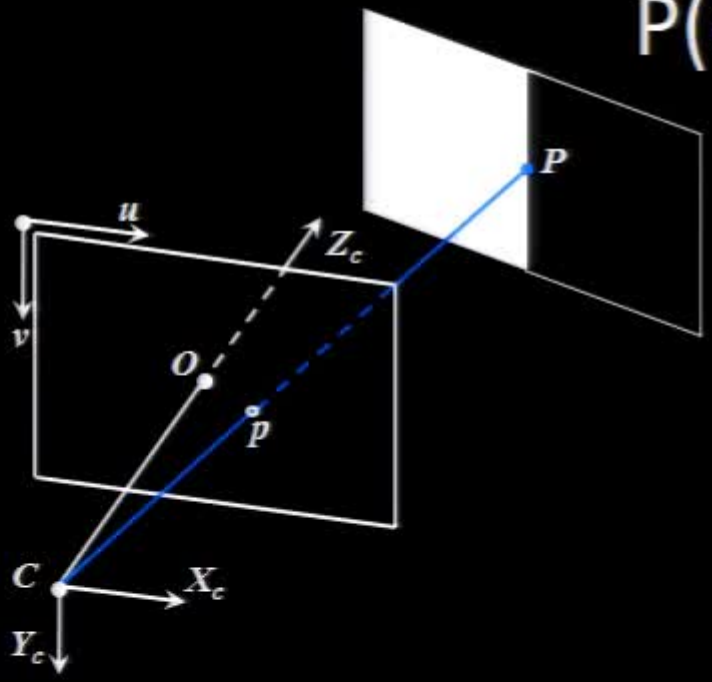
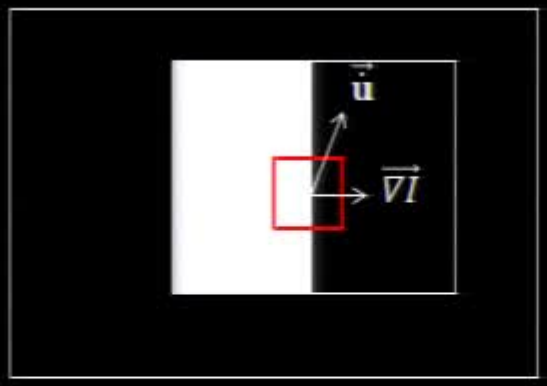




[Censi & Scaramuzza, *Low Latency, Event-based Visual Odometry*, ICRA'14]

Simultaneous Mosaicing and Tracking with DVS

H. Kim, A. Handa, … A. J. Davison, *BMVC 2014*.

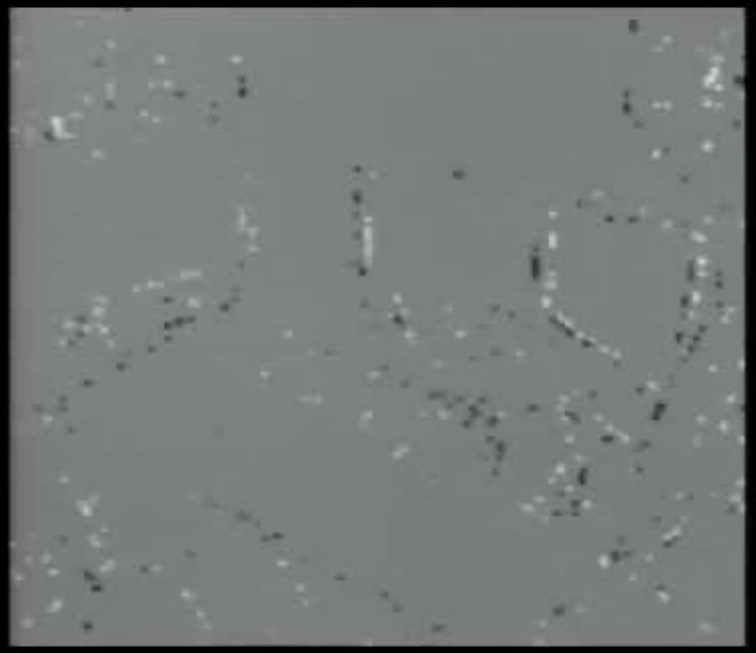
H. Kim, A. Handa, … A. J. Davison, *BMVC 2014*.

Simultaneous Mosaicing and Tracking with an Event Camera

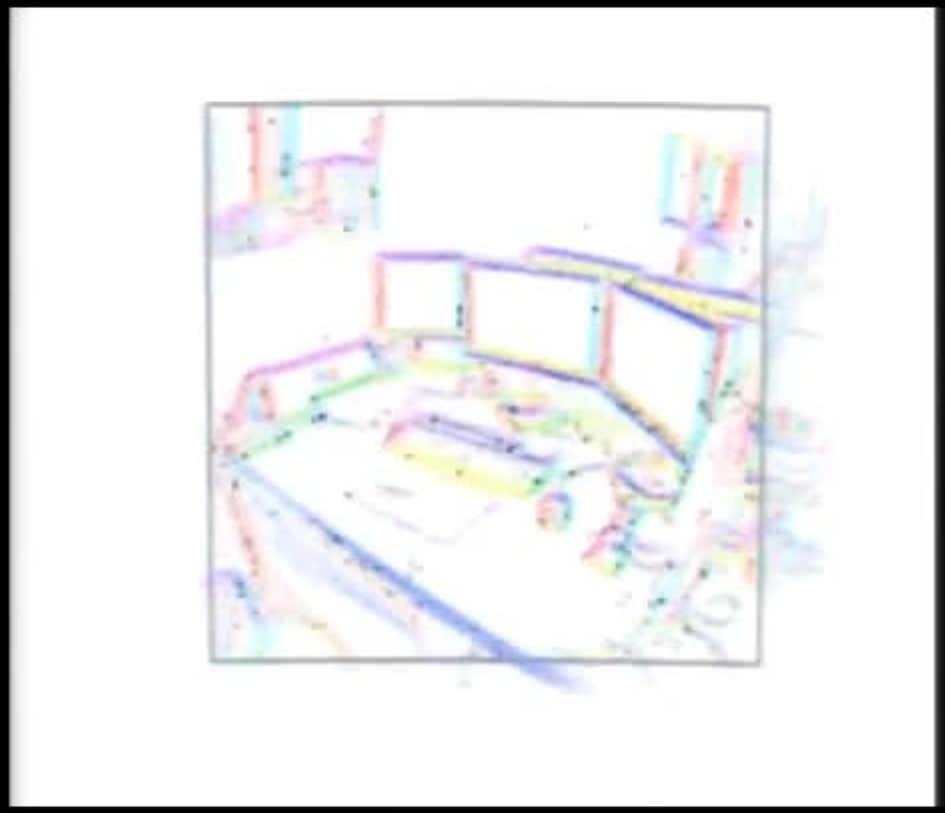
Hanme Kim [1], Ankur Handa [2], Ryad Benosman [3],
Sio-Hoi Ieng [3], Andrew J. Davison [1]

[1] Imperial College London
[2] University of Cambridge
[3] UPMC Univ Paris 06

Event Camera & Scene



Visualisation of Events

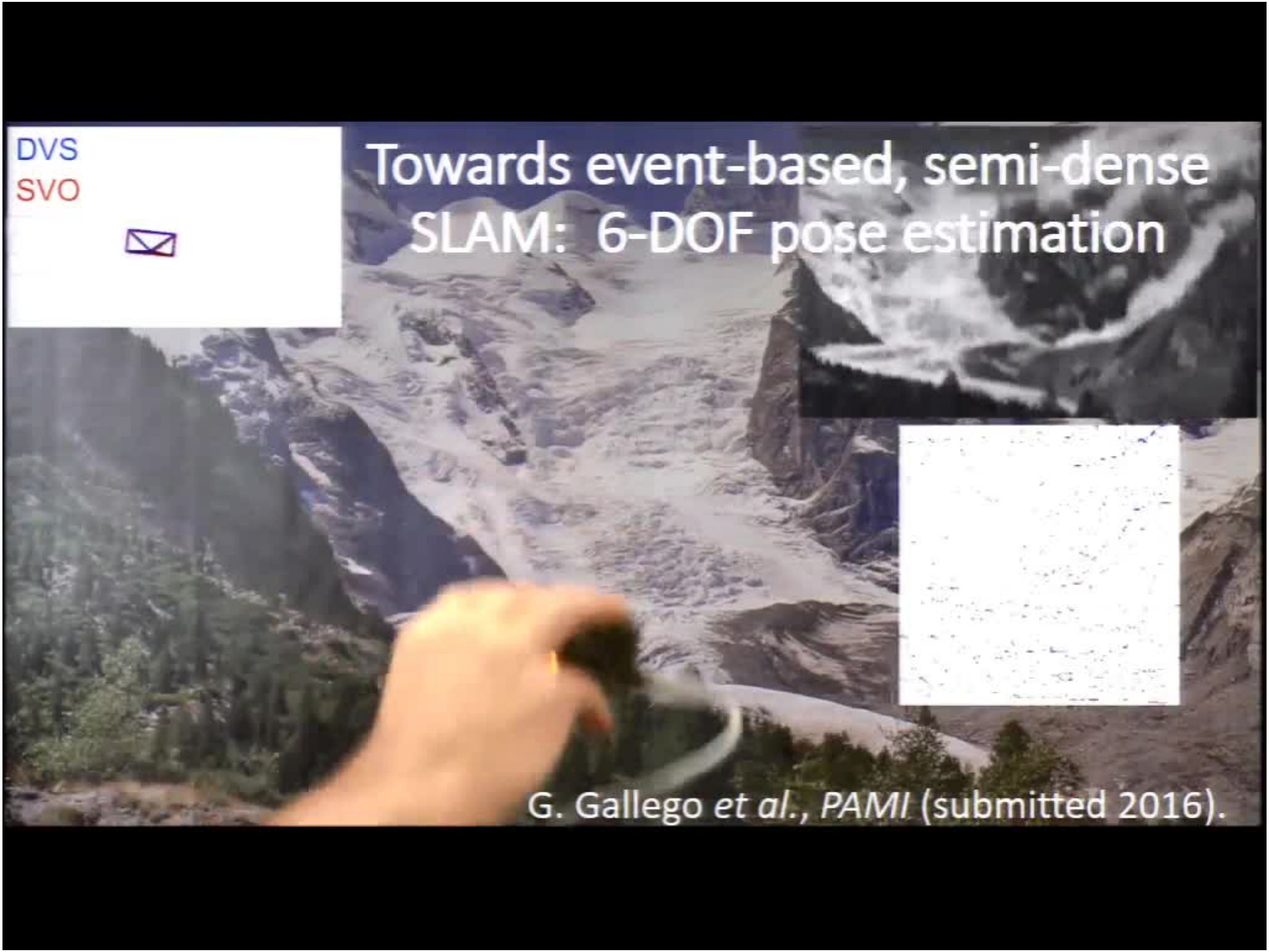


Gradient Map Estimation

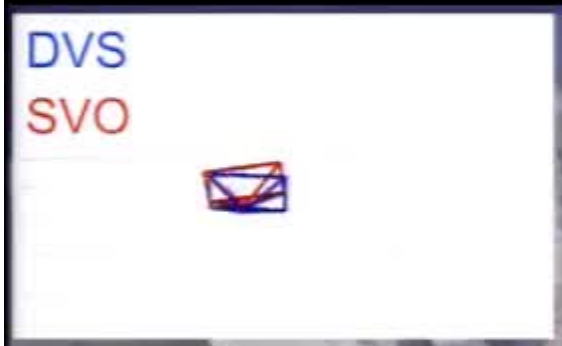
Scene Reconstruction

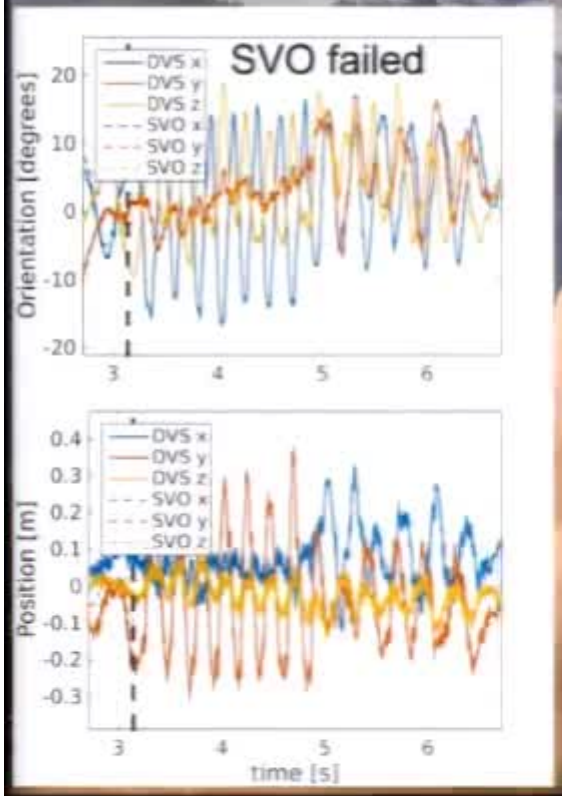

Input Events
Gradient Map Estimation
Scene Reconstruction


Towards event-based, semi-dense SLAM: 6-DOF pose estimation
DVS
Standard camera
G. Gallego *et al.*, *PAMI* (submitted 2016).


DVS
SVO
Towards event-based, semi-dense SLAM: 6-DOF pose estimation
G. Gallego *et al.*, *PAMI* (submitted 2016).

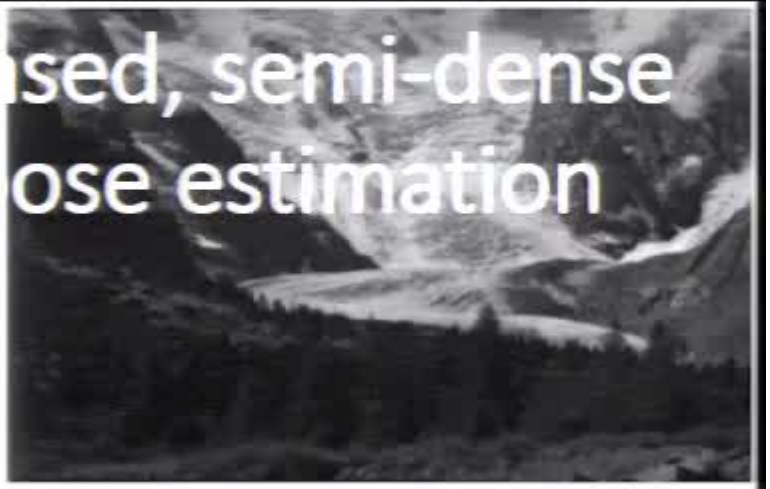
Towards event-based, semi-dense SLAM: 6-DOF pose estimation

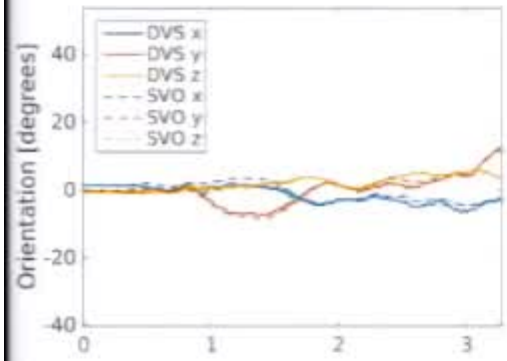


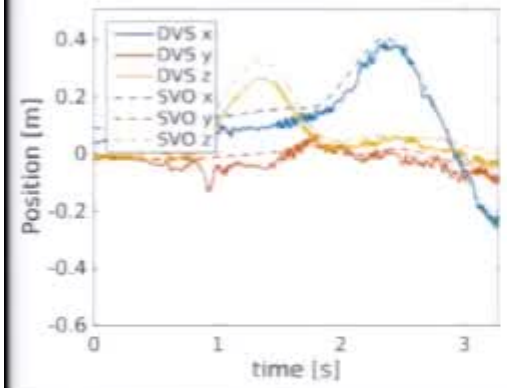


1/5x

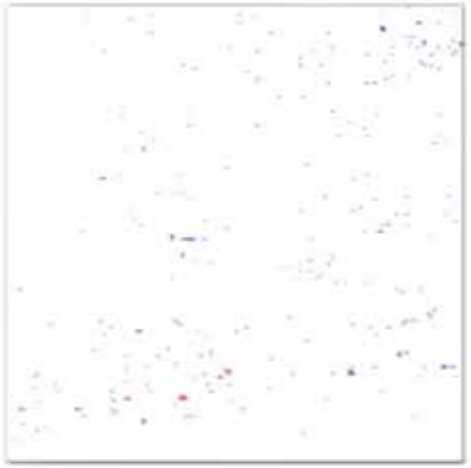
G. Gallego *et al.*, *PAMI* (submitted 2016).







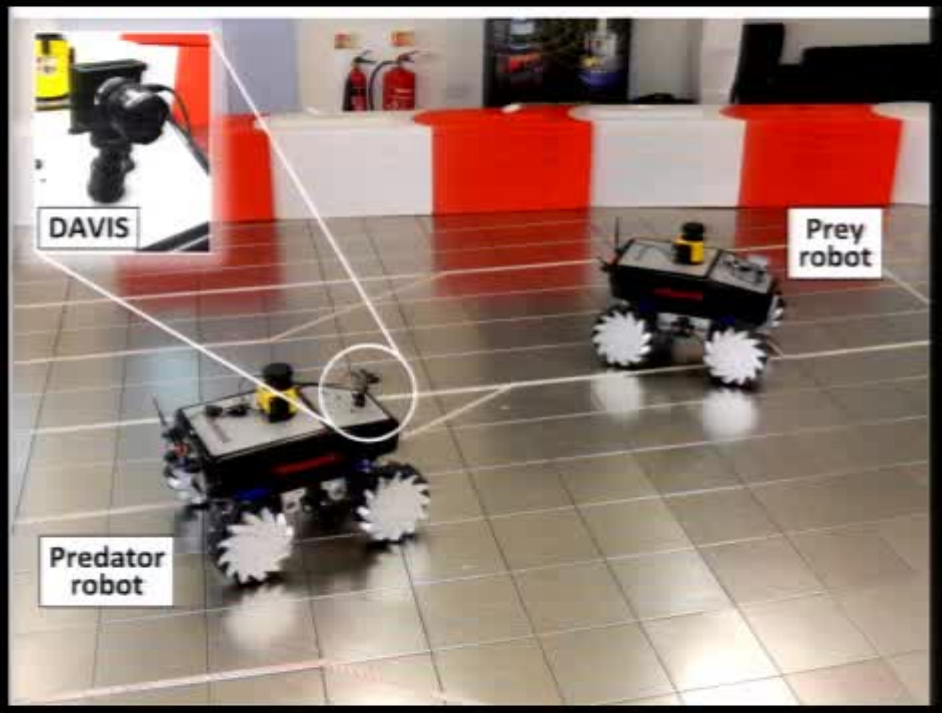
"Indoor Experiment"
(see Figs. 4-7 in paper)



Steering a Predator Robot using a Mixed Frame/Event-Driven Convolutional Neural Network

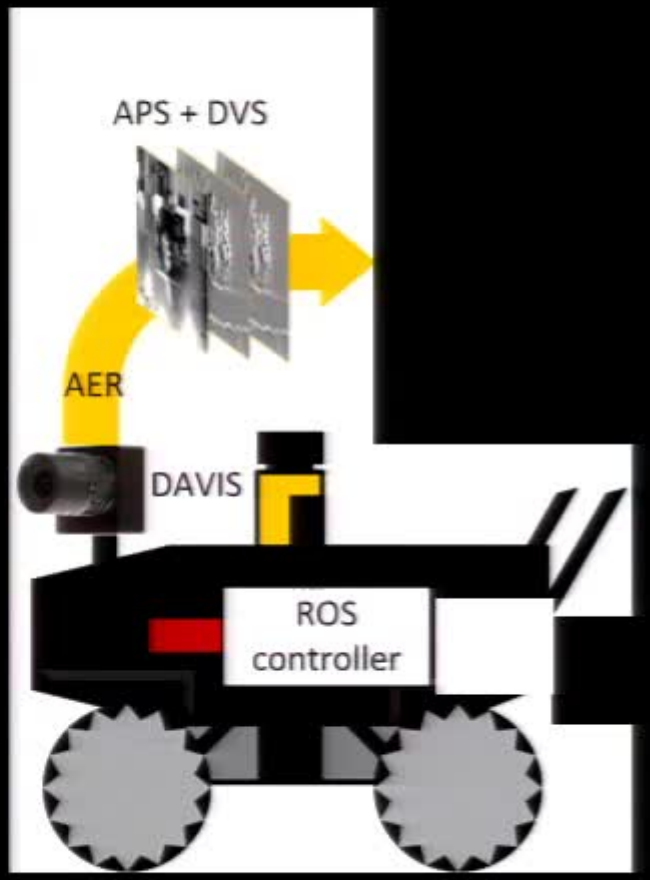
Moeys, D. P. *et al.* IEEE Event-Based Control, Communication, and Signal Processing, (EBCCSP), Krakow, Poland, June 2016

Steering a Predator Robot using a Mixed Frame/Event-Driven Convolutional Neural Network.

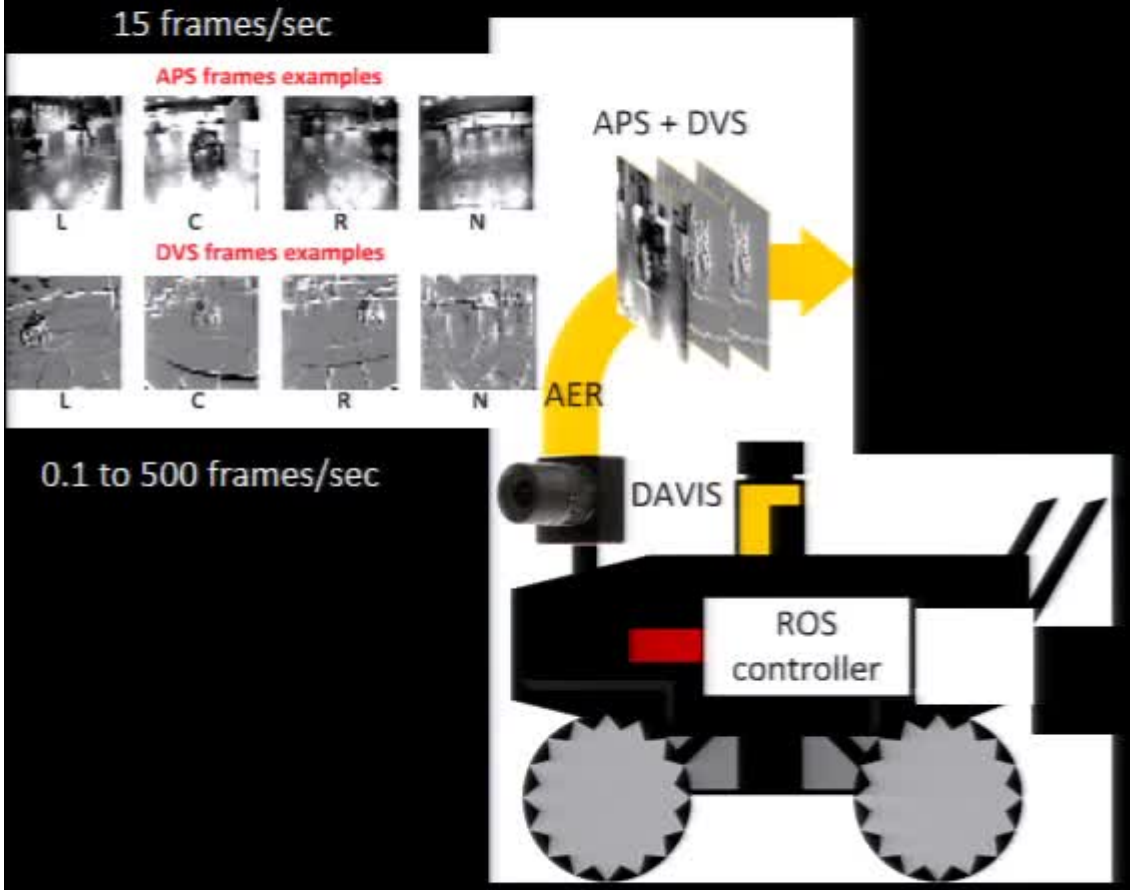


Moeys, D. P. *et al.* IEEE Event-Based Control, Communication, and Signal Processing, (EBCCSP), Krakow, Poland, June 2016

A closed-loop system



A closed-loop system



Accumulation of DVS events over time

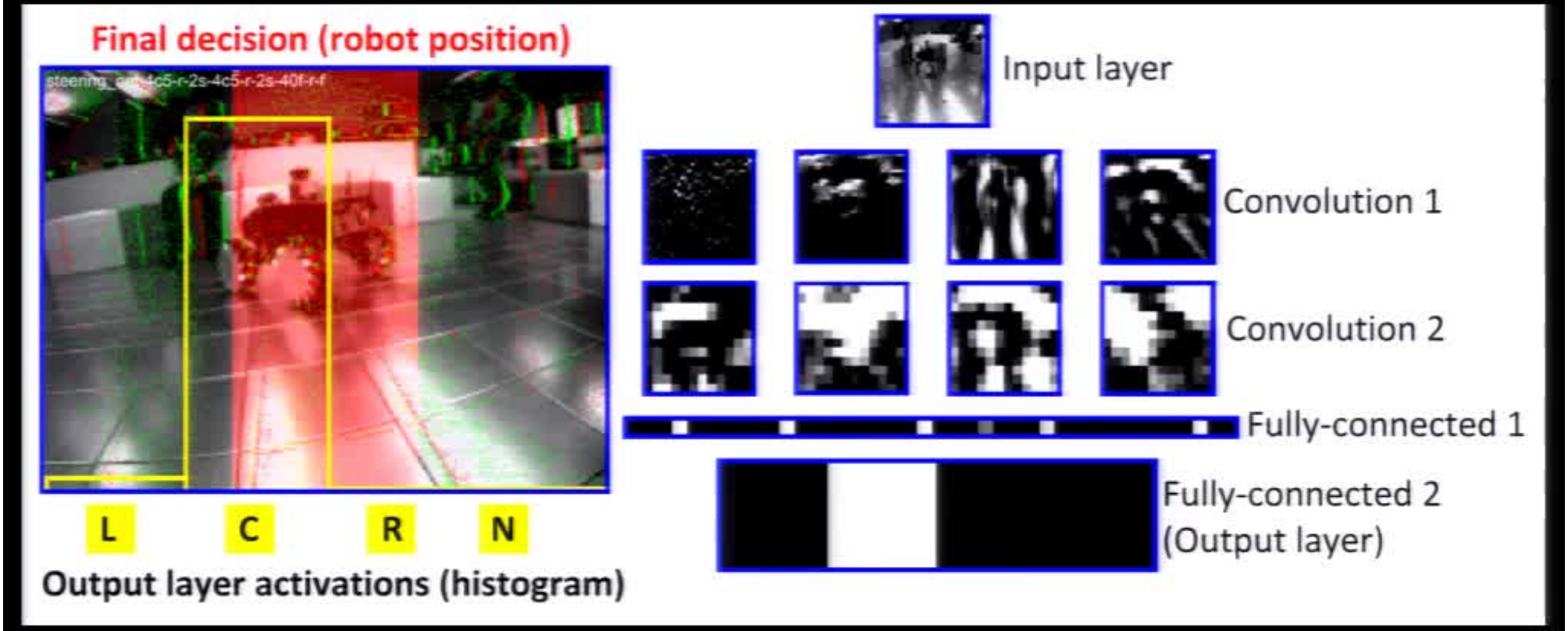
180

240

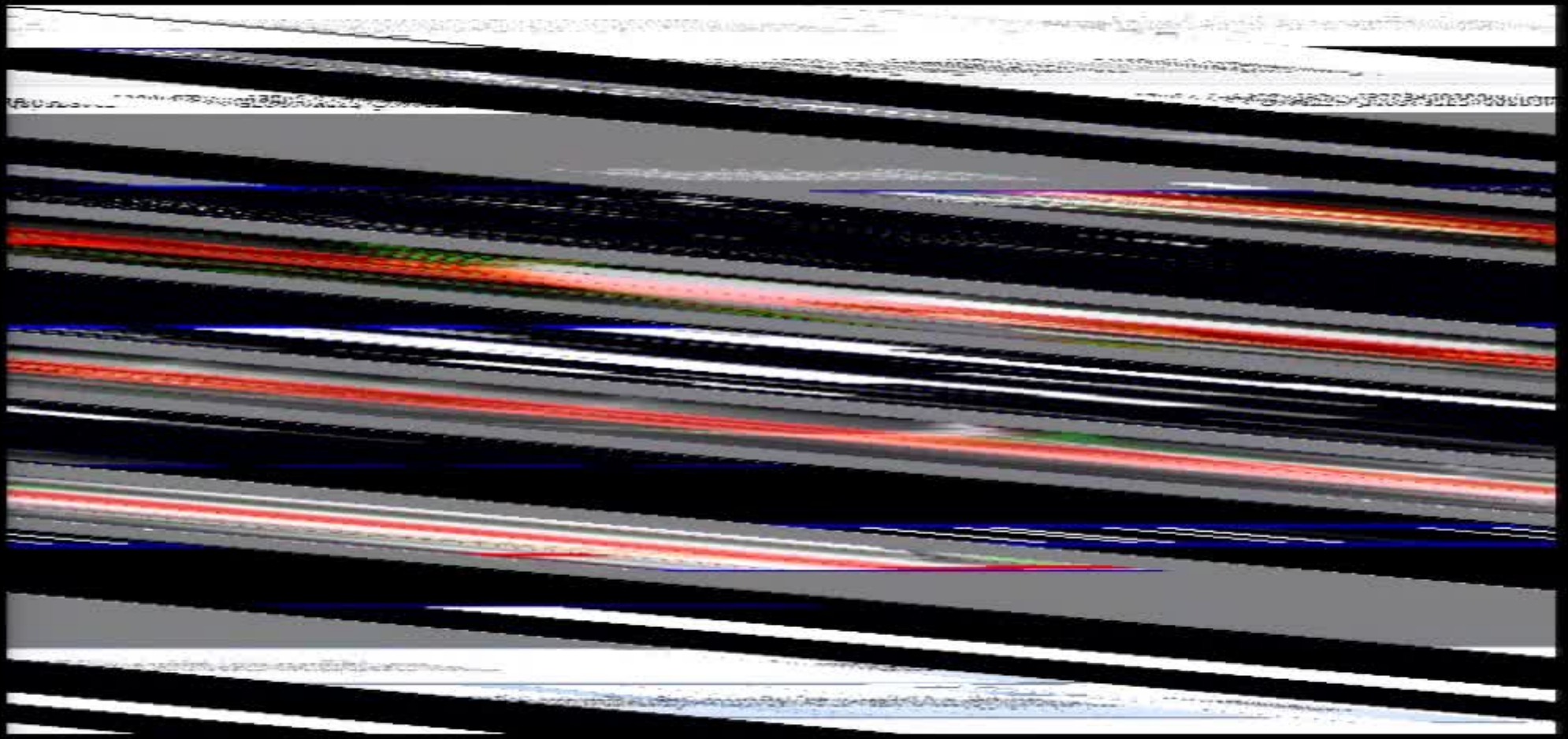
With a few thousand events in 40k pixel array, image can already be recognized.

(CNN is actually driven by 36x36 subsampled histogram.)

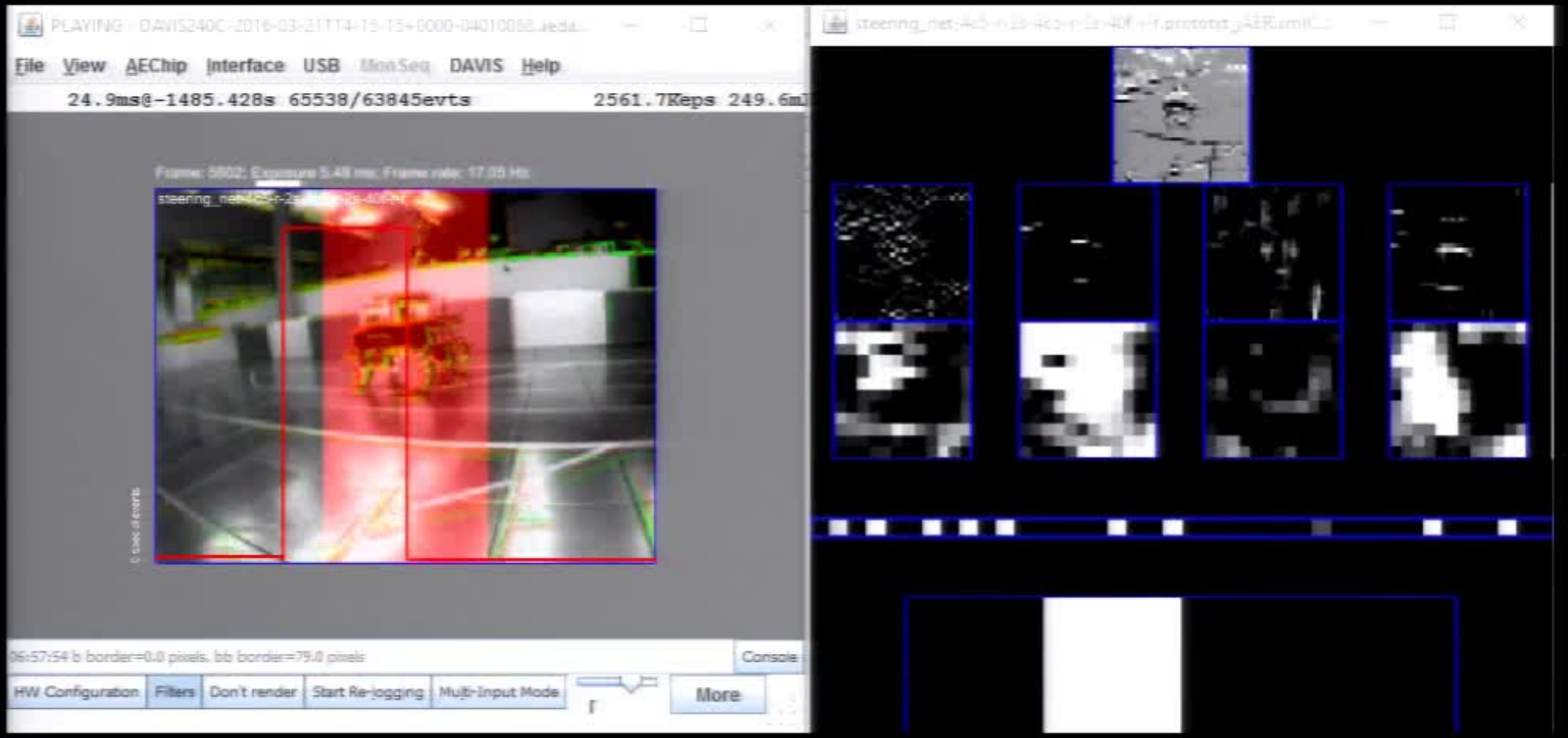
jAER implementation



CNN in action



CNN in action



Closed-loop results

The field of event-driven sensory computing is wide open for fundamental mathematical and practical development