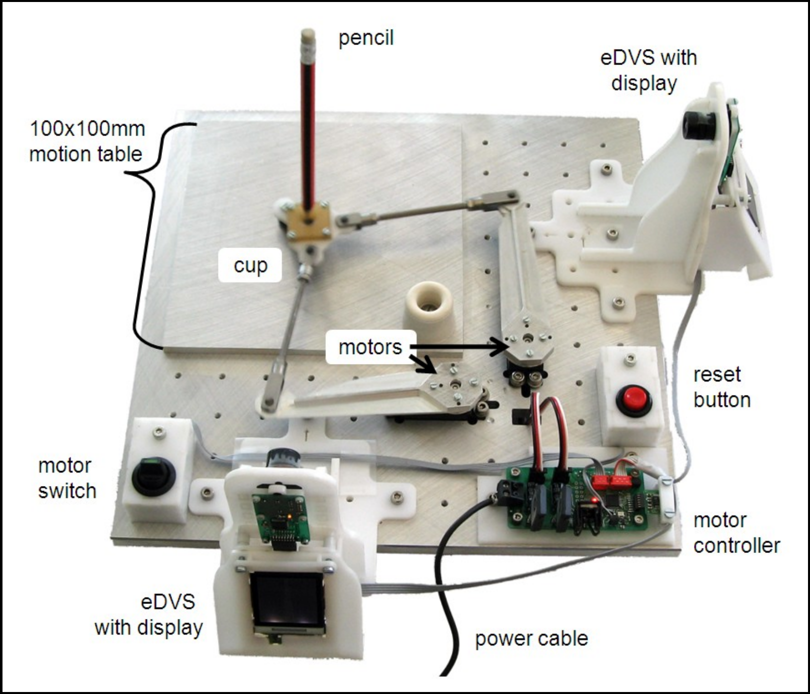
pencil
eDVS with display
100x100mm motion table
cup
motors
reset button
motor switch
motor controller
eDVS with display
power cable

Event-Driven Sensing

Embedded & Realtime Systems

Konstantinos Samaras-Tsakiris

June 1, 2016

Problem Statement

Requirements of many robotic applications:

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- **Low latency control**

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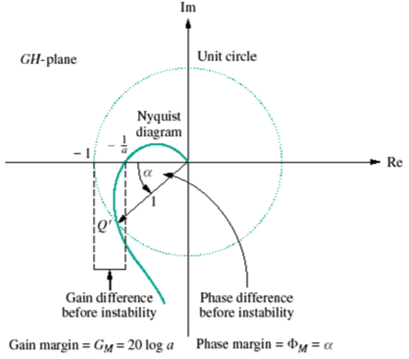
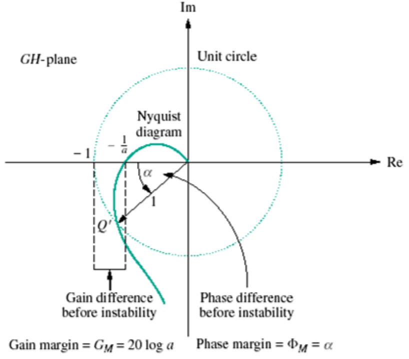


Problem Statement

Requirements of many robotic applications:

- **Low latency control**
- Non-redundant information from sensors – saves on:
  - Processing resources
  - Power consumption
  - Communication bandwidth

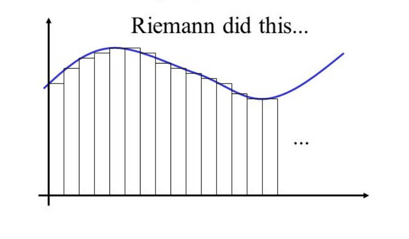


Event-driven Sampling

Lebesgue vs Riemann

Event-driven sampling

Also called "Lebesgue sampling"



Lebesgue vs Riemann

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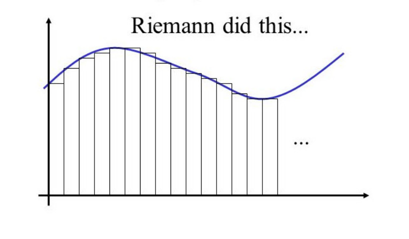
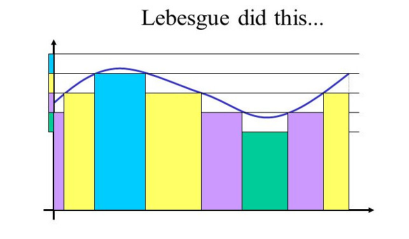
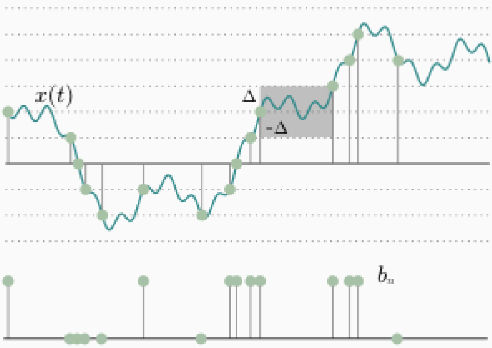




Lebesgue sampling → Events



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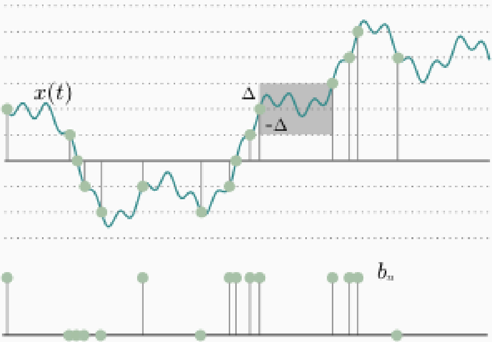

Lebesgue sampling $\rightarrow$ Events

Event Typically boolean "message" - a spike, or $\delta(t)$

Sensor output Asynchronous stream of events - a train of $\delta(t)$

Some event-driven systems

- Position encoders
  - Pulse when position has changed by specific amount

  $\rightarrow$ *Time encoding*

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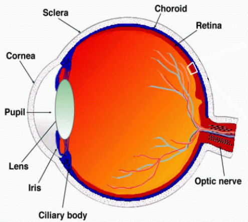

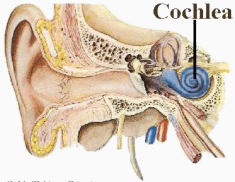

Alec N. Salt, Washington University

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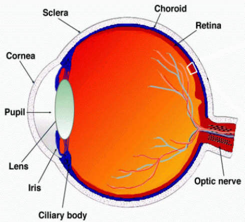

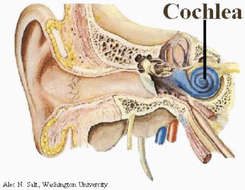

Biological neurons!

Comparison of periodic & event-driven control

Definitions

The control attempts to keep the system state at the origin. Let the system to control be defined by:

$$dx = u\,dt + dv$$

where

x**:** System state

u**:** Control signal

v**:** Disturbance (Wiener process)

d**:** Lebesgue sampling interval

Comparison of periodic & event-driven control

$$dx = u\,dt + dv$$

Periodic sampling with period h

Using a minimum variance controller, the control law becomes:

$$u = -\frac{1}{h}\frac{3+\sqrt{3}}{2+\sqrt{3}}\,x$$

and the variance becomes:

$$V_R = \frac{3+\sqrt{3}}{6}\,h$$

Comparison of periodic & event-driven control

$$dx = u\,dt + dv$$

Event-driven sampling with mean period h_L

Need different control strategy: an impulse that instantly returns the system to the origin. T_d is the time it takes for $|x(t_k)| = d$ for the 1st time. Mean exit time and mean sampling period:

$$h_L := E[T_d] = d^2$$

And the steady state variance:

$$V_L = \frac{d^2}{6} = \frac{h_L}{6}$$

Comparison of periodic & event-driven control

Comparison

To compare, assume the mean sampling rates are equal: $h = h_L$.

Then:

$$\frac{V_R}{V_L} = 4.7$$

But each follows a different control strategy to allow simple analysis.

Comparison of periodic & event-driven control

Comparison

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Then:

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But each follows a different control strategy to allow simple analysis.

Periodic sampling with impulse control as well:

$$\frac{V_R'}{V_L} = 3$$

$\boxed{\text{Event-driven sampling offers } \textit{3 times less variance}}$

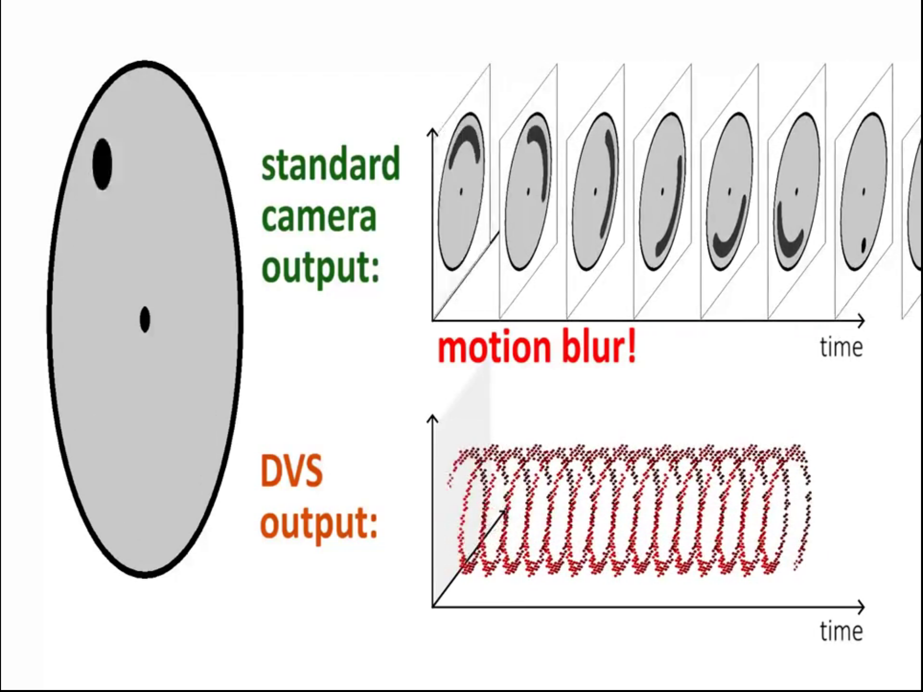
The difference is even larger for unstable systems

Consequences for control

Event signals are incompatible with traditional signal processing of continuous signals. But offer other benefits:

- Take control action only as necessary - not on steady state!
- Same control efficiency with lower sampling rate

Dynamic Vision Sensor


standard camera output:
motion blur!
time
DVS output:
time

From frames to events

Normal camera

From frames to events

Normal camera

- Rolling or global shutter
- Fixed frame rate
- Single pictures at constant rate

From frames to events

Normal camera

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Event-driven camera

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Event-driven camera

- Independent pixels
- Each detects brightness change in its receptive field
  - *Logarithmic* changes

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Fechner's Law

From frames to events

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- change $>$ threshold $\rightarrow$ event (asynchronous)
  - event: $e_k = x_k, y_k, t_k, p_k$ – coordinates, timestamp & polarity

From frames to events

Event-driven camera

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- High temporal resolution (microseconds)
- Low spatial resolution ($128 \times 128px$)
- Dynamic range $120dB$ vs. $60dB$ for traditional image sensors
- Shared event bus
  - Statistical time division multiplexing

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$\boxed{\text{Asynchronous event stream instead of frames}}$

Event Processing

Problem satisfaction

An event-driven sensor can address the issues stated at the beginning

- Low latency
- Little data redundancy

Event Processing

Problem satisfaction

An event-driven sensor can address the issues stated at the beginning

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Communication protocol

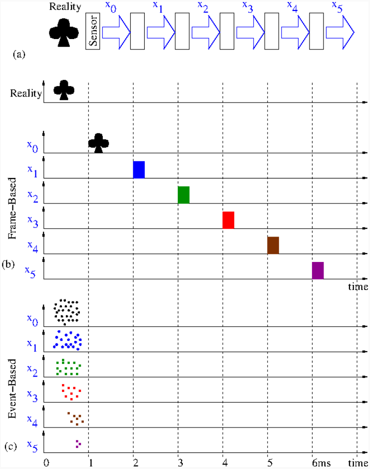
Address Event Representation

Requires different processing methods from standard sensors, based on spatio-temporal correllation

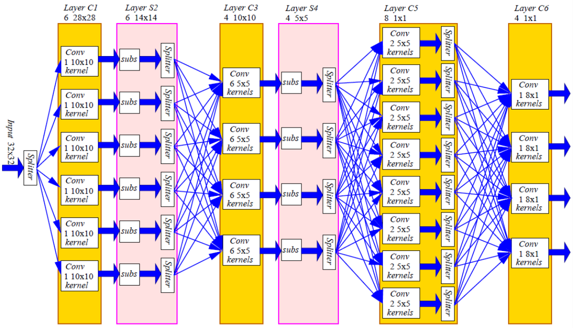
Pseudo-simultaneity

Pseudo-simultaneity of event processing

Each event adds only little information, but is processed very fast, and the response time is not throttled by the frame rate. The output event stream lags behind the input only by a few events.



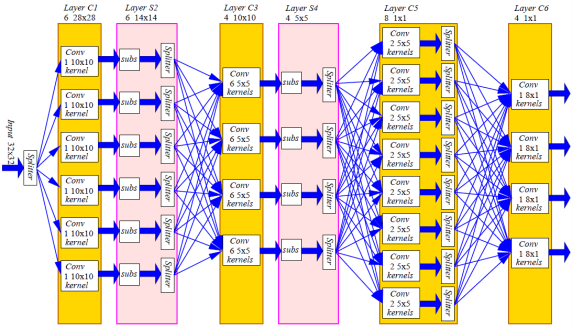
Example Visual Event Processor: Convolutional NN



Implementations:

1. GPU

Example Visual Event Processor: Convolutional NN



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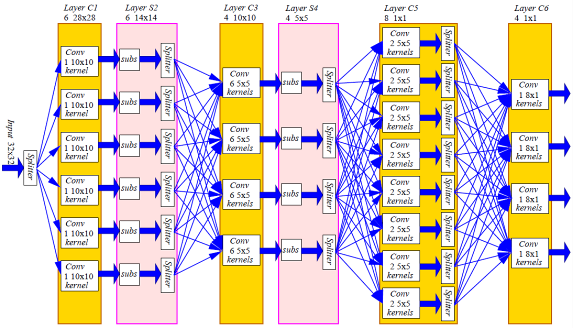

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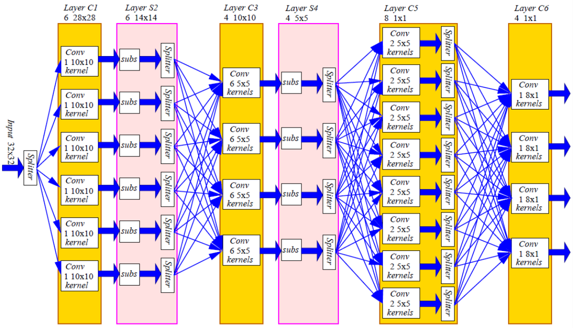

Implementations:

1. GPU
2. FPGA
3. Custom digital hardware
4. Custom analog hardware

Back to the Pencil Balancer

Pencil balancer description

Visual balancing robots

Typical
- Frame-based sensors
- Complex nonlinear control

Pencil balancer description

Visual balancing robots

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This one	- Event-driven sensors
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Pencil balancer description

Visual balancing robots

Typical	- Frame-based sensors
	- Complex nonlinear control
This one	- Event-driven sensors
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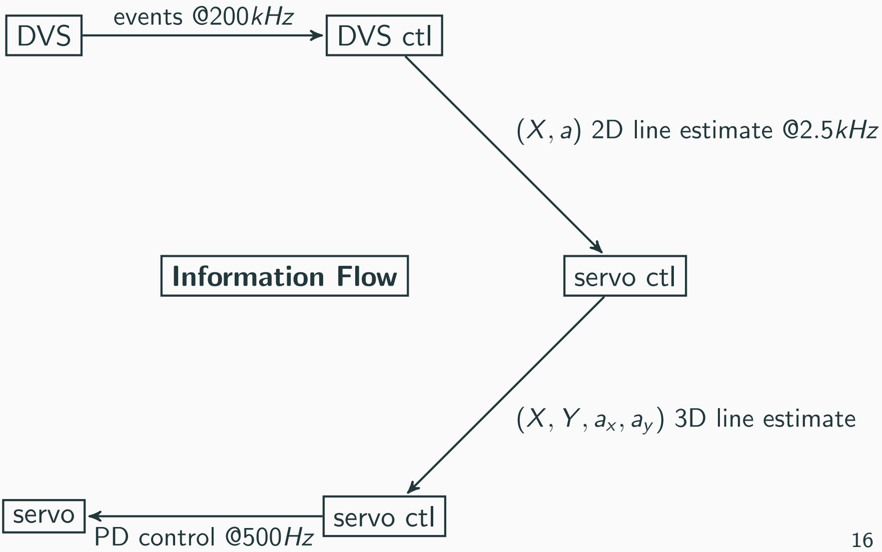
System elements:

1. Monitors object with 2 DVS
2. Actuates with 2 independent servos
3. Controls with linear PD algorithm

Wrapping up with pencil balancer



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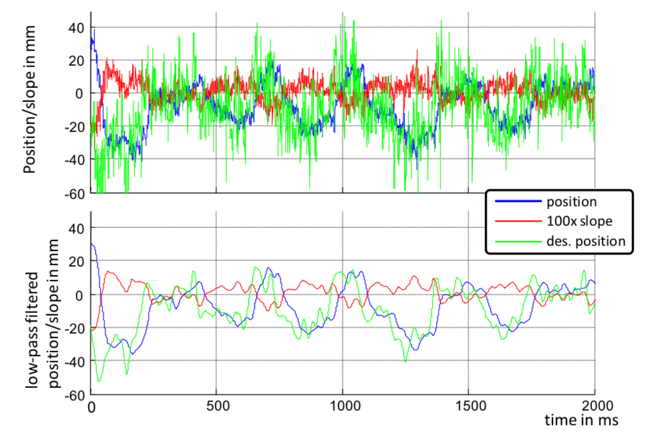

Thank you!

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3. Jorg Conradt, Raphael Berner, Matthew Cook, “An Embedded AER Dynamic Vision Sensor for Low-Latency Pole Balancing”, IEEE 12th International Conference on Computer Vision Workshops, ICCV Workshops, 2009

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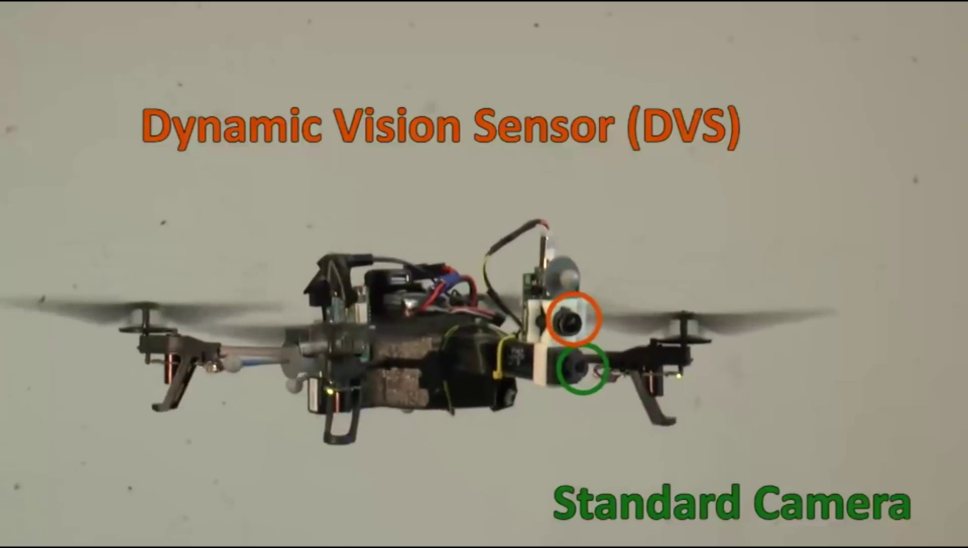
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