Computational Neuroscience for Technology: Event-based Vision Sensors and Information Processing

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Neuroscientific System Theory
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NEUROSCIENTIFIC SYSTEM THEORY
Technische Universität München

28.11.2014 Qualcomm Vienna

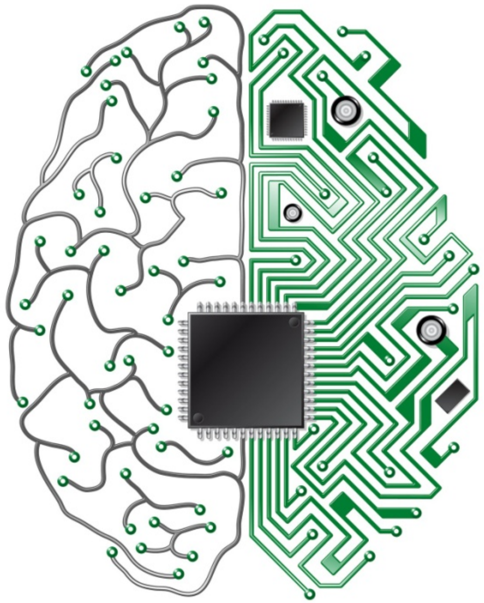
Neuromorphic Engineering

Neuro - morphic

"to do with neurons", i.e. neurally inspired

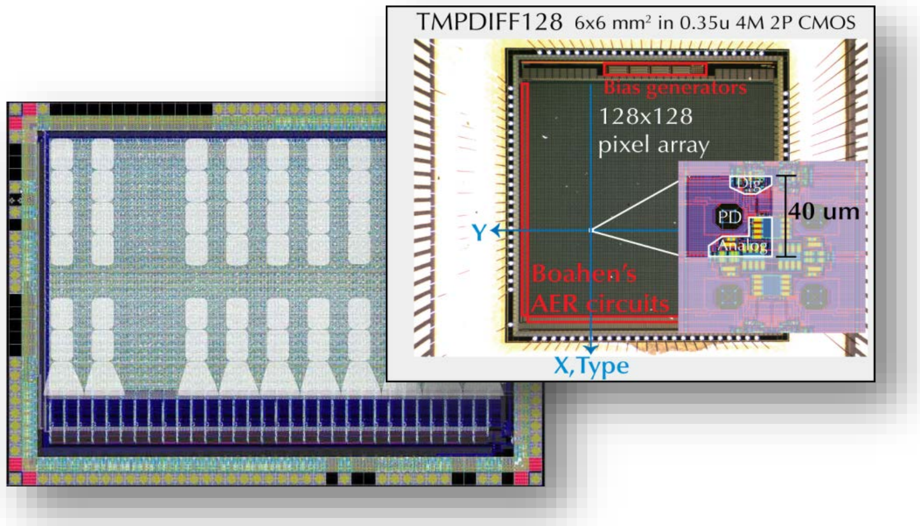
"structure or form"

Discovering key principles by which brains work and implementing them in technical systems that *intelligently* interact with their environment.



Examples:

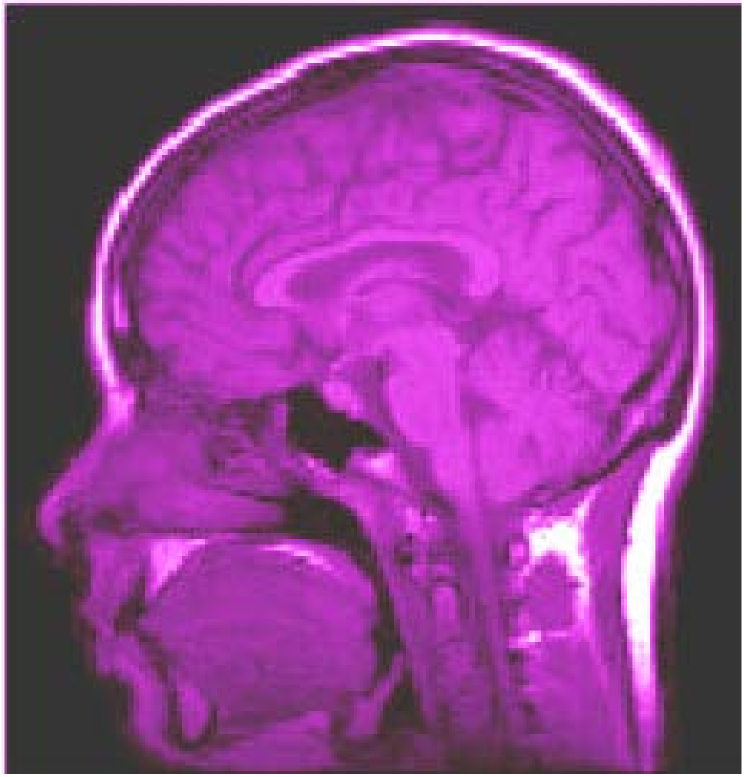
- analog VLSI Circuits to implement neural processing
- Sensors, such as Silicon Retinae or Cochleae
- Distributed Adaptive Control, e.g. CPG based locomotion
- Massively Parallel Self-Growing Computing Architectures
- Neuro-Electronic Implants, Rehabilitation



Computation in Brains

Getting to know your Brain

- 1.3 Kg, about 2% of body weight
- 10^{11} neurons
- Neuron growth:
  250.000 / min (early pregnancy)
  … but also … loss 1 neuron/second



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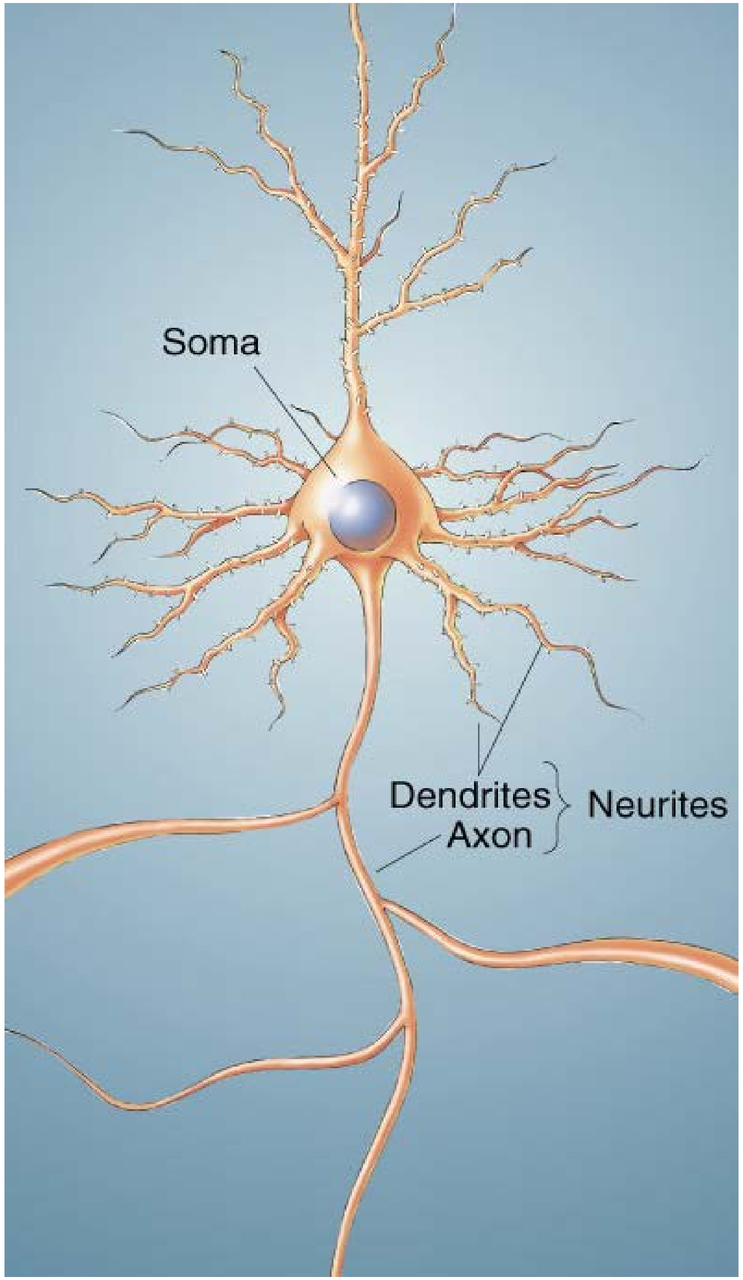
"Operating Mode" of Neurons

- Analog leaky integration in soma
- Digital pulses (spikes) along neurites
- 10^{14} stochastic synapses
- Typical operating "frequency":
  ≤100 Hz, typically ~10Hz, asynchronous



Computation in Brains ... and Machines

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- 50g, irrelevant for most applications
- 2 • 10^{9} transistors (Intel Itanium)
- ideally no modification over lifetime

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- Digital signal propagation
- Reliable signal propagation
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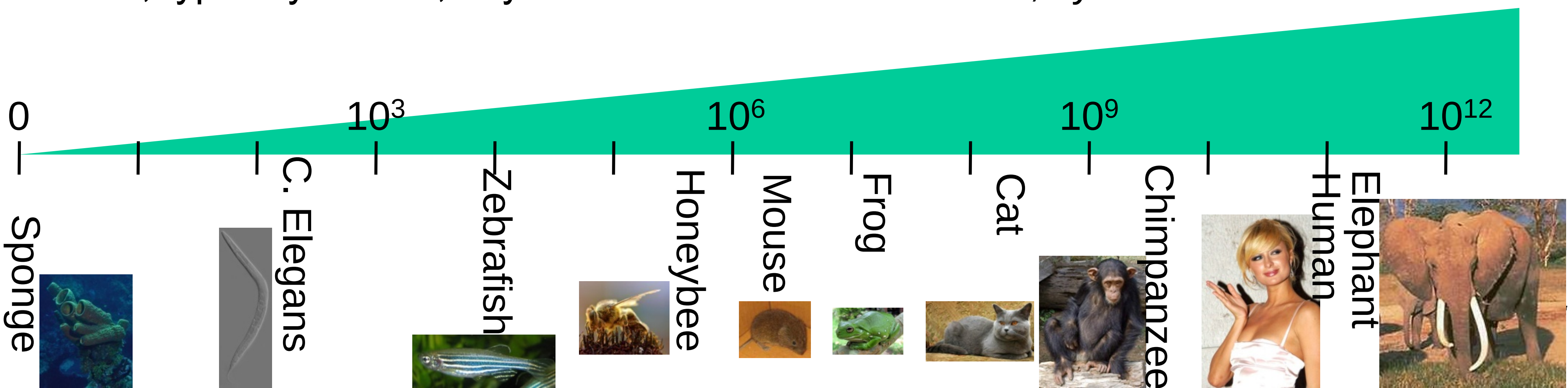


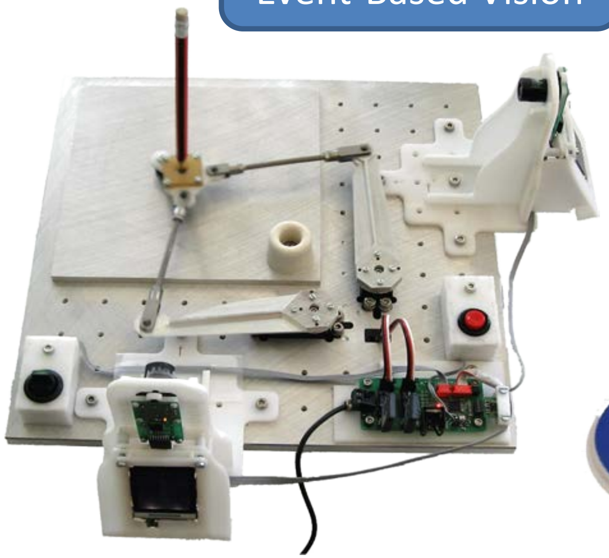
Research Area «Neuroscientific System Theory»

Neuronal-Style Information Processing in Closed-Control-Loop Systems

- Distributed Local Information Processing
- Growing and Adaptive Networks of Computational Units
- Neuromorphic Sensor Fusion and Distributed Actuator Networks
- Event-Based Perception, Cognition, and Action

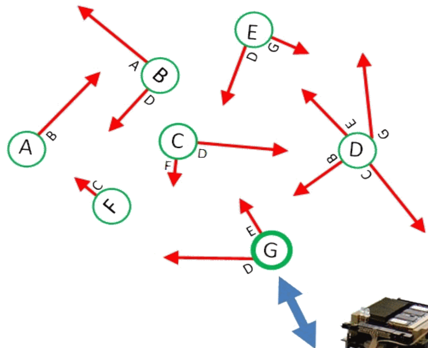
On-Board Vision-Based Control of Miniature UAVs

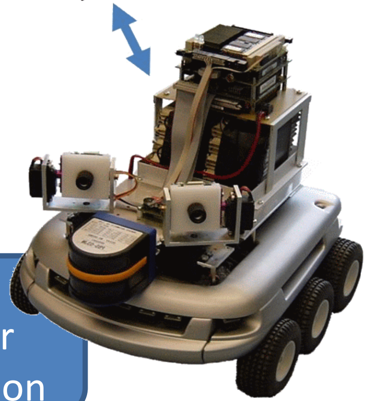
High-Speed Event-Based Vision



Event-Based Navigation

Distributed Sensing and Actuation

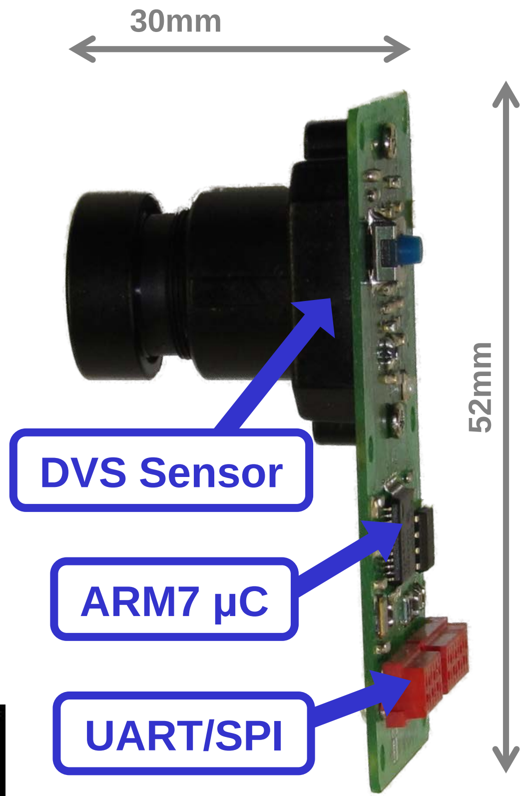


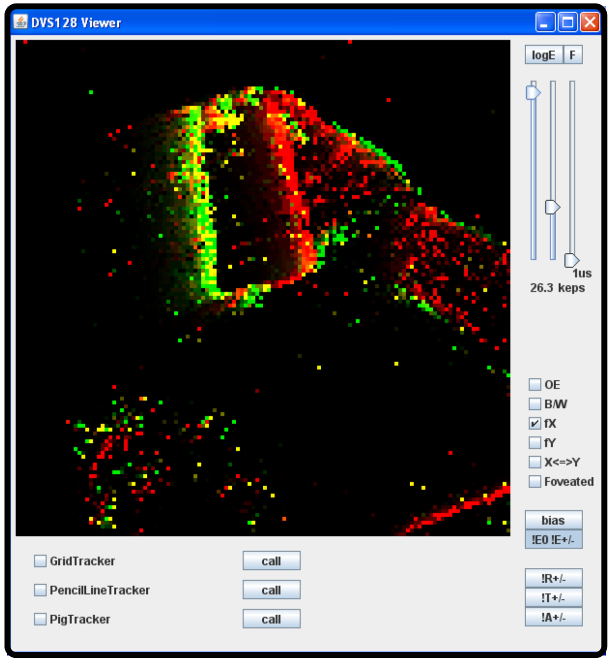


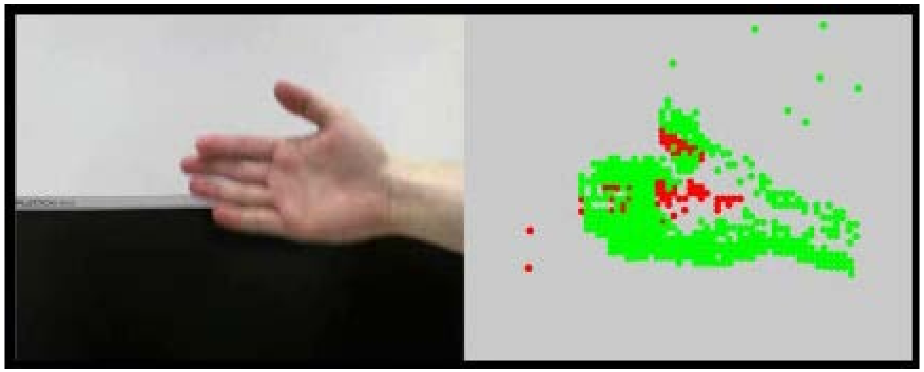
Distributed Local Cognitive Maps for Spatial Representation

Retinal Inspired Dynamic Vision Sensor

- 128 x 128 pixels, each signals
  temporal changes of illumination (“events”)
- Asynchronous updates (no image frames)
- 15 µs latency, up to 1Mevents/sec

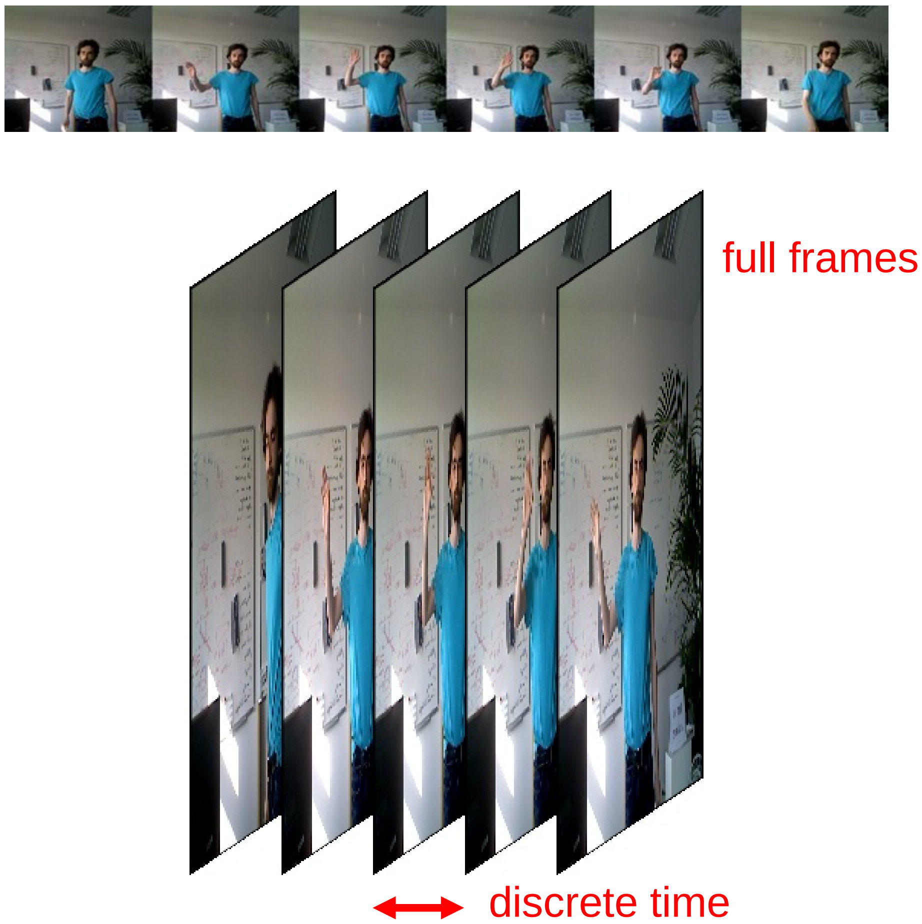




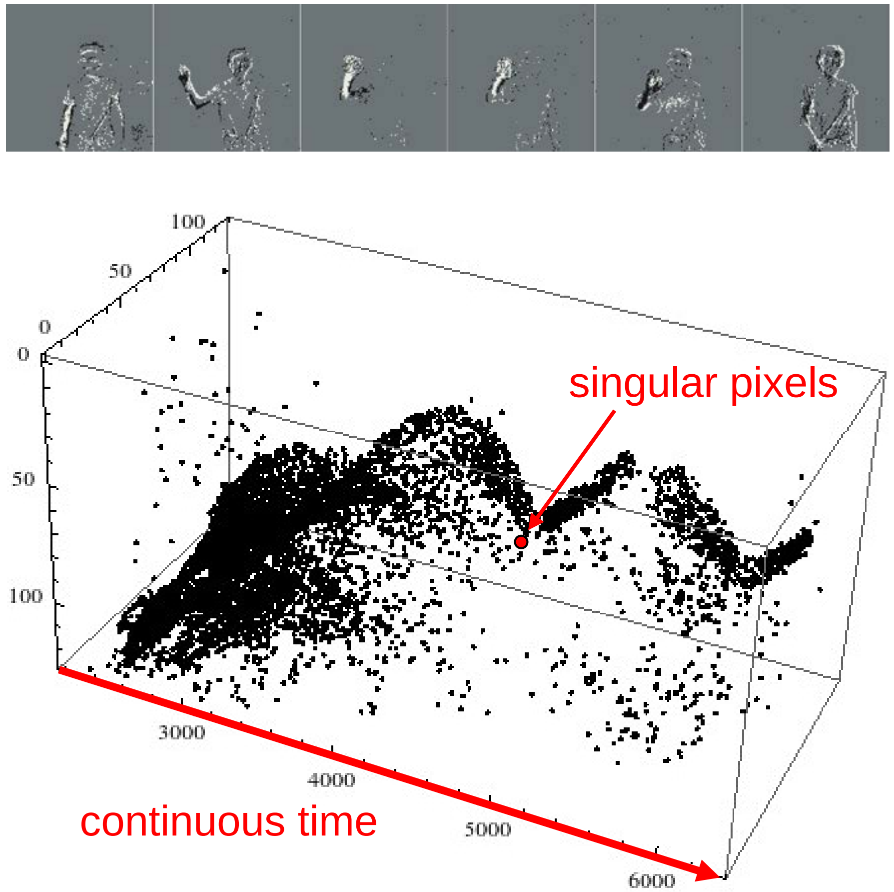


Event - Based Vision

Frame - based



Event - based



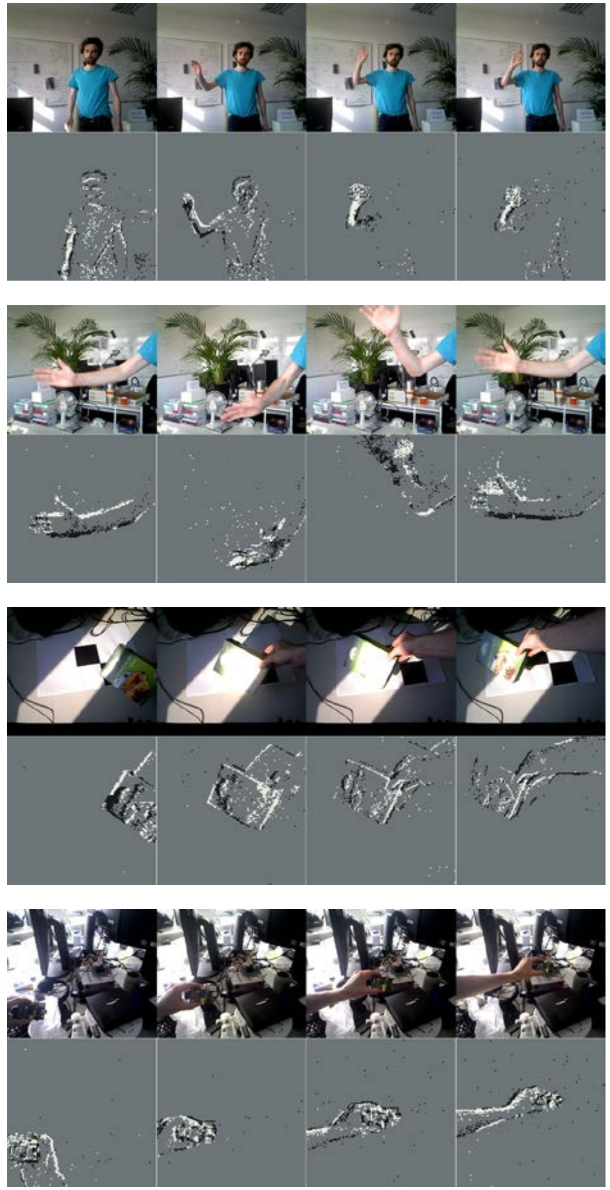
Event - Based Vision

Advantages

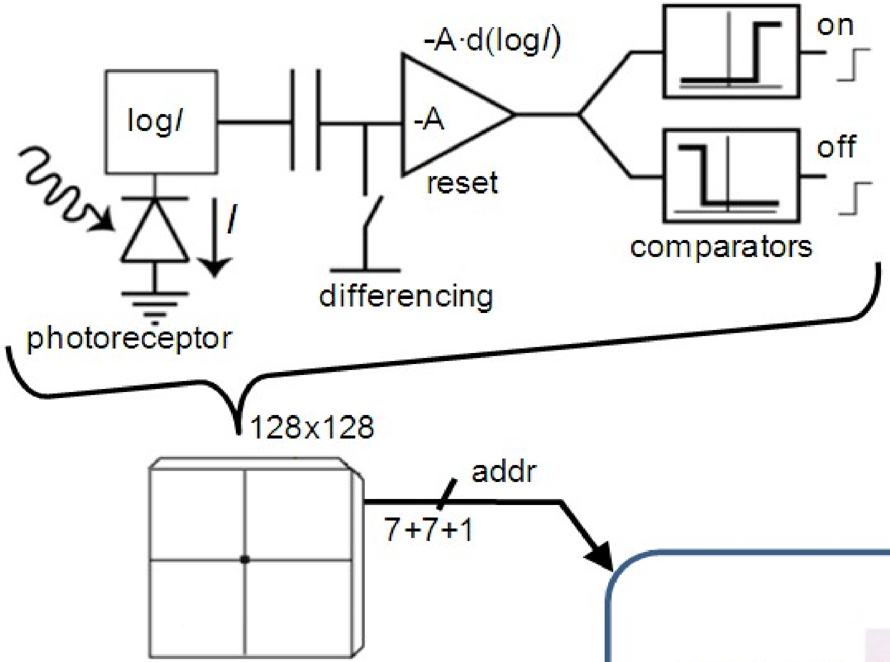
- Sparse data stream: ~0.1 MB/s bandwidth
- ~10us response time
- Local contrast adjustment per pixel
- Automatic preprocessing

Challenges

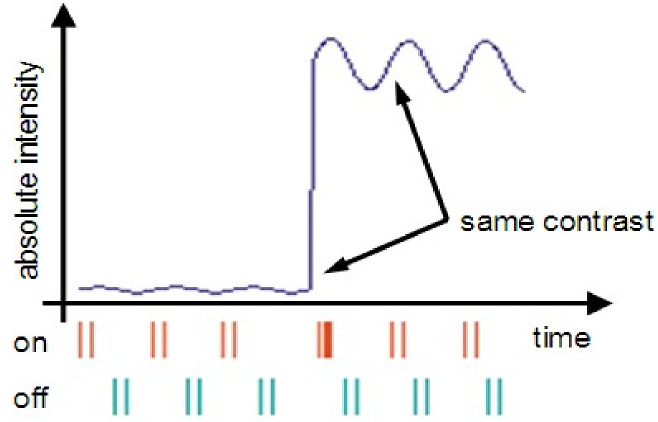
- Static scenes
- New vision algorithms
  for tracking, localization, ...



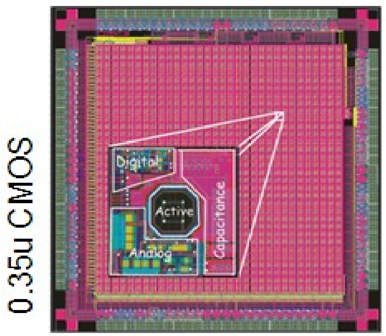
An Asynchronous Temporal Difference Vision Sensor



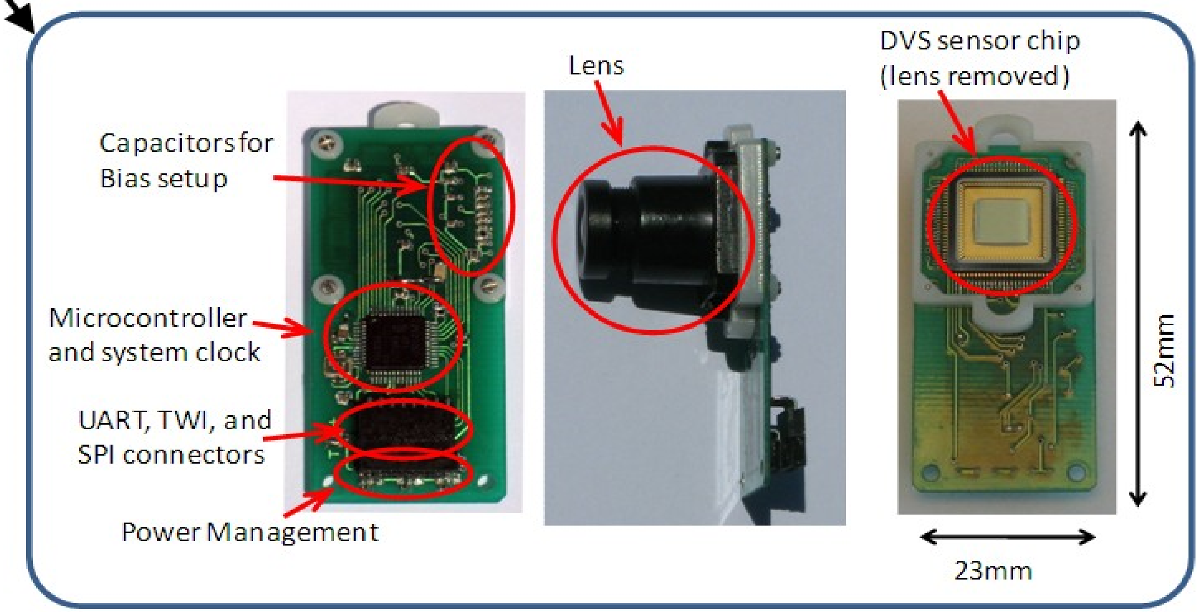
DVS pixel and camera architecture (simplified pixel schematics)



A relative change in illumination causes an event



Photograph of retina chip



Embedded Microcontroller and DVS on small PCB

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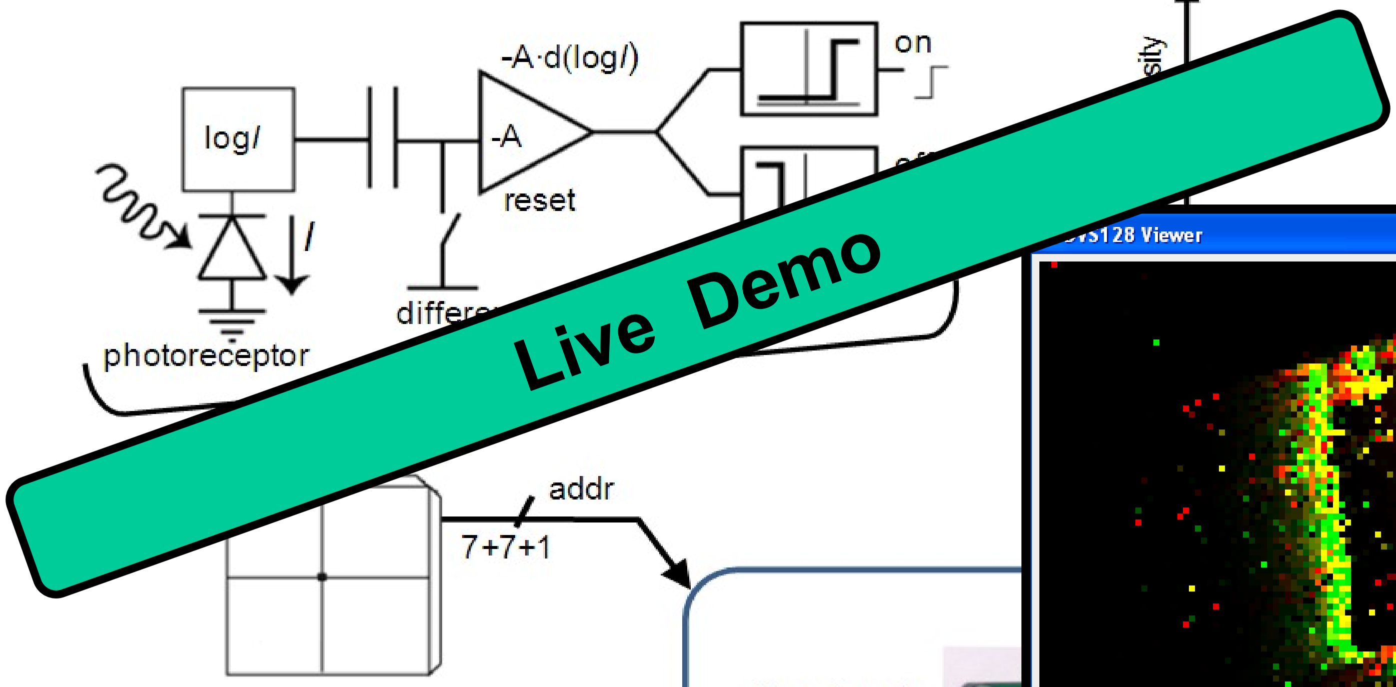

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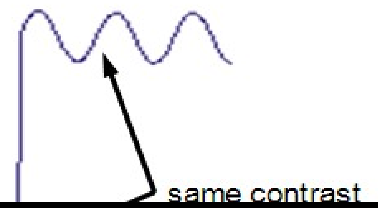

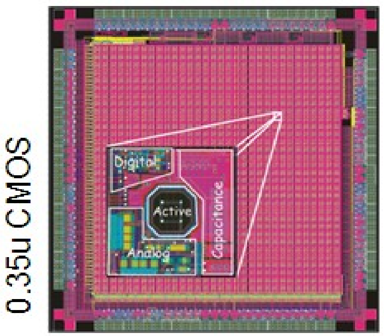

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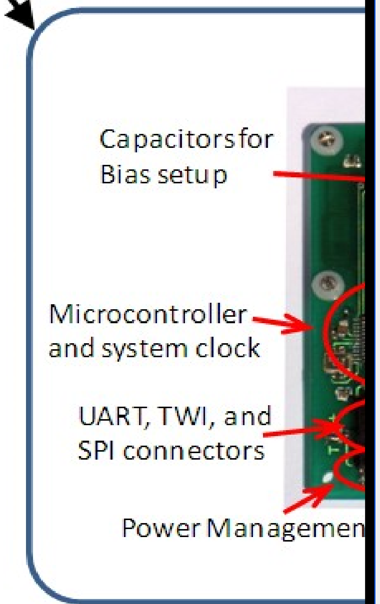
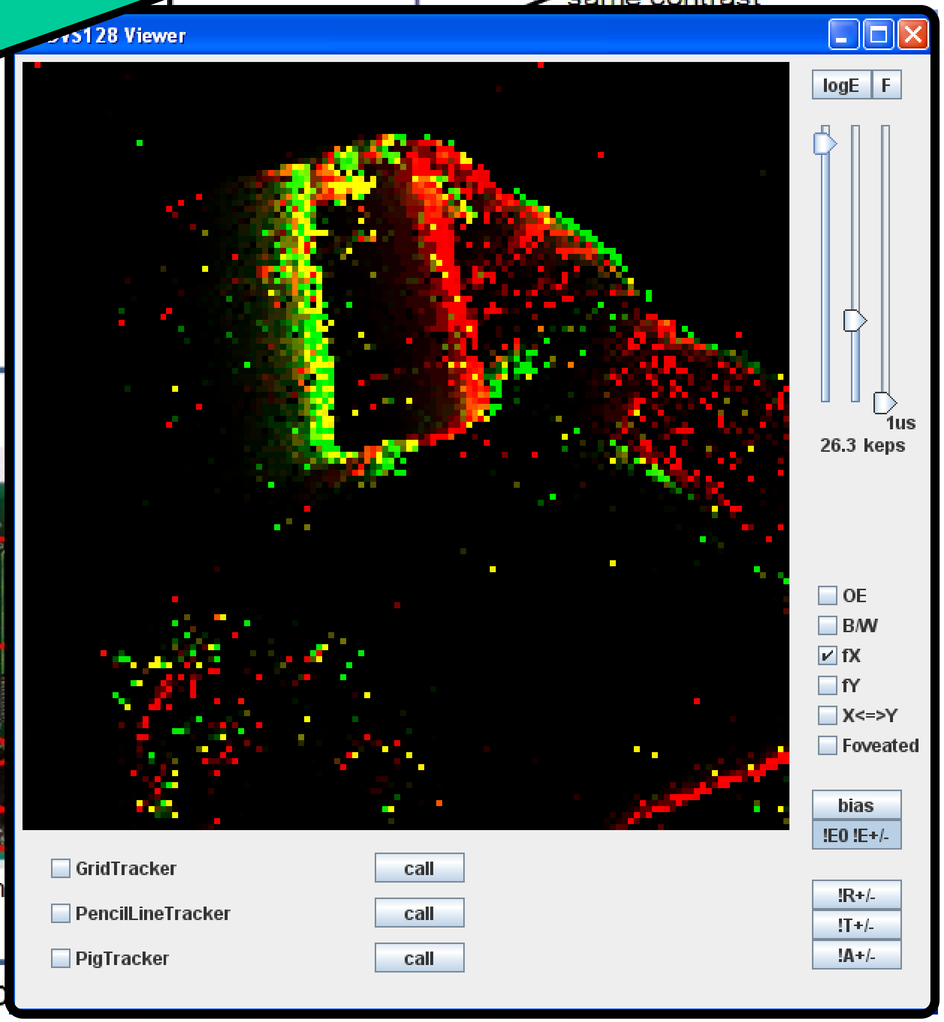
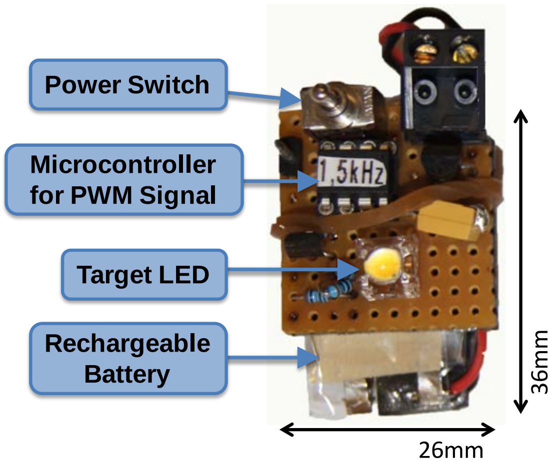
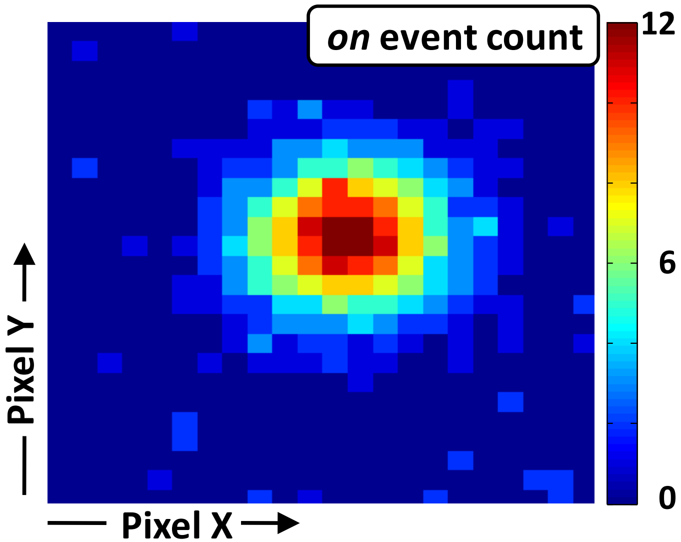


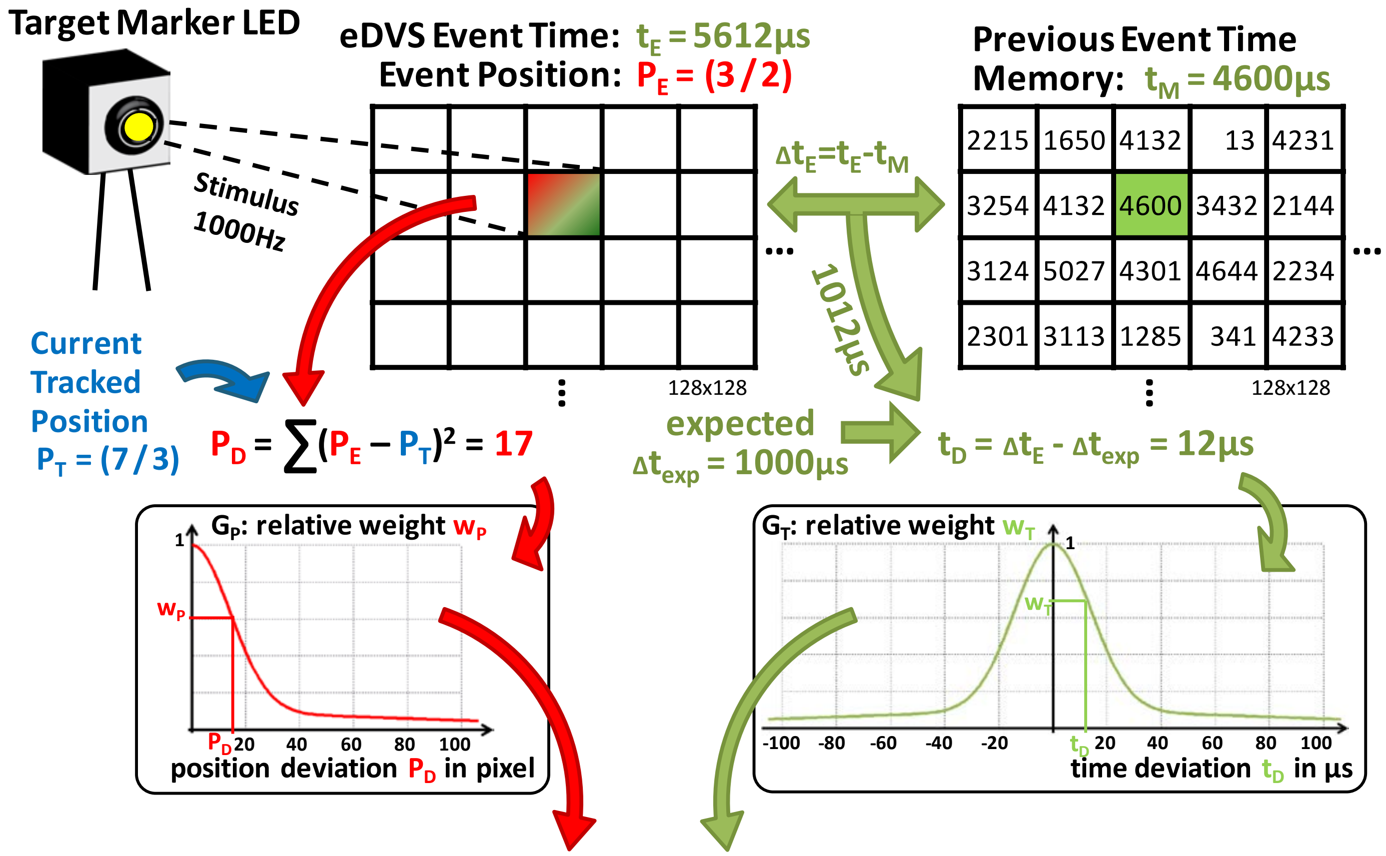
Embedded Microc



Application Example: Tracking an Active Object







Position Update: $P_{T+1} = (1 - \eta(w_T + w_P)) \cdot P_T + \eta(w_T + w_P) \cdot P_E$

Müller et al, ROBIO 2011

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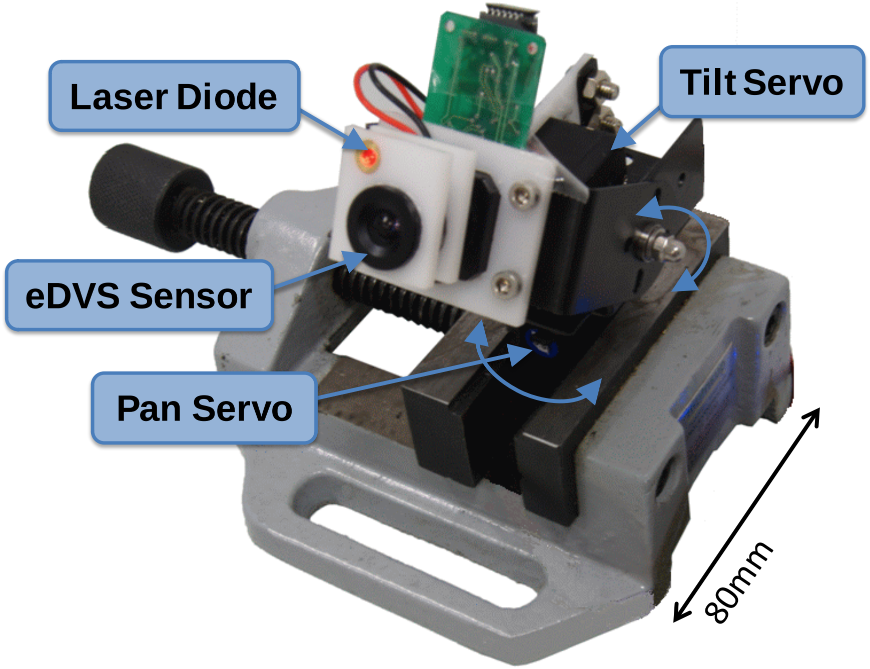

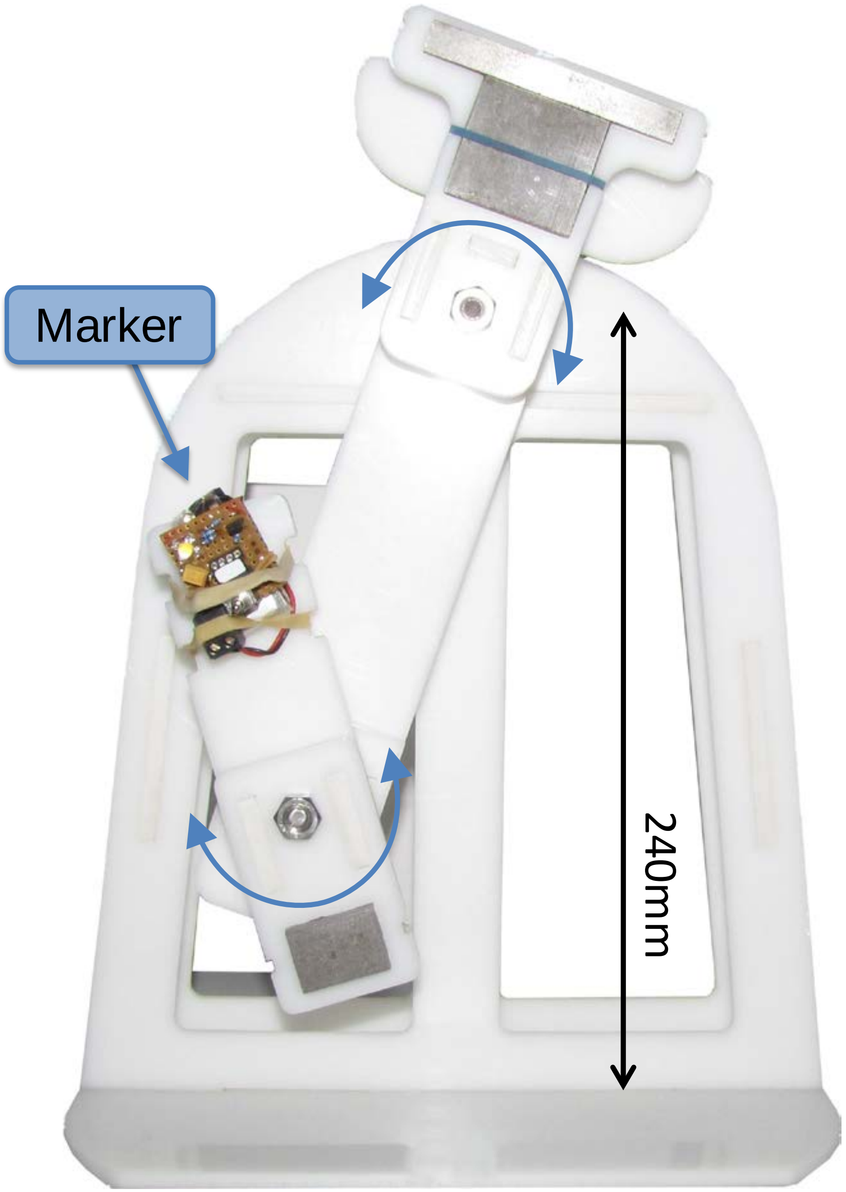

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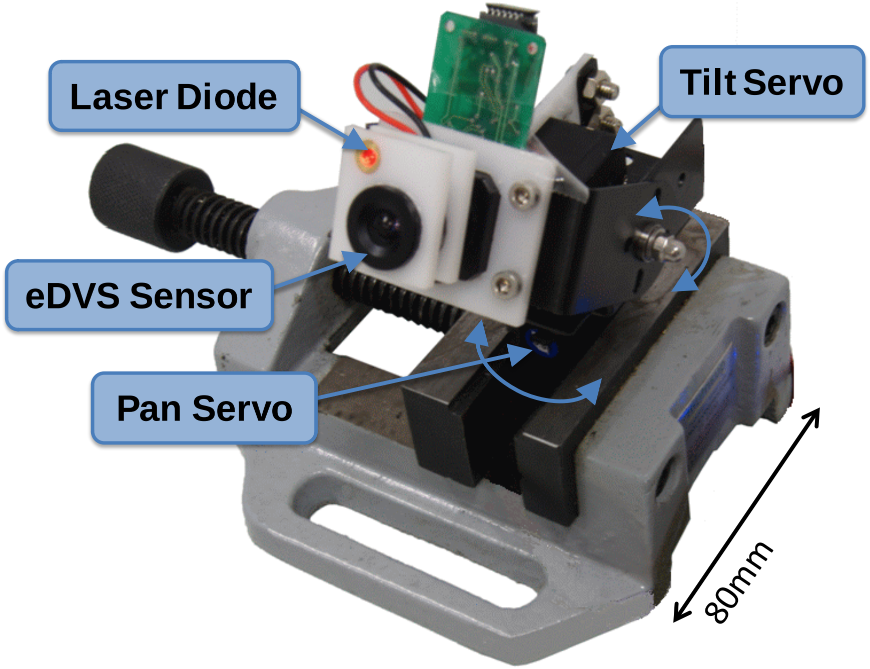
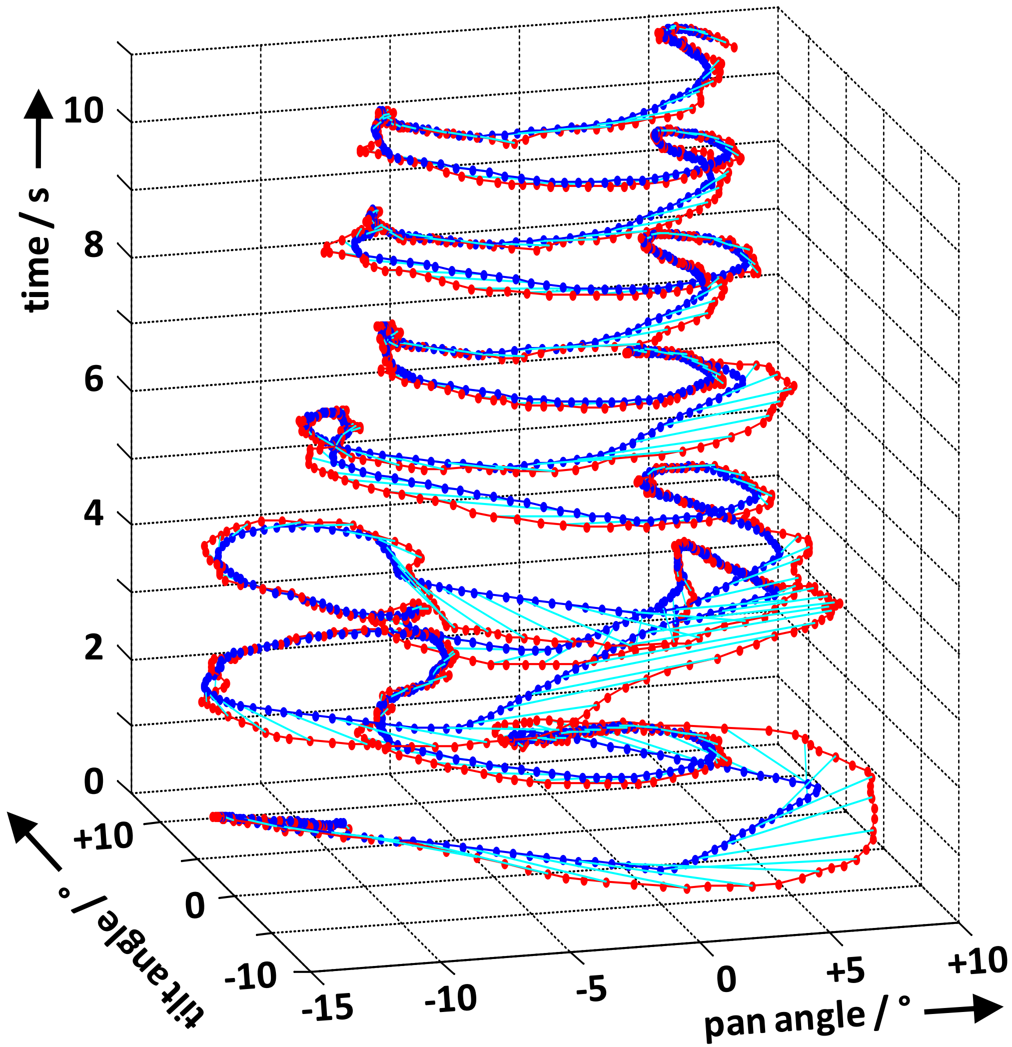
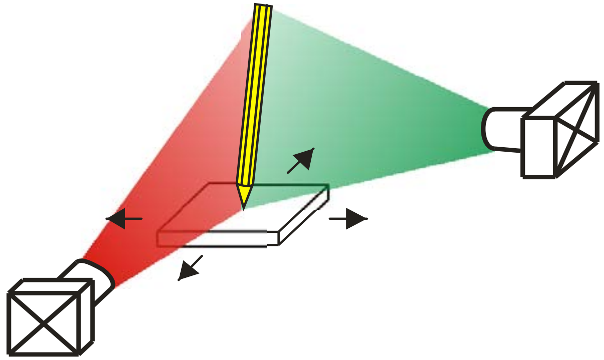
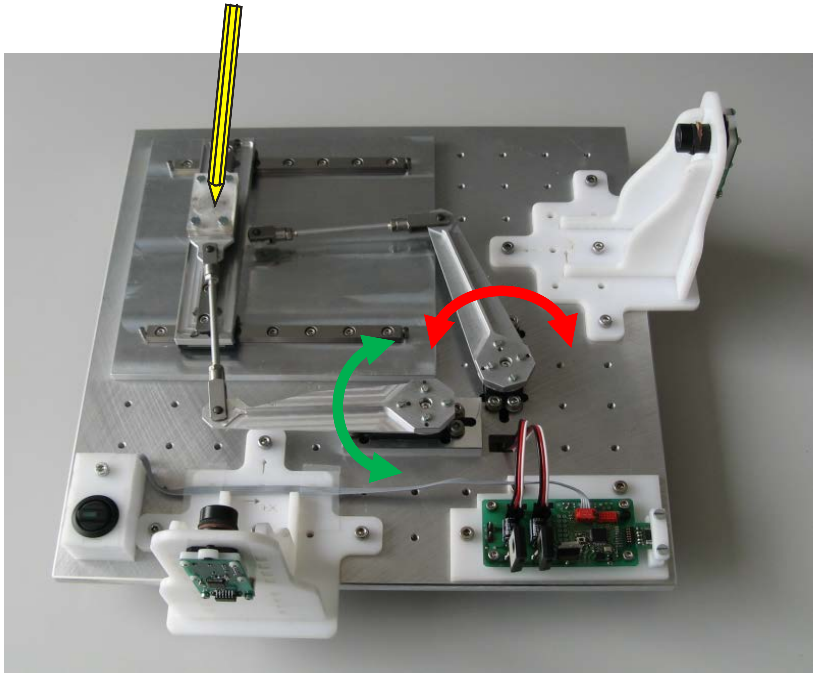
Georg Müller





(Fun) Application Example: High Speed Balancing of Short Poles





Conradt et al, ISCAS 2009

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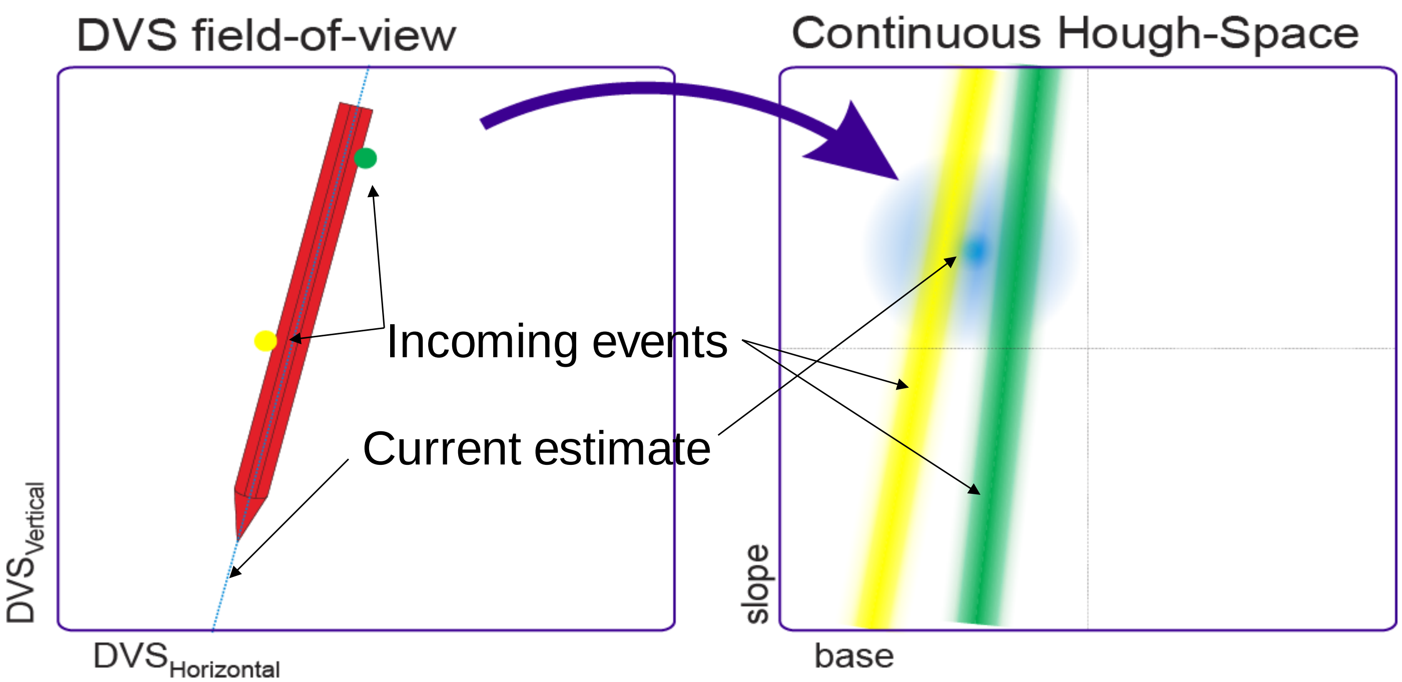
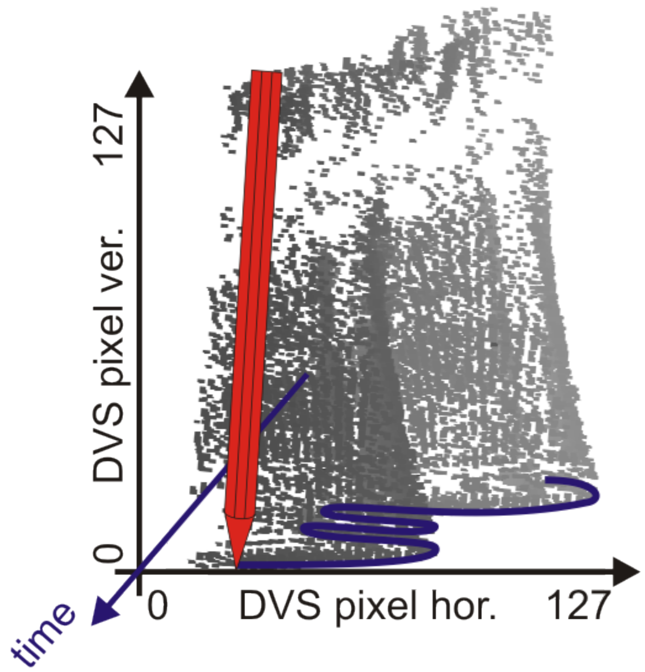
Converting Events into Meaning



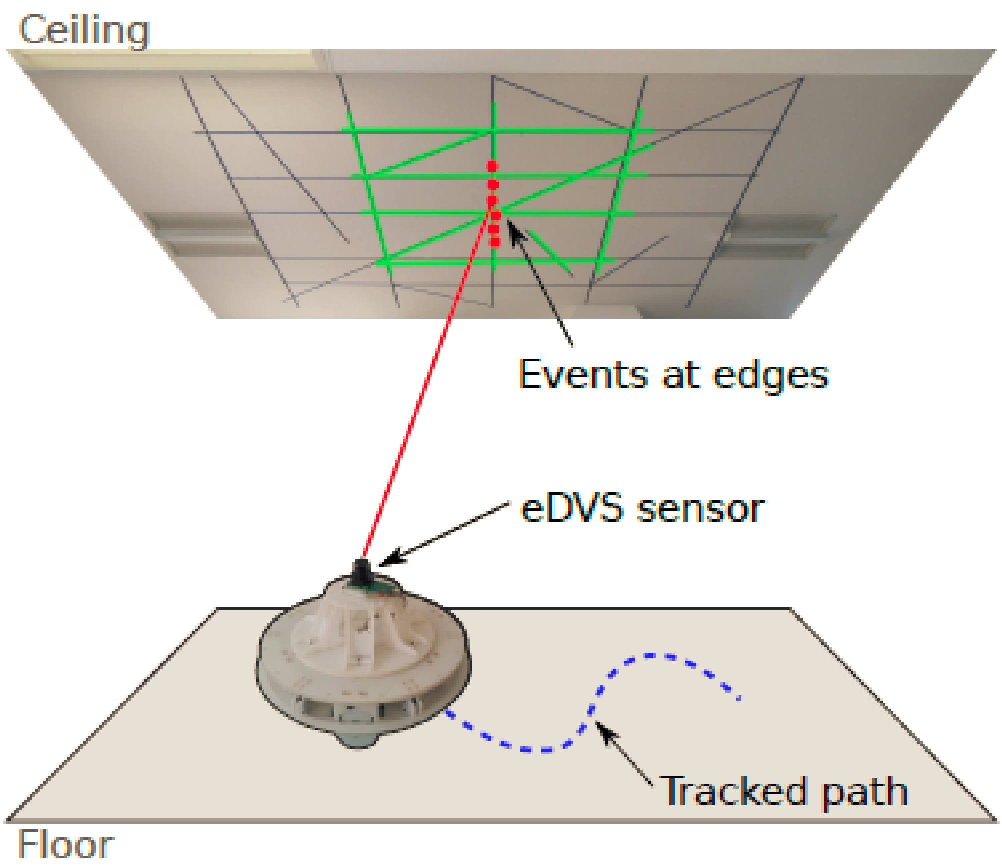


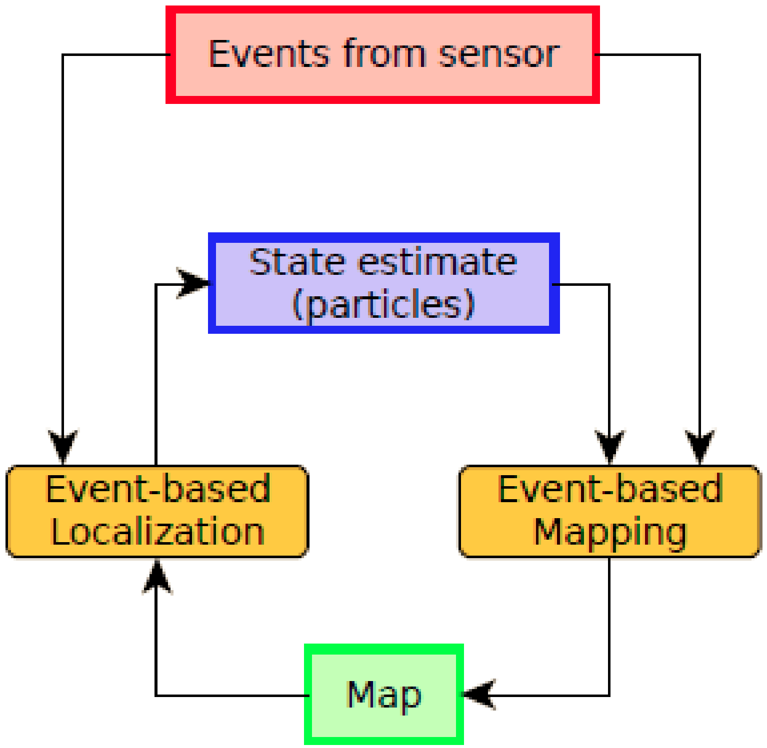
Conradt et al, ECV 2009

Extended Application Example: High Speed Tracking

Application Example: SLAM for Event-Based Vision Systems

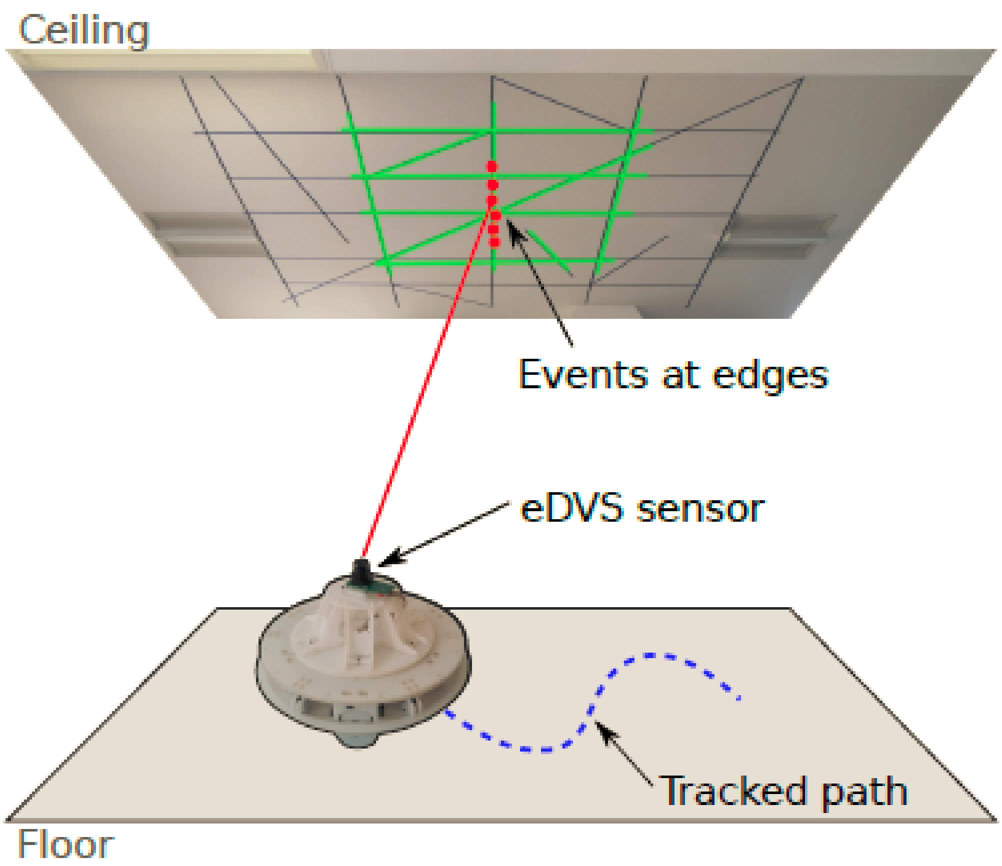
Framework: Particle Filter

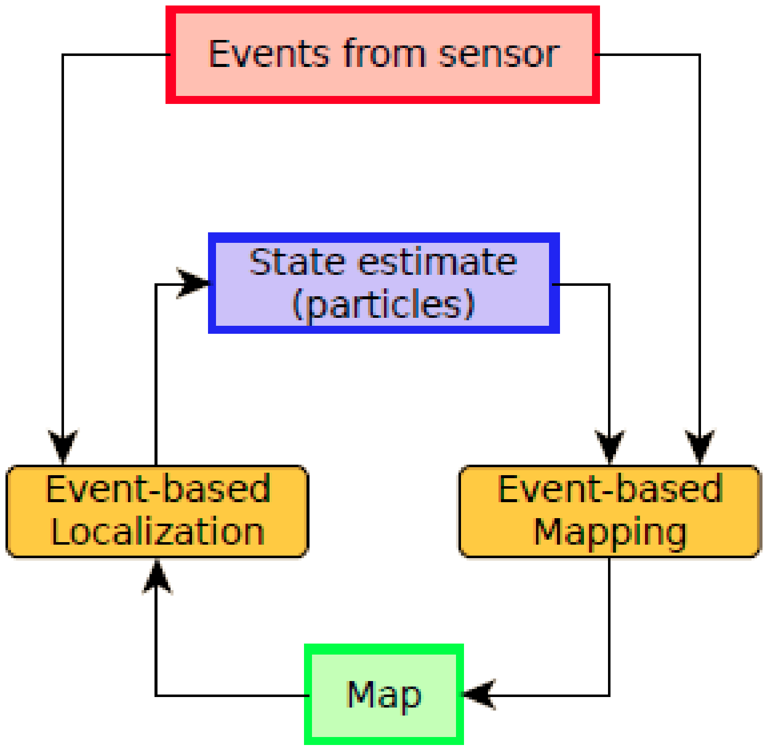




Application Example: SLAM for Event-Based Vision Systems

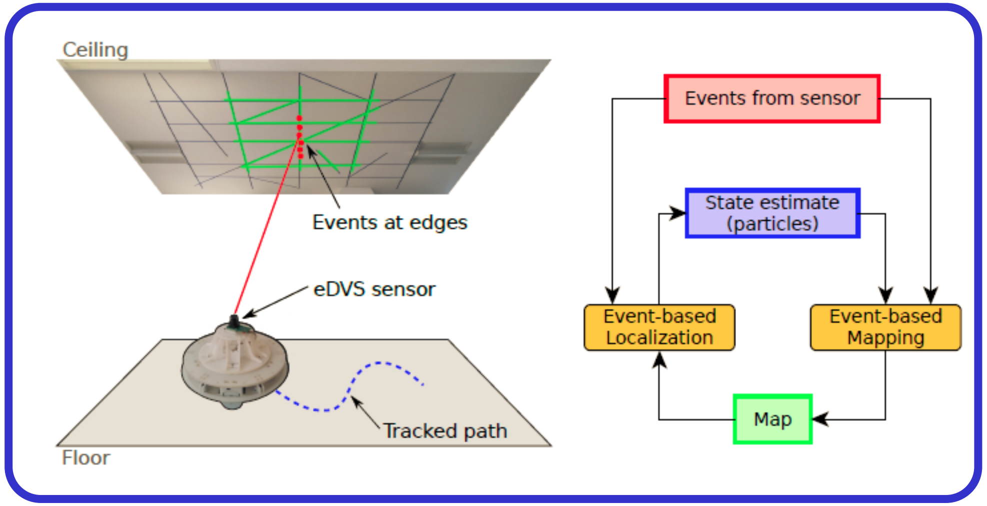
Event Based Localization





Application Example: SLAM for Event-Based Vision Systems

Event Based Mapping



$$\mathcal{M}(u) = \frac{\#\text{ of occurred events for } u}{\#\text{ of possible obervations for } u} =: \frac{\mathcal{O}(u)}{\mathcal{Z}(u)}$$

$$\mathcal{O}^{(k)}(u) = \mathcal{O}^{(k-1)}(u) + \sum_{i=1}^{n} s_i^{(k)} \mathcal{N}\left(u \,\middle|\, \mu^{-1}(e^{(k)}|x_i^{(k)}), \sigma\right), \; \mathcal{O}^{(0)} = 0$$

$$\mathcal{Z}^{(k)}(u) = \mathcal{Z}^{(k-1)}(u) + \|\mu(u|x_*^{(k)}) - \mu(u|x_*^{(k-1)})\|, \; \mathcal{Z}^{(0)} = 0$$

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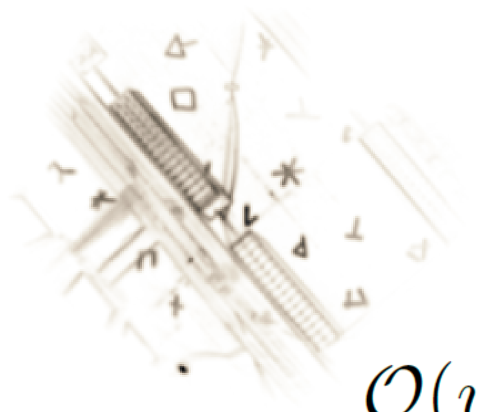
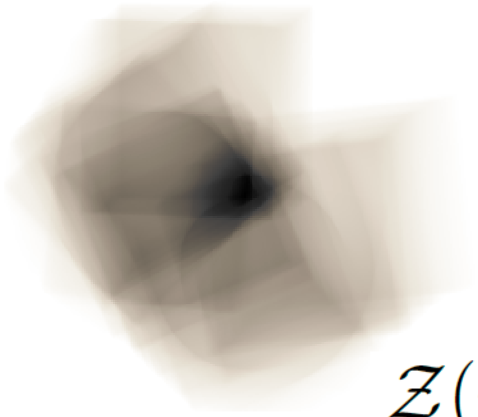


$\mathcal{O}(u)$



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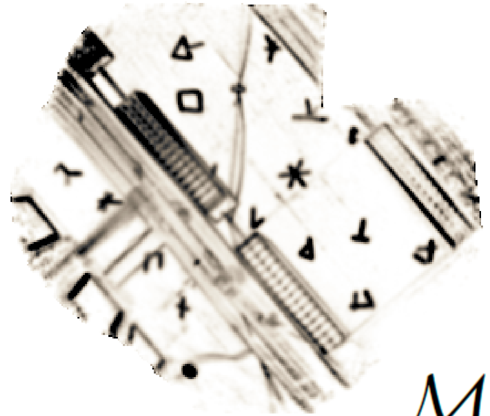

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Weikersdorfer et al, ICVS 2013

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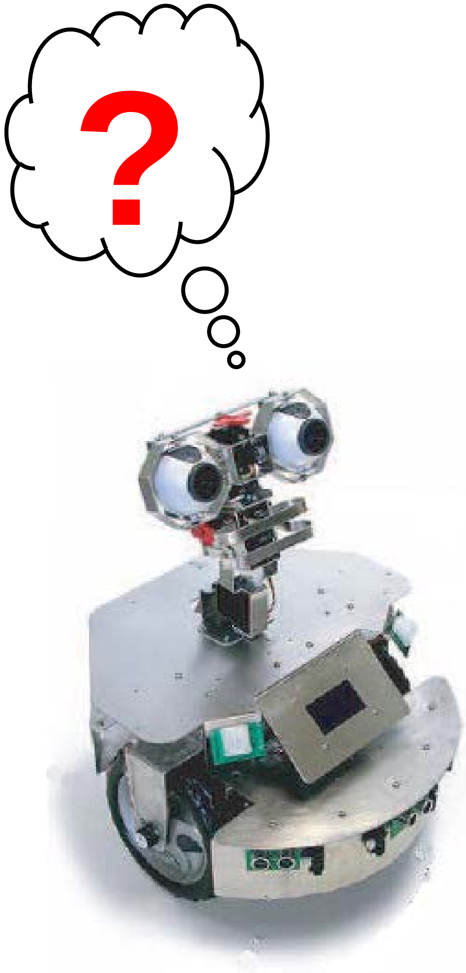
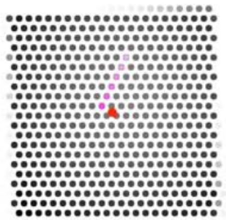




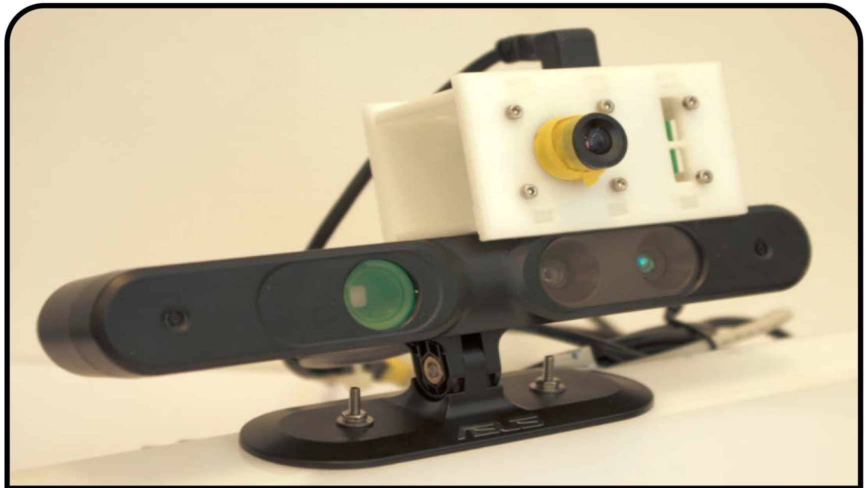
5x real time

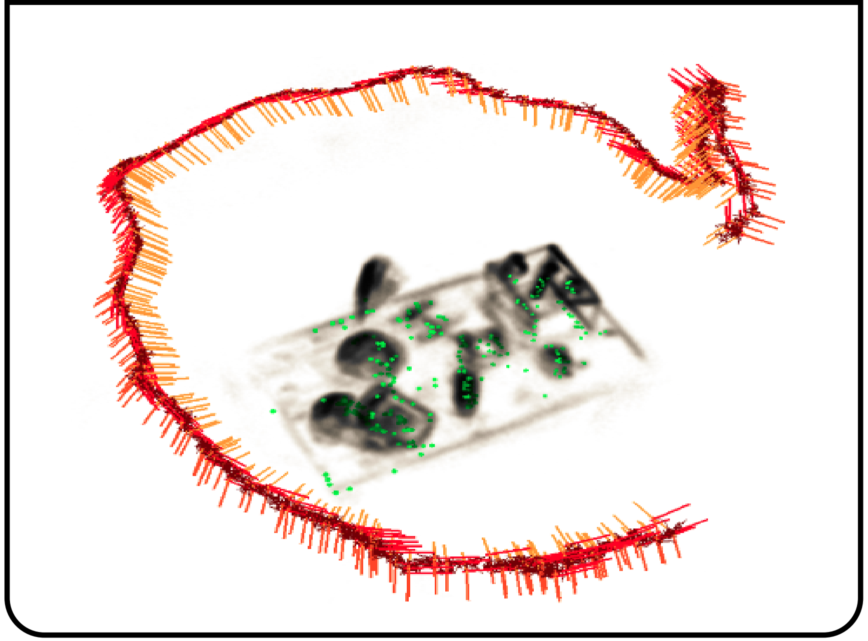
Event-based 3D SLAM
with a depth-augmented Dynamic Vision Sensor

David Weikersdorfer, David B. Adrian,
Daniel Cremers, Jörg Conradt

Technische Universität München, Germany

- Sensor combination: event-based dynamic vision and PrimeSense object distance
- Sparse sensory data allows real-time processing and integration
- Localization update rates of > 100 Hz on standard PC
- Suitable for small autonomous mobile robots in high-speed application scenarios



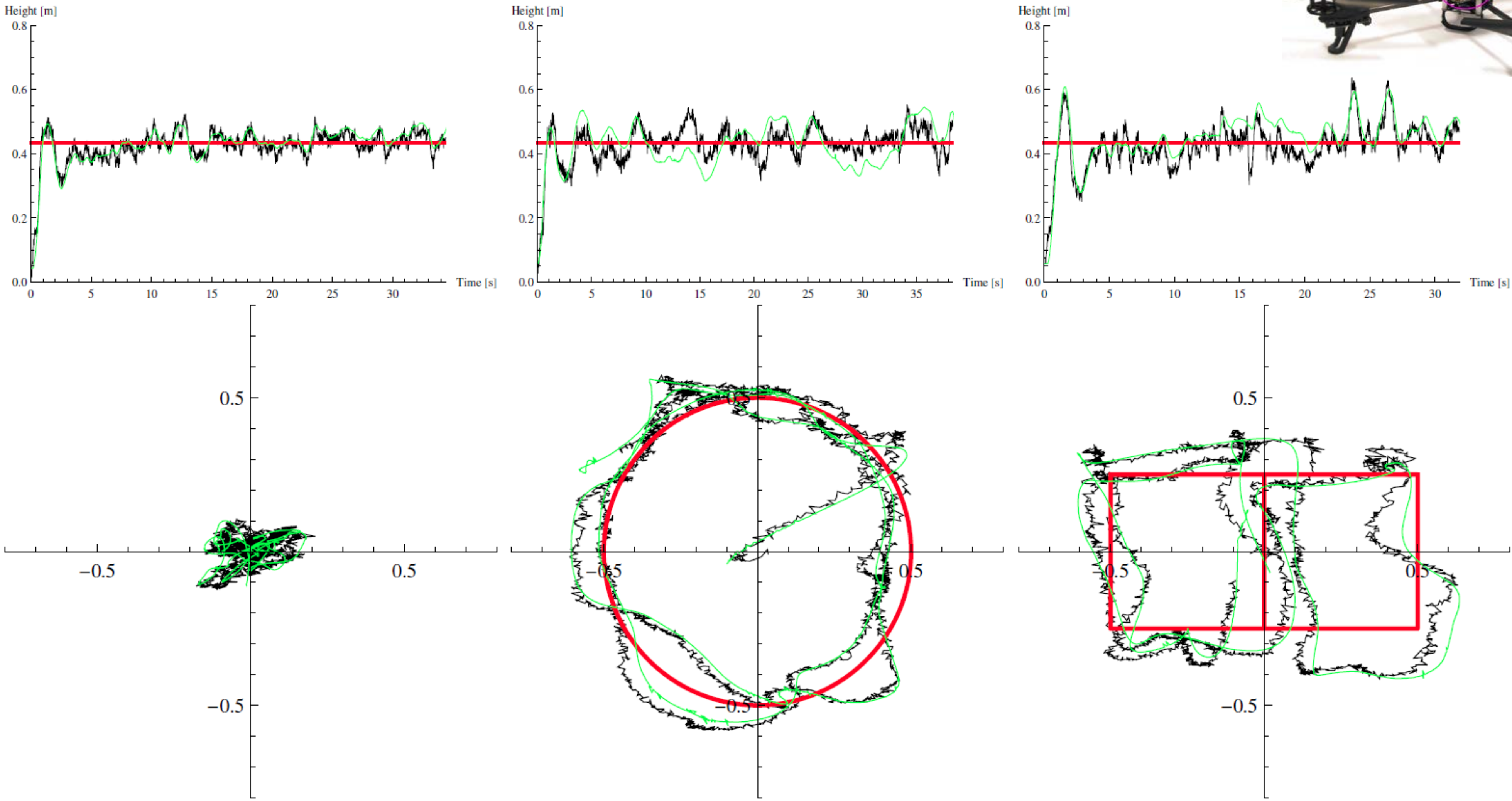


An Autonomous Indoor Quadrocopter (eb3D SLAM)

Parrot AR.Drone
diam. ca. 80 cm

Selected hardware components : eDVS (**red**), Mini-PC (**blue**),
Primesense IR projector (yellow) and IR camera (**green**), and drone control board (**magenta**).

An Autonomous Indoor Quadrocopter (eb3D SLAM)

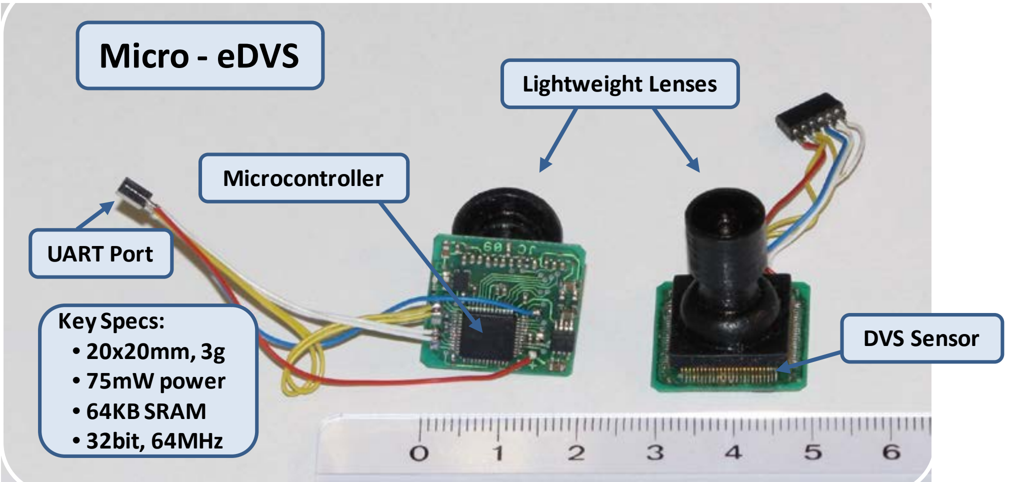


Evaluation against ground truth: **eb-3DSLAM**

desired trajectory **ext. tracker (OptiTrack Flex13)**

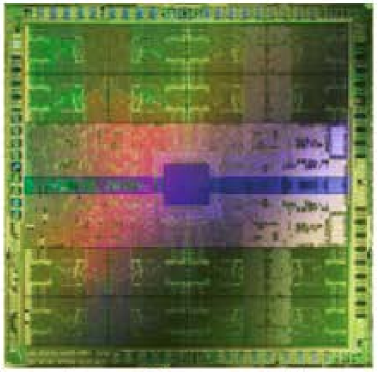
Outlook: An Autonomous Indoor Micro Quadrocopter (3D SLAM)

Key Technical Specs:
- Diameter 16cm
- Weight 38g
- Autonomy 14min



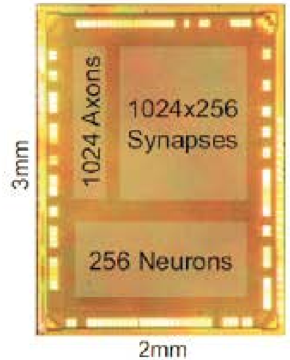
Neuromorphic Computing Landscape

A neuro-computing renaissance

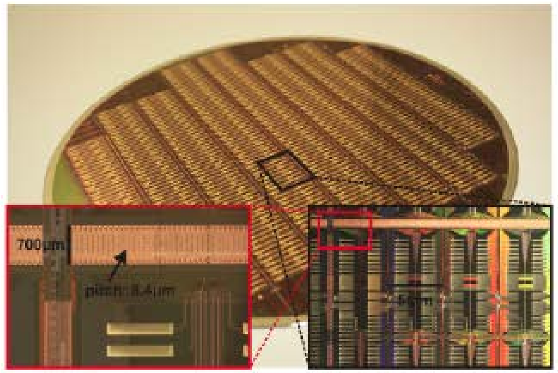


SW simulated neural networks (CPUs, GPUs).

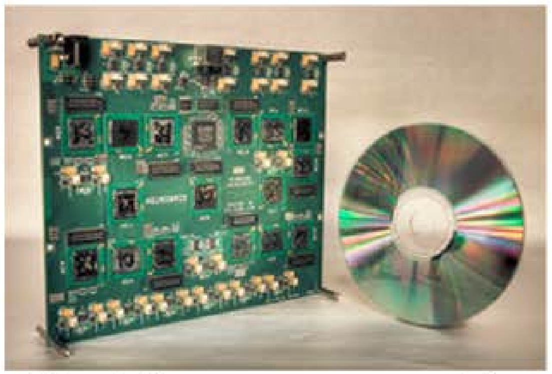
Real-time ARM-based neural network simulator (SpiNNaker).



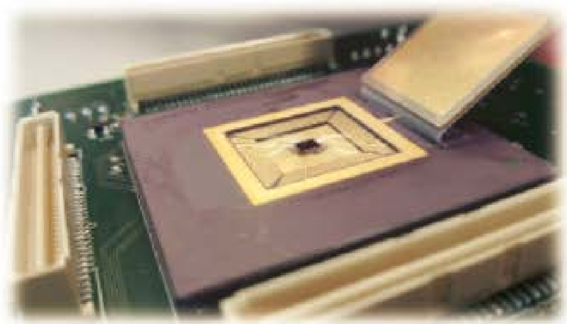
Fully digital *cognitive computing* chips (IBM).



Wafer-scale analog neural accelerators (BrainScaleS).



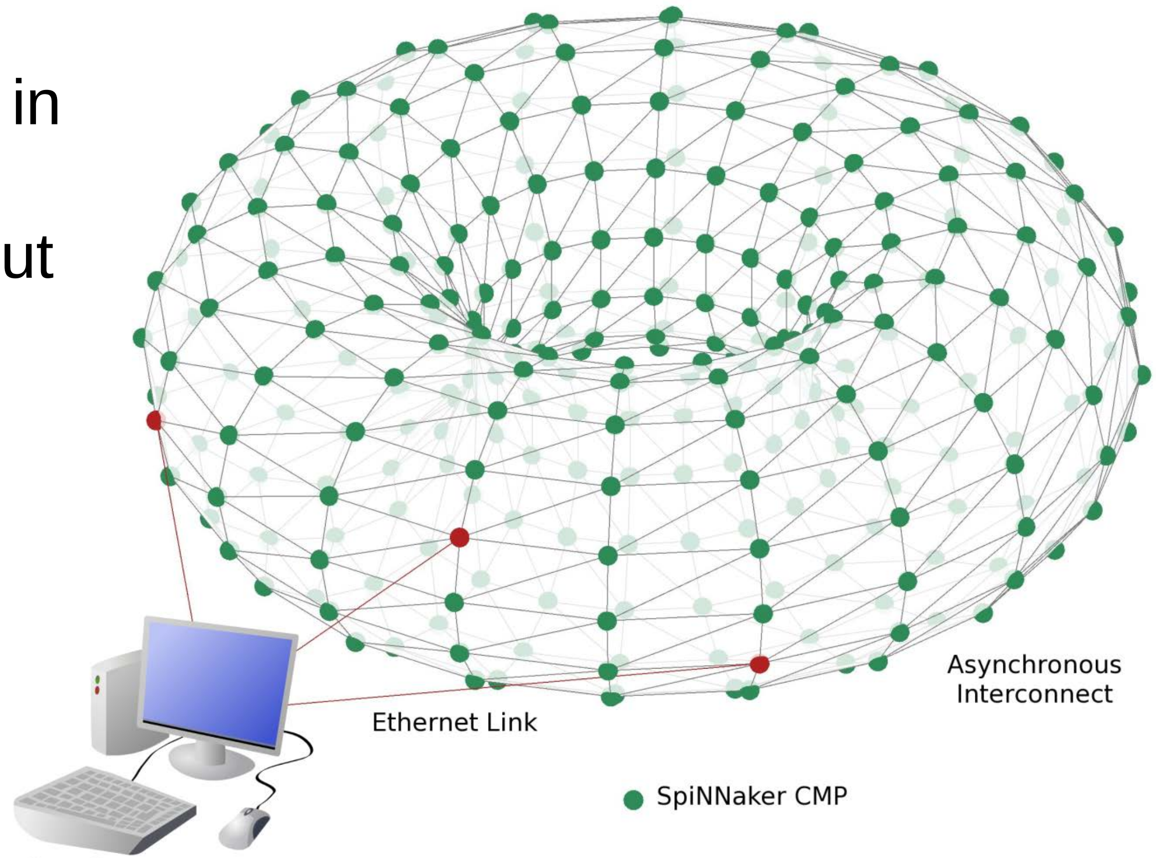
Real-time neuromorphic multi-chip emulator (NeuroGrid).



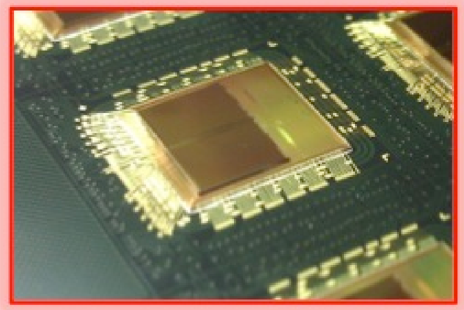
Real-time multi-neuron chip with plastic synapse neuron circuits (neuroP).

SpiNNaker Project

- A million mobile phone processors in one computer
- Able to model about 1% of the human brain…
- …or 10 mice!

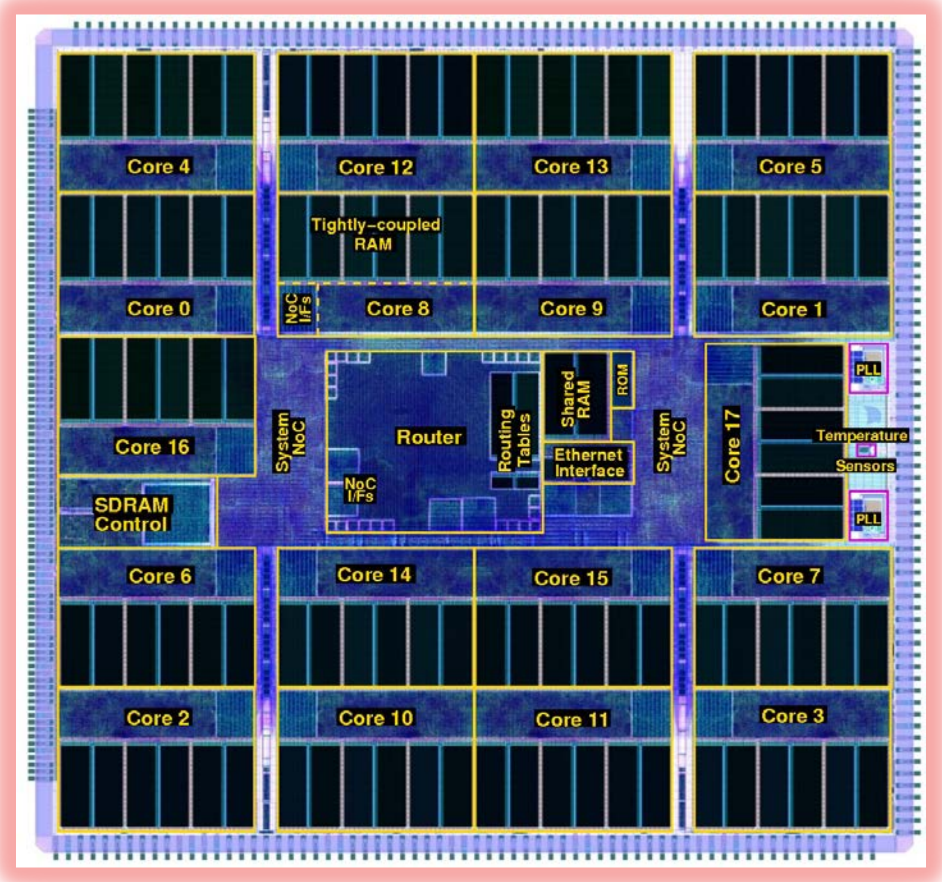


SpiNNaker Chip



Mobile
DDR
SDRAM
interface

Multi-chip
packaging by
UNISEM Europe



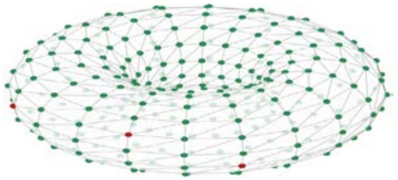
SpiNNaker

Biologically
Inspired
Massively
Parallel
Architectures

MANCHESTER 1824

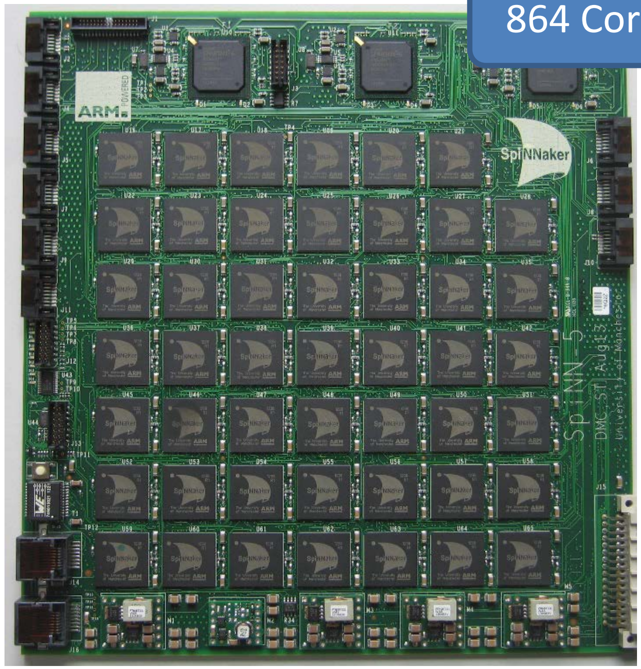
Distributed Neuronal Computation "on chip"

Asynchronous Spiking Neural Computation Hardware for low-power real-time operation in Closed-Loop Systems



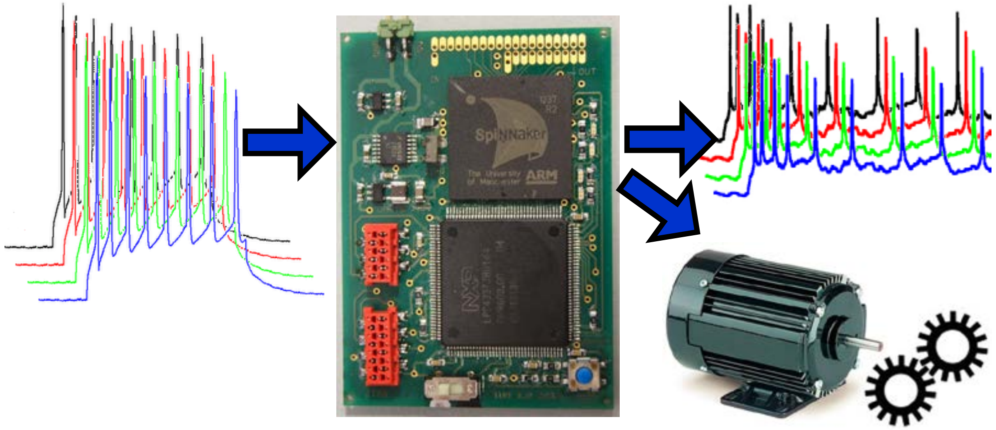
... to simulate 1 Billion
Spiking Neurons
in real-time

864 Core "Rack Version"



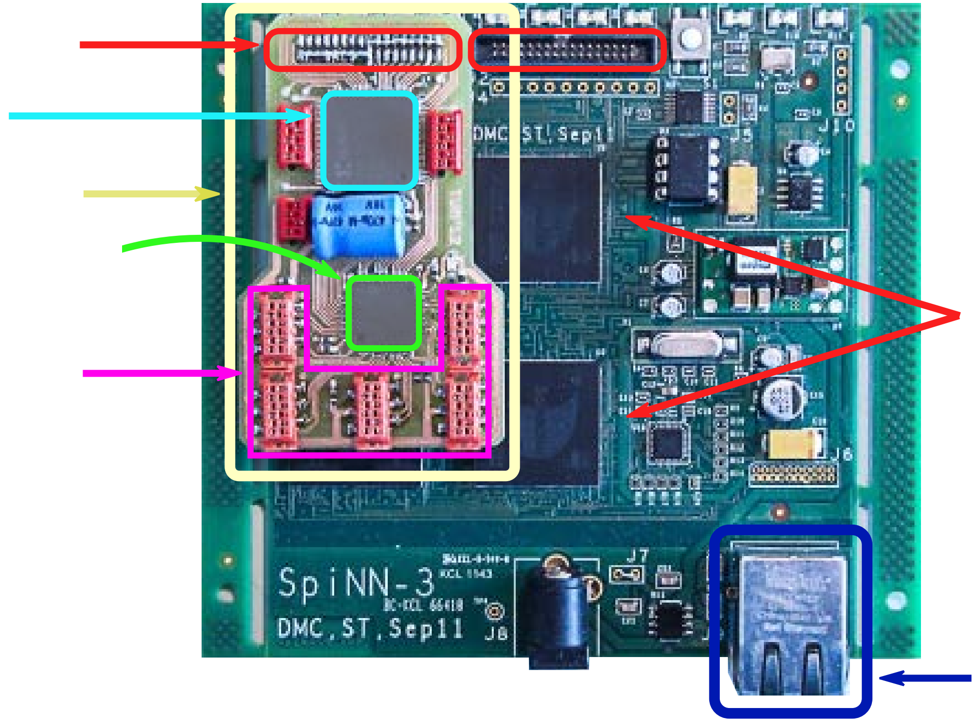
72 Core Evaluation

18 Core Stand-Alone Prototype

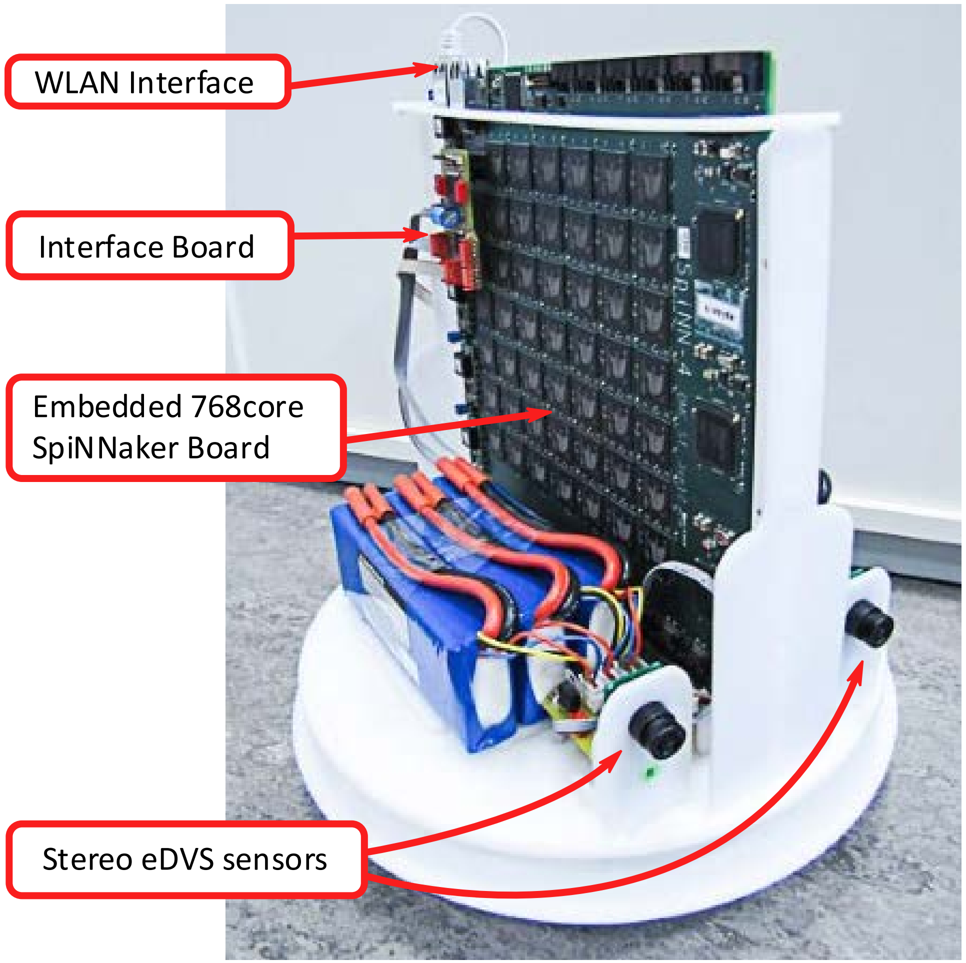


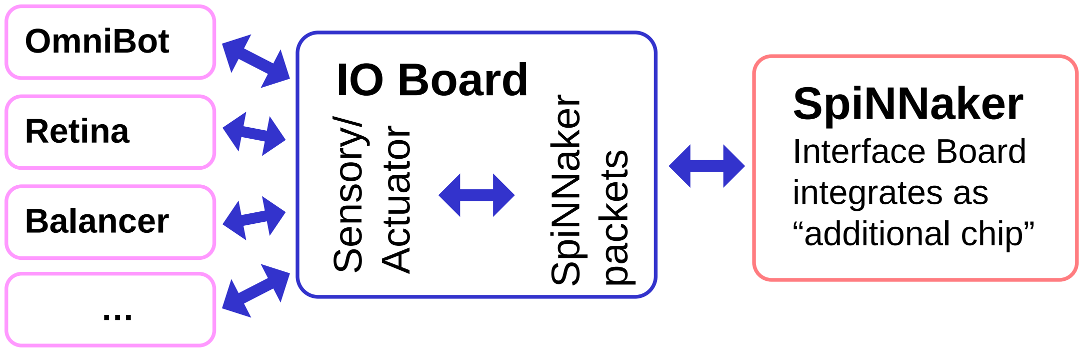
- Multi-channel spiking input and output
- Stand-alone spiking computing system
- Simulates ~20.000 neurons in real time
- Small (~20x20mm); low power (~600mW)
- Flexibly configurable, extendable, stackable

The SpiNNaker – Robot Interface Board



NST SpOmniBot





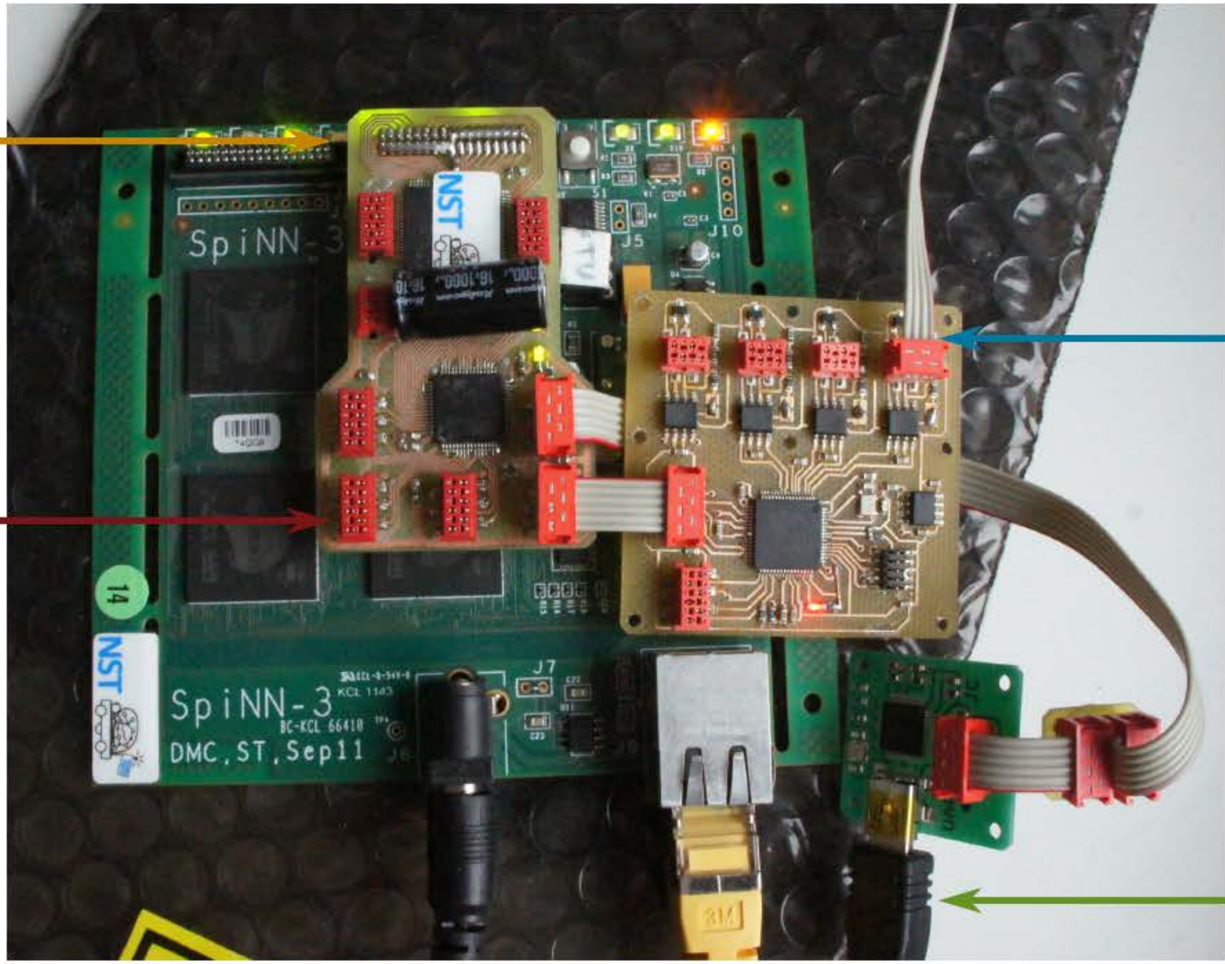
Interface to Compliant Robotic Arm

SpiNN-Link:

IO-board interacts with SpiNNaker on its native BUS and protocol

UART:

IO-board UART ports to connect to peripherals



CAN:

IO-board's own 4x CAN controller

USB/UART:

interact with IO-board, live interaction with running simulation

Power:

5 V, <1 A

Ethernet:

control SpiNNaker, set up simulation

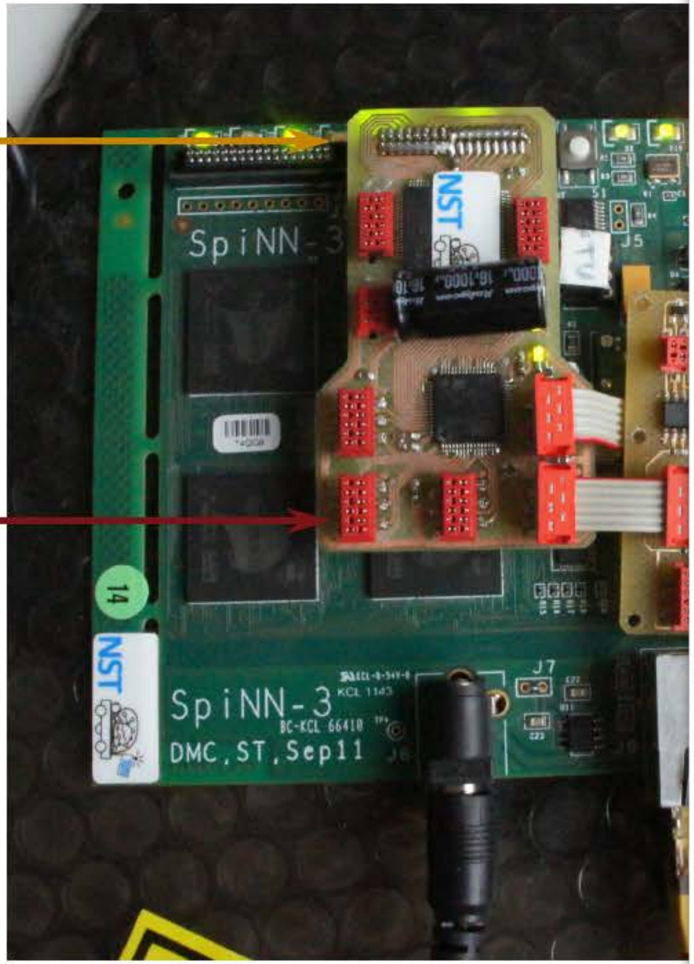
Interface to Compliant Robotic Arm

SpiNN-Link:

IO-board interacts with SpiNNaker on its native BUS and protocol

UART:

IO-board UART ports to connect to peripherals



Power:

5 V, <1 A

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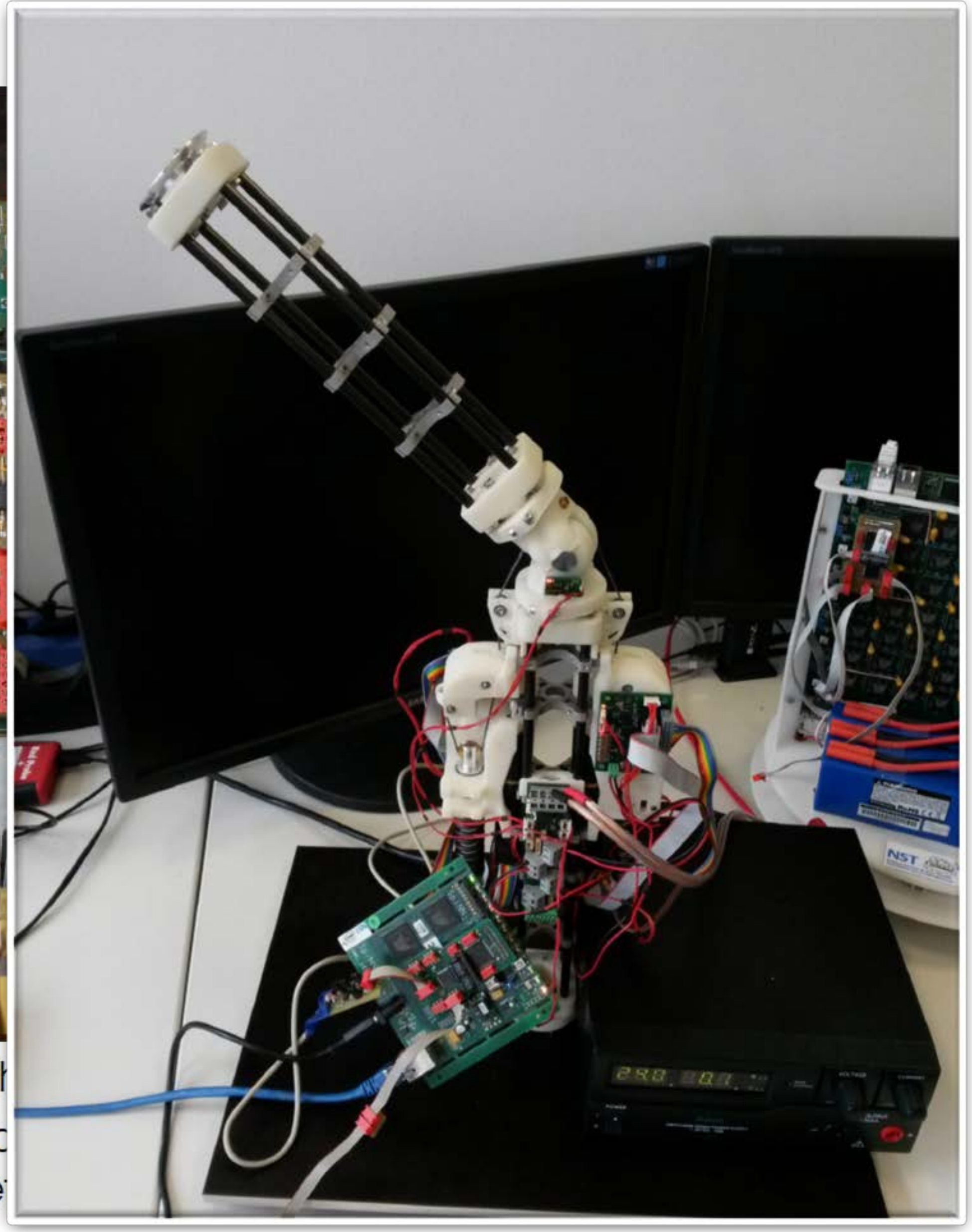


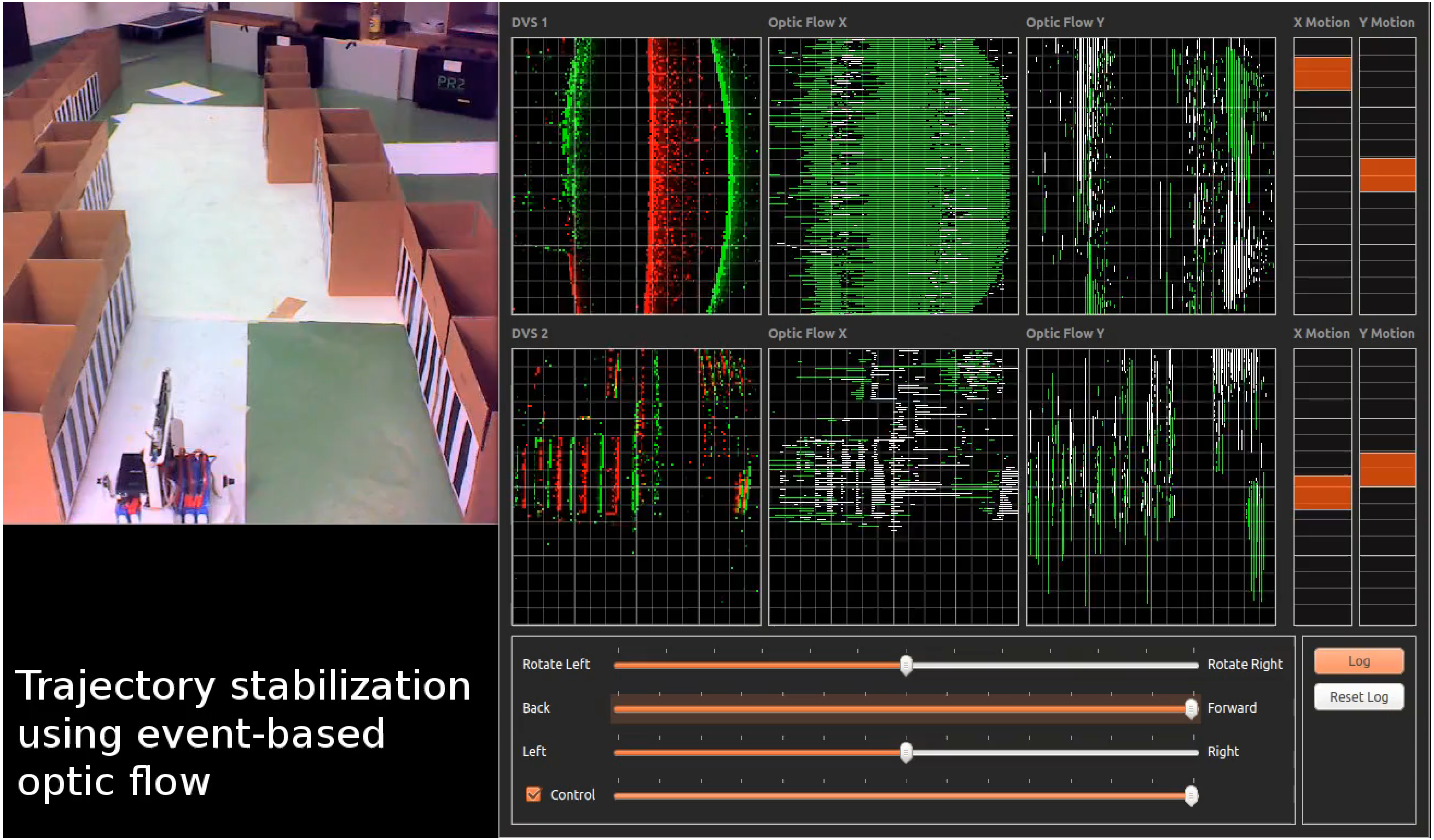
Example Projects: SpOmniBee

- 2 laterally facing retinas
- Retina events feed into SpiNNaker
- Distributed computation of local optical flow
- Global combination of optic flow
- Computation of Motor commands on SpiNNaker, send to robot

Goal:

keep SpOmnibot centered in hallway with marking, similar to Srinivasan’s Bee experiments

Application Example: Event-Based Optic Flow for Robot Control



Example Projects: Ball Balancer

- One Retina to observe the platform in top-down view
- Two motors to control platform's pan and tilt angles
- SpiNNaker Interface Board is connected to retina and motors

Goal: Keep ball (one or more!) on a certain trajectory

Neural Principles for System Control