Reliable computation in recurrent, spiking, and plastic networks: from proof of concept to real-world applications

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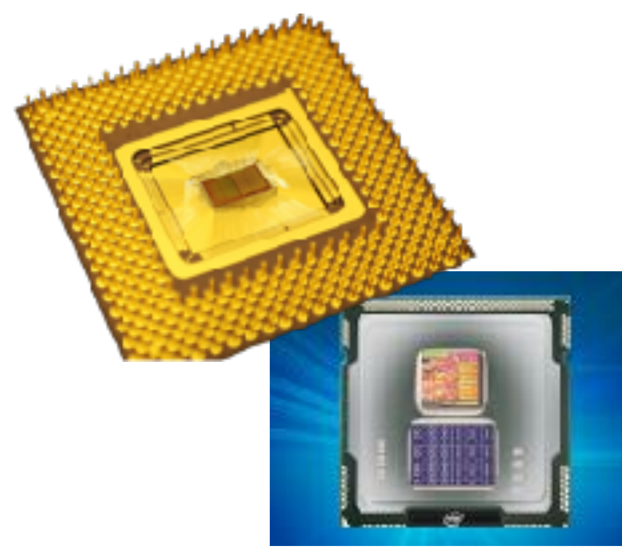
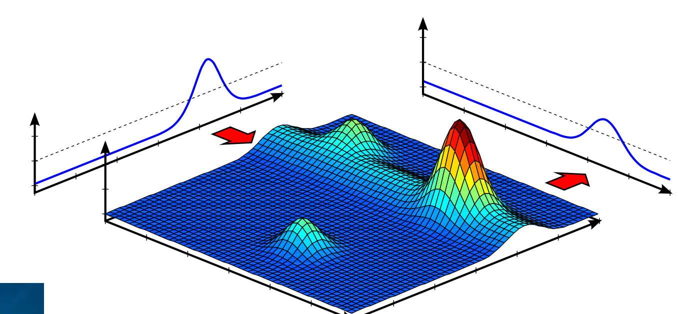
Research group
“Neuromorphic Cognitive Robots"





Intelligent systems: Artificial vs Biological

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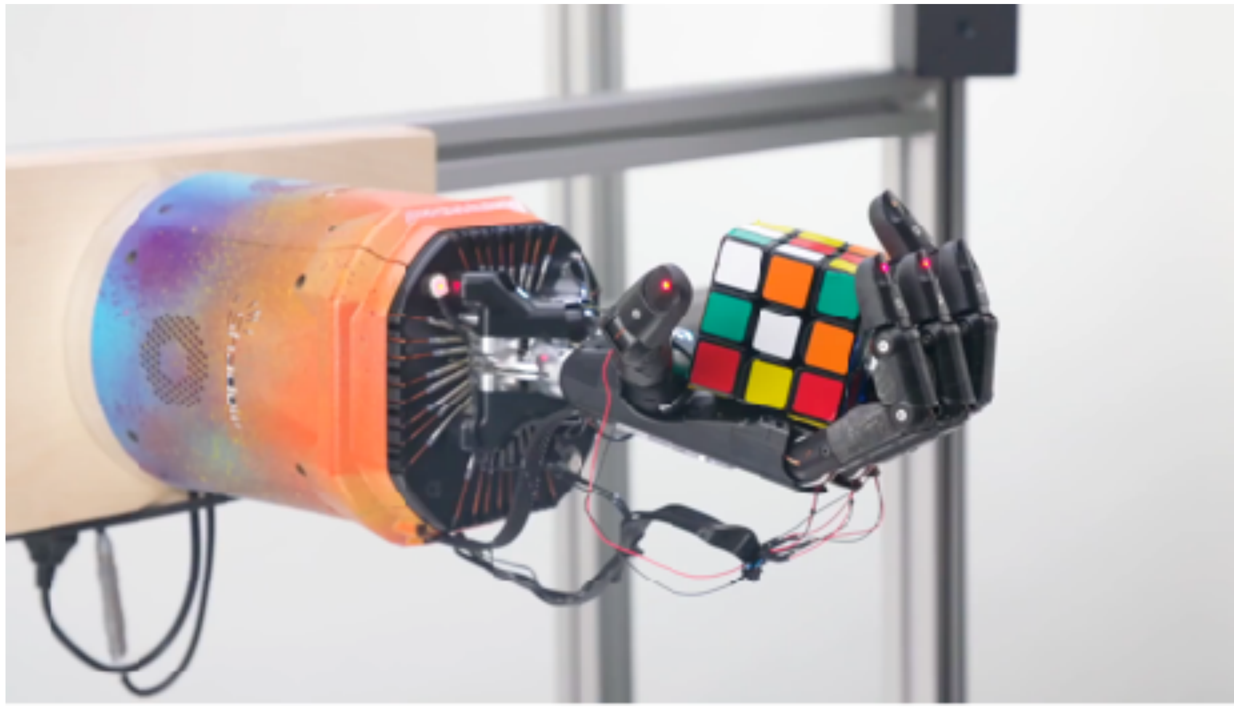
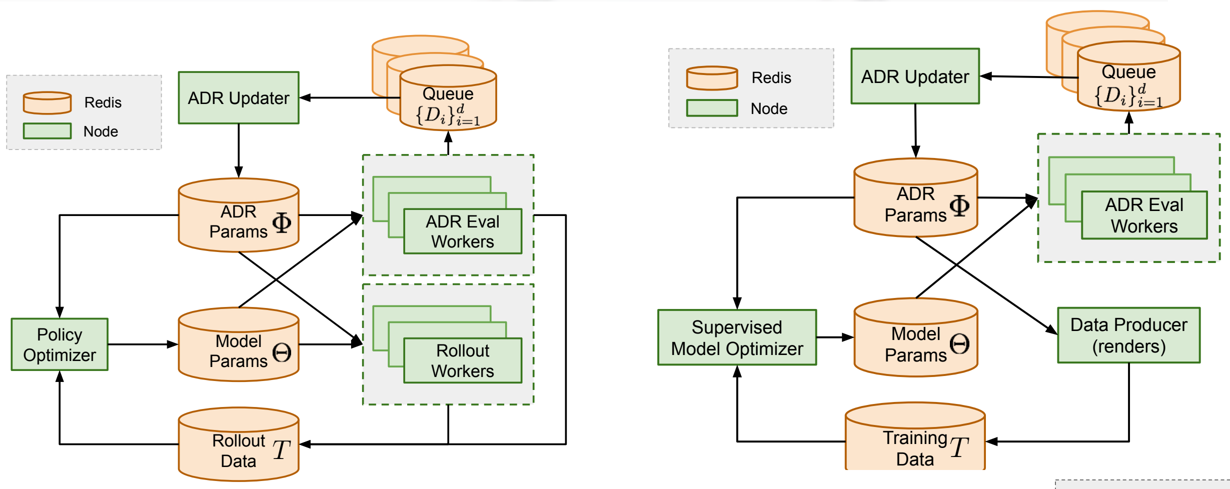
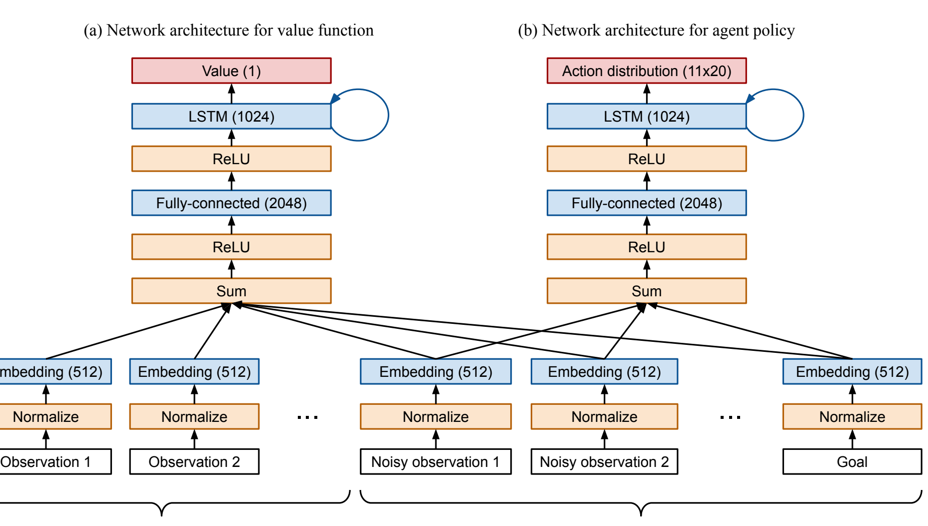
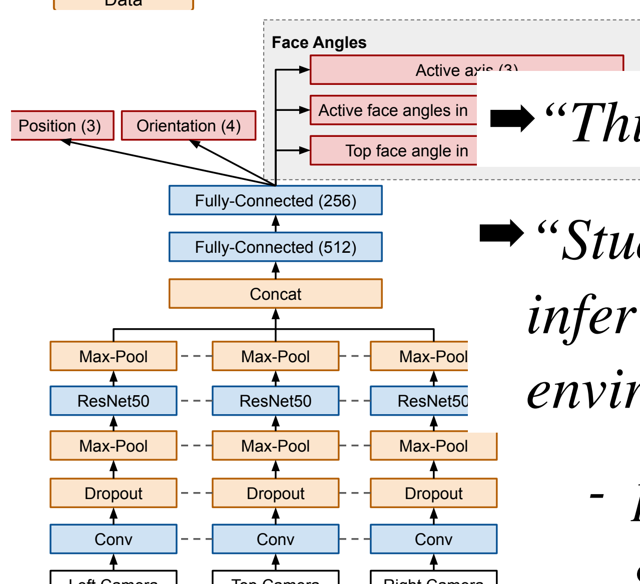








➡ 8 × 8 = 64 NVIDIA V100 GPUs

+ 8 × 115 = 920 worker machines with 32 CPU

➡ training the policy continuously for several month

= 13 thousand years

- 13,863,132 trainable parameters per network

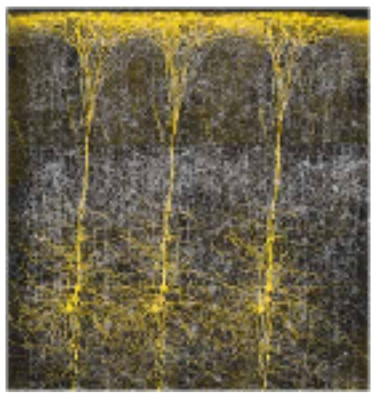
➡ *“This has worked surprisingly well (policy cloning)”*

➡ *“Study whether the policy has learned to infer and store useful information about the environment in its recurrent state”*

- *prediction accuracy rapidly improves to over 80% for certain parameters….*

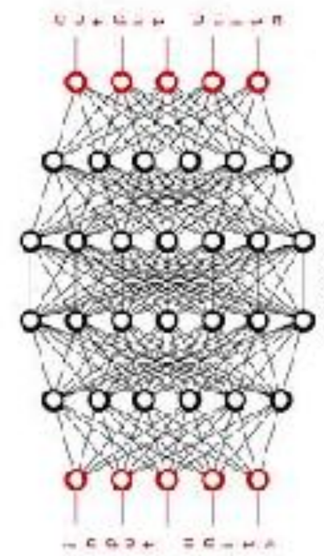
What do we know about biological neuronal systems?

Biological neural networks



- ☑ Massively parallel
- ☑ Massively recurrent
  - filtering
  - stable states
- ☑ Event-based
  - save power
  - be fast
- ☑ Plastic
  - can learn on the fly

Artificial neural networks



- ☑ GPU, parallel computing
- ☐ Recurrence is difficult: leads to loops; non-Markovian; no clear input and output
- ☐ Processing is clocked, asynchrony is hard to deal with; no gradients to learn
- ☐ “Training”. Plasticity is difficult: Convergence? Testing?

➡ Dynamical NS, “Type B”

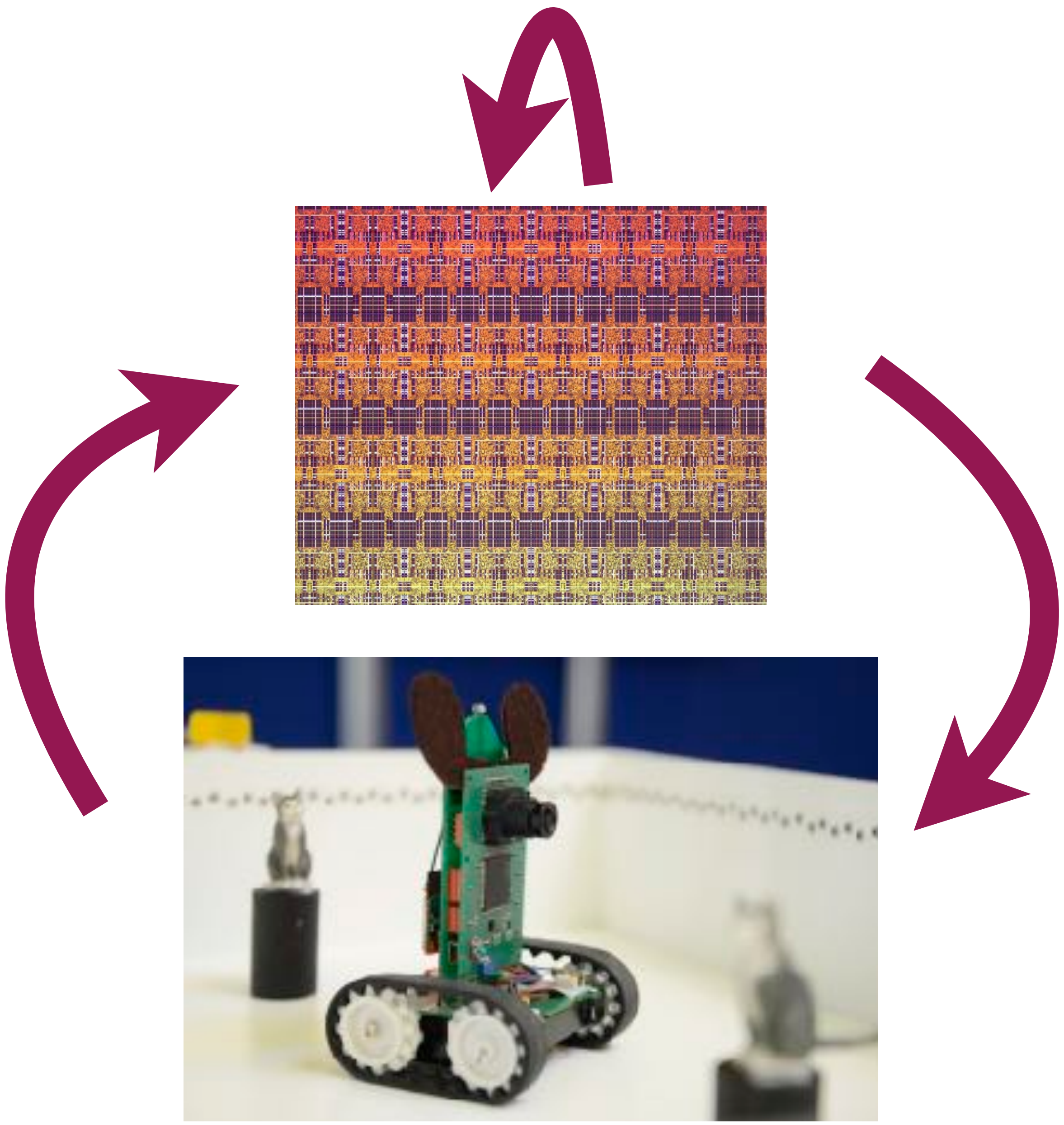
- “Computing” with the substrate
- Control

➡ Turing-compliant NS, “Type A”

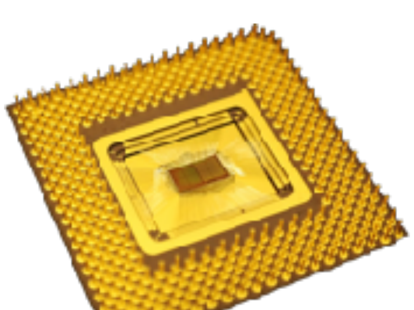
- Turing Machine: the computing substrate doesn’t matter
- Information processing

Can we build, control, and use neuronal systems of Type B?

Neuromorphic controllers



ROLLS



Loihi

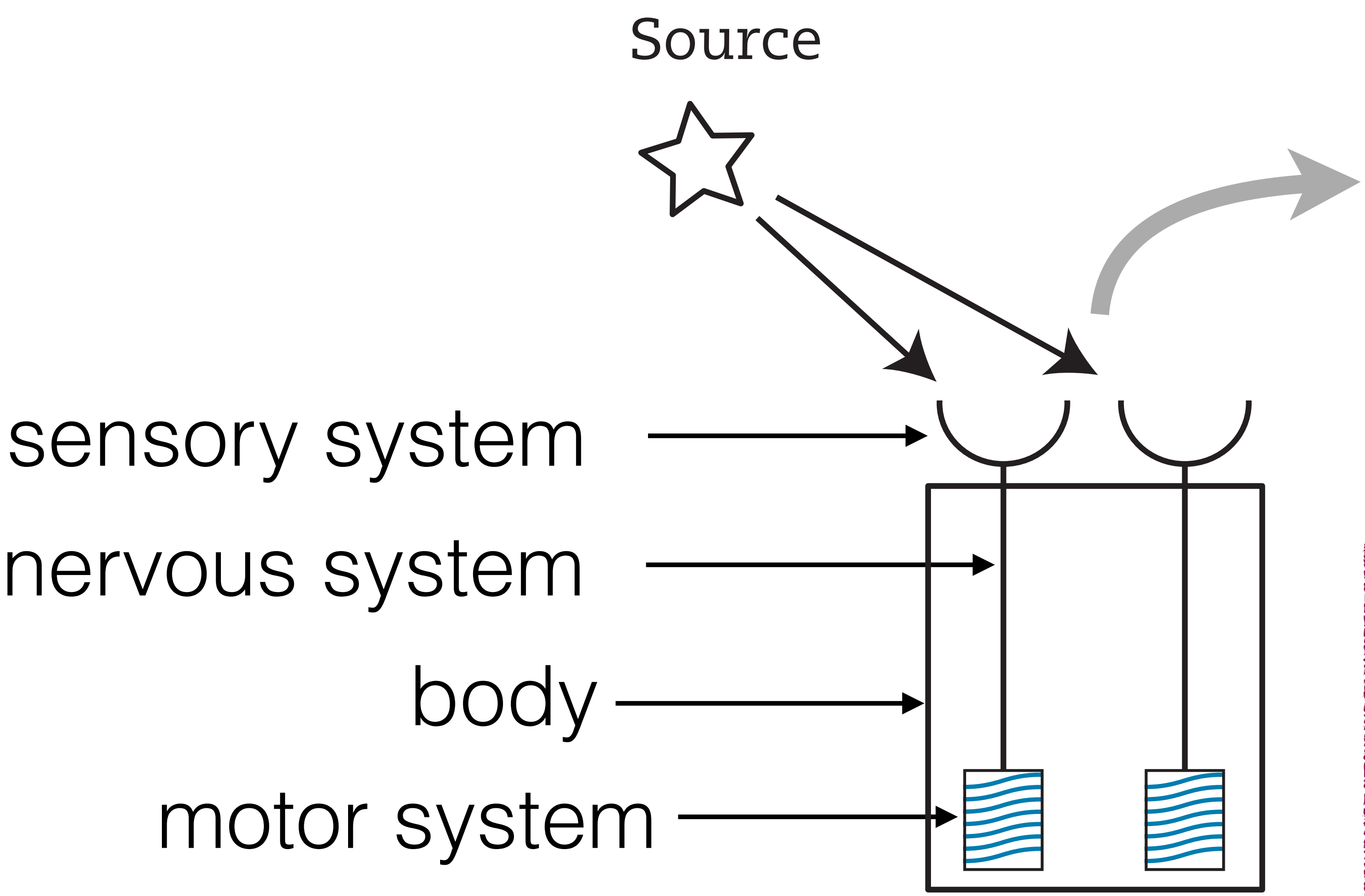
➡ Massive concurrence
- I/O interfaces
- “encoding”
  - rate, timing, place

➡ Massive recurrence
- flexible connectivity
- attractor dynamics

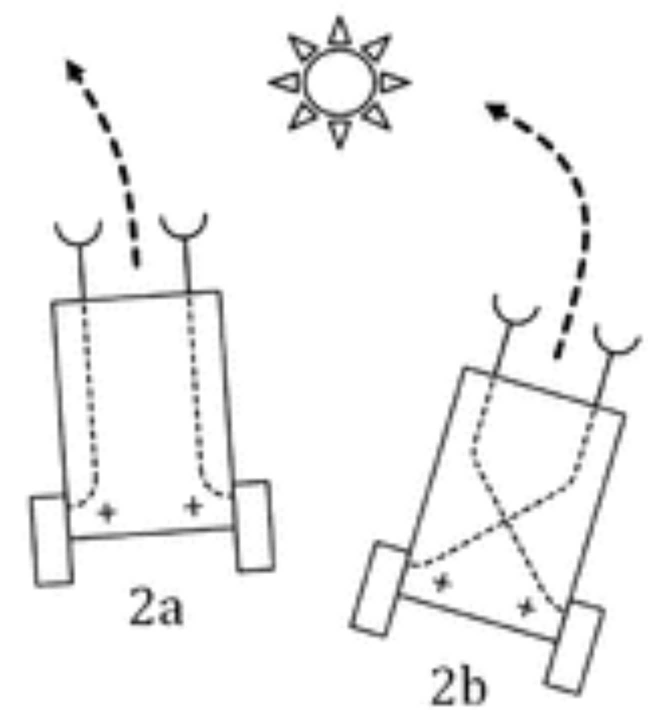
➡ Event-based
- spiking
- and analogue

➡ Plastic
- on-chip local learning
- “memory trace”

Reactive behaviour in navigation (Braitenberg)

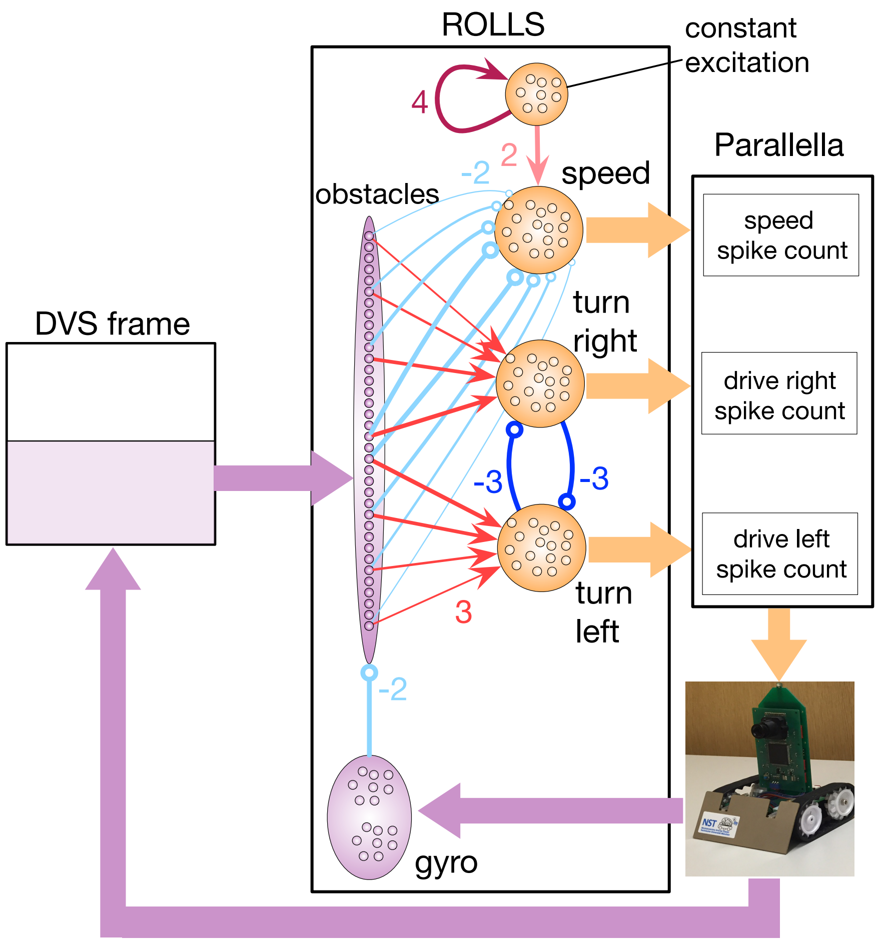


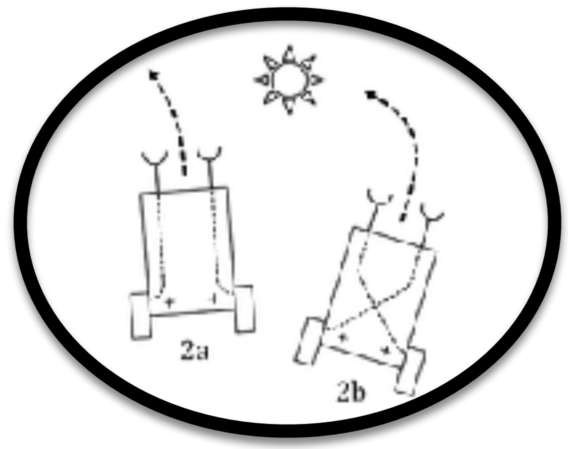
Different behaviours:



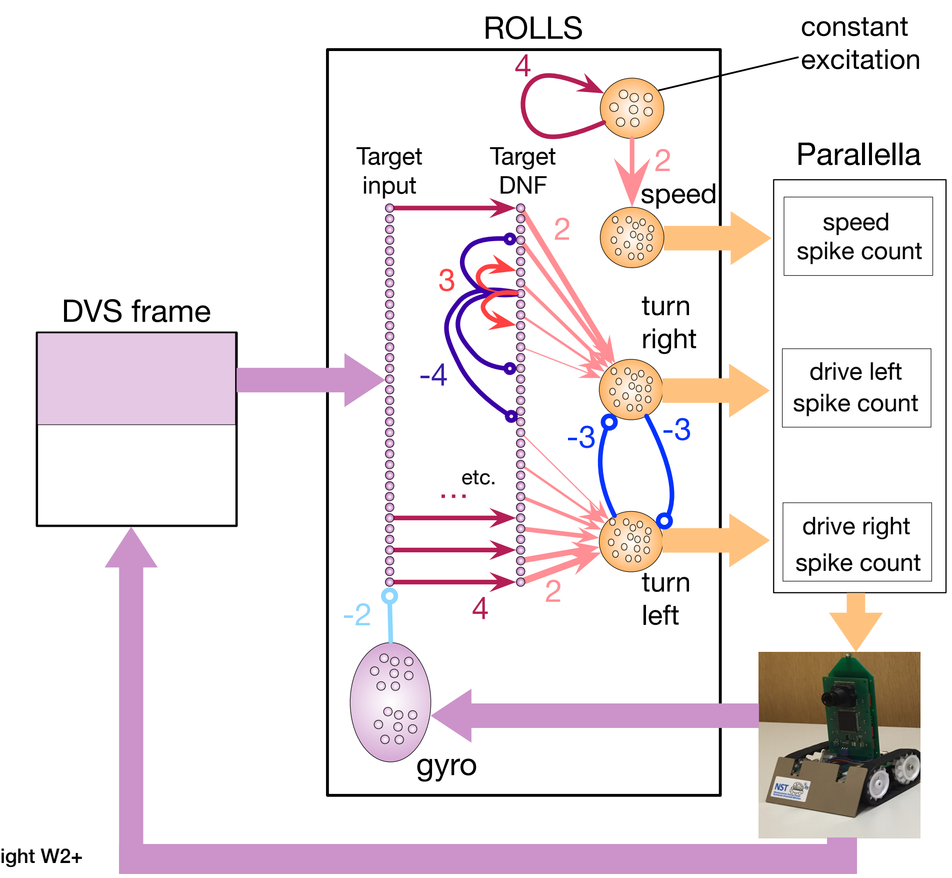
Braitenberg “de luxe” on a neuromorphic chip

Obstacle avoidance

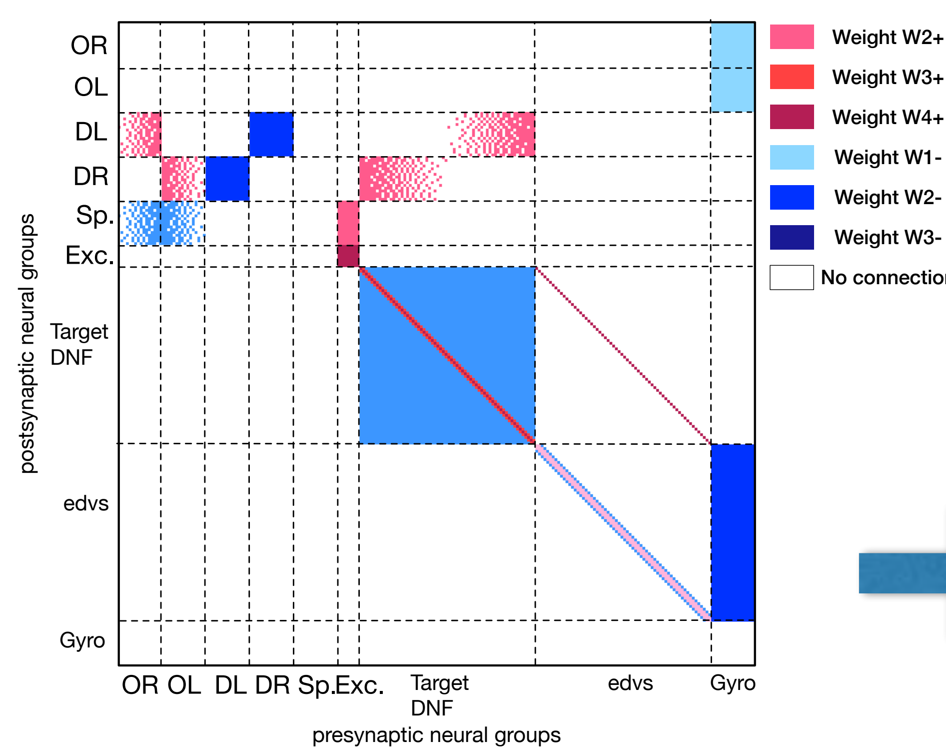




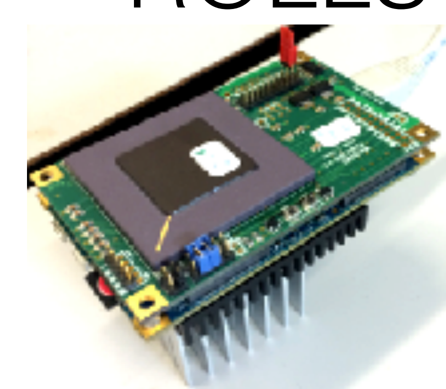
Target acquisition



Connectivity

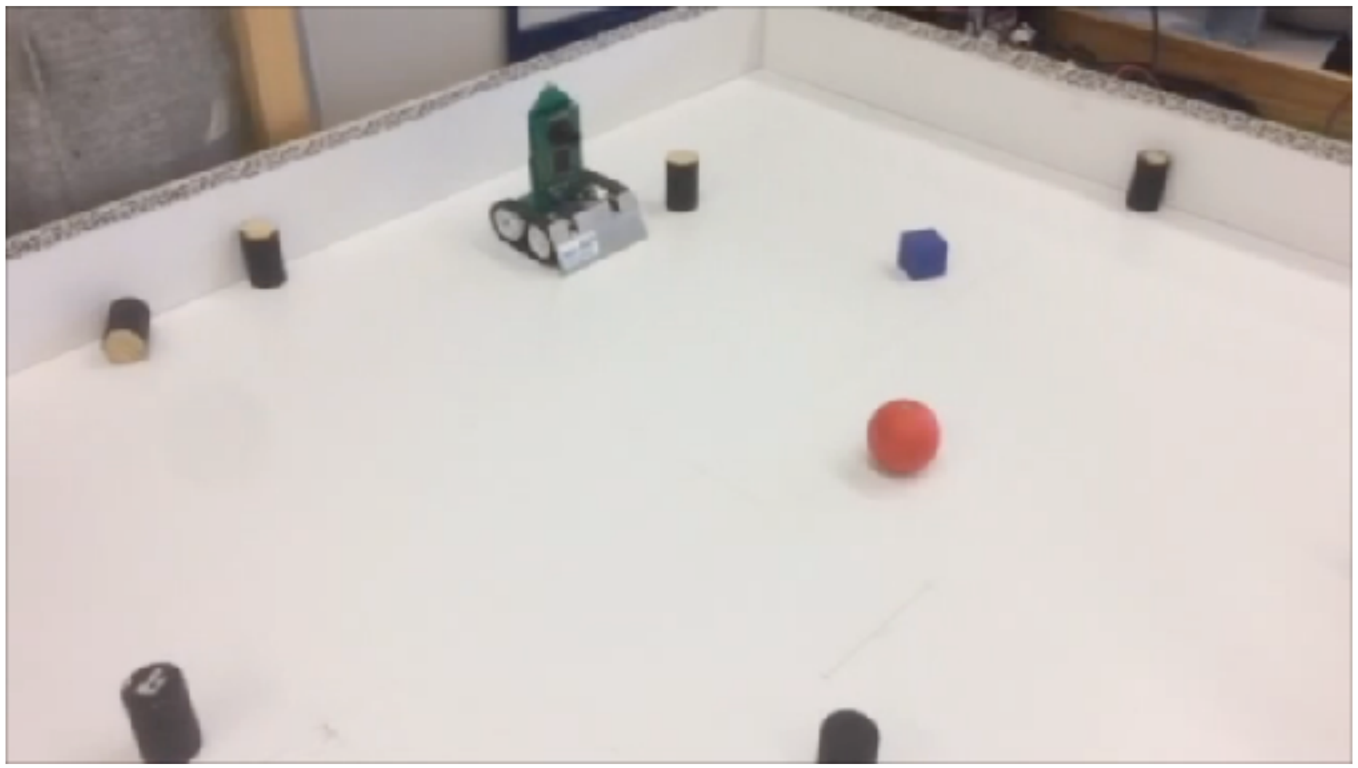


ROLLS

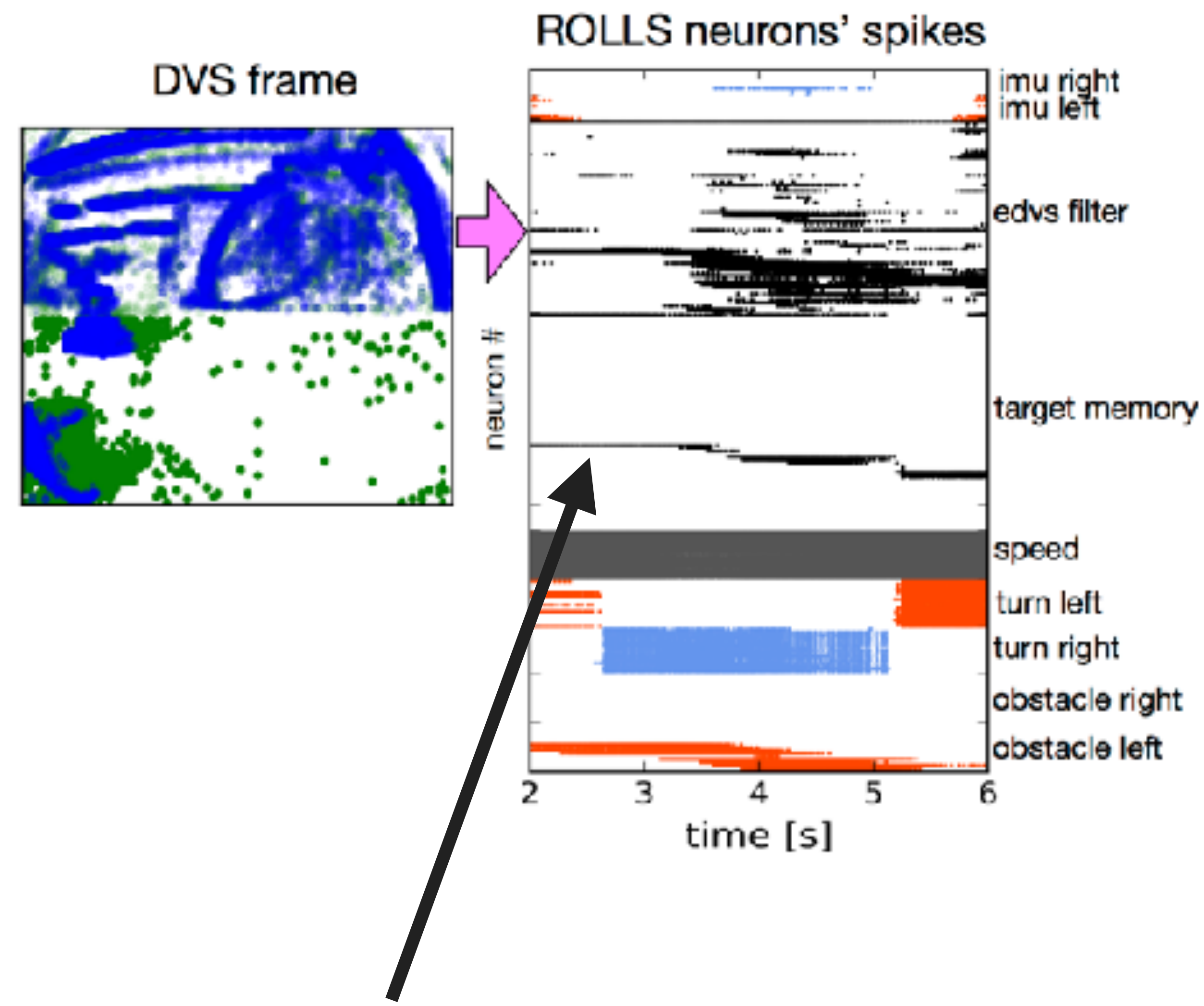


Navigation with a neuromorphic device

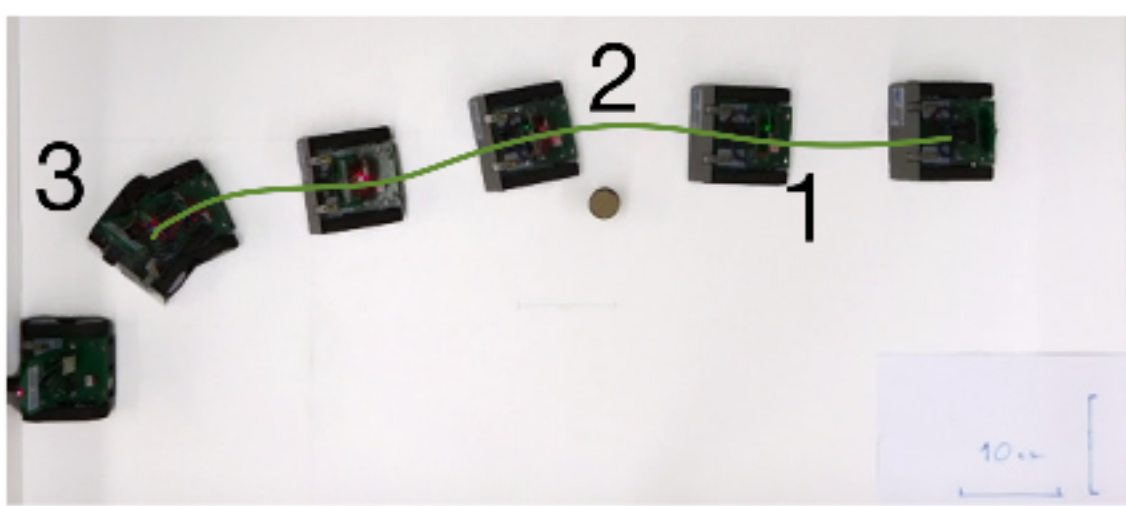
Avoiding obstacles



Output of the sensor and the chip



Target acquisition



WTA / DNF
(recurrence, filtering)

Milde, M.; Blum, H.; Dietmüller, A; Sumislawska, D.; Conradt, J.; Indiveri, G. & Sandamirskaya, Y. Obstacle avoidance and target acquisition for robot navigation using a mixed signal analog/digital neuromorphic processing system Frontiers in Neurorobotics, 2017.

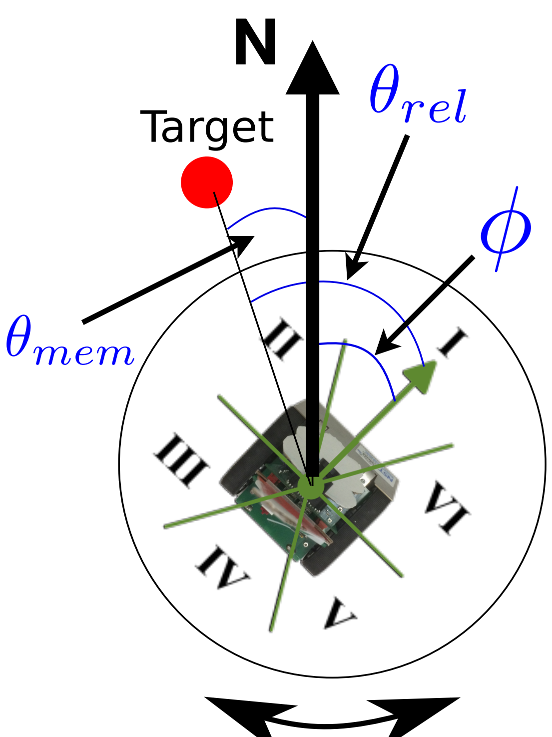
Reference frames

View-based target representation:

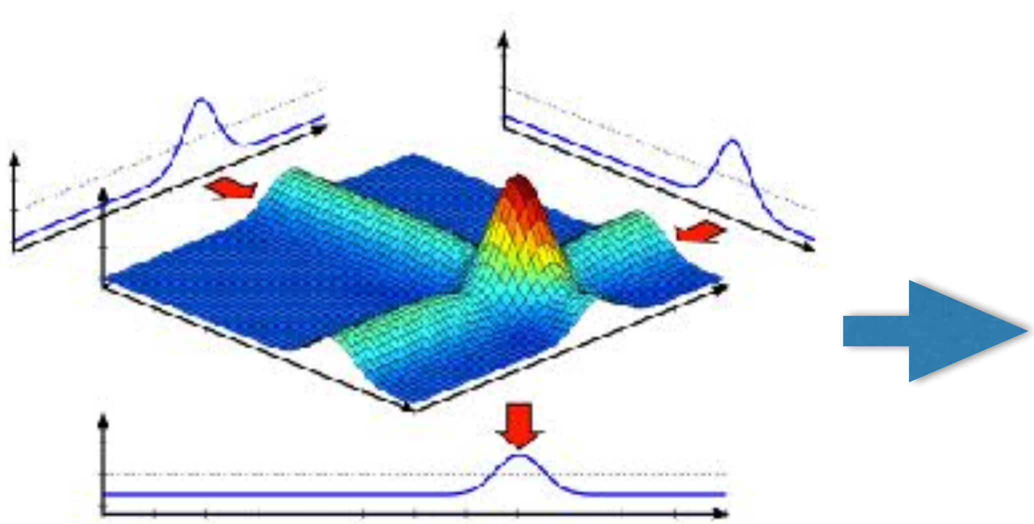
- target in view

- target lost from view

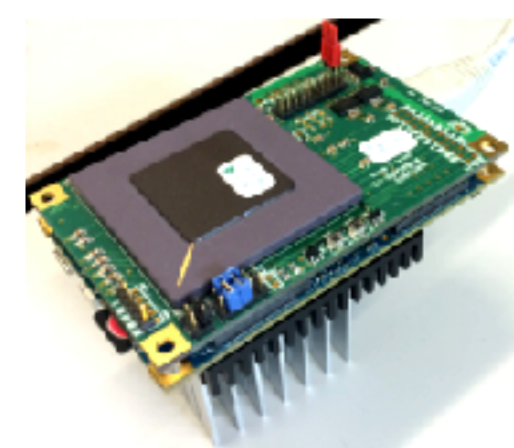
Allocentric target representation:



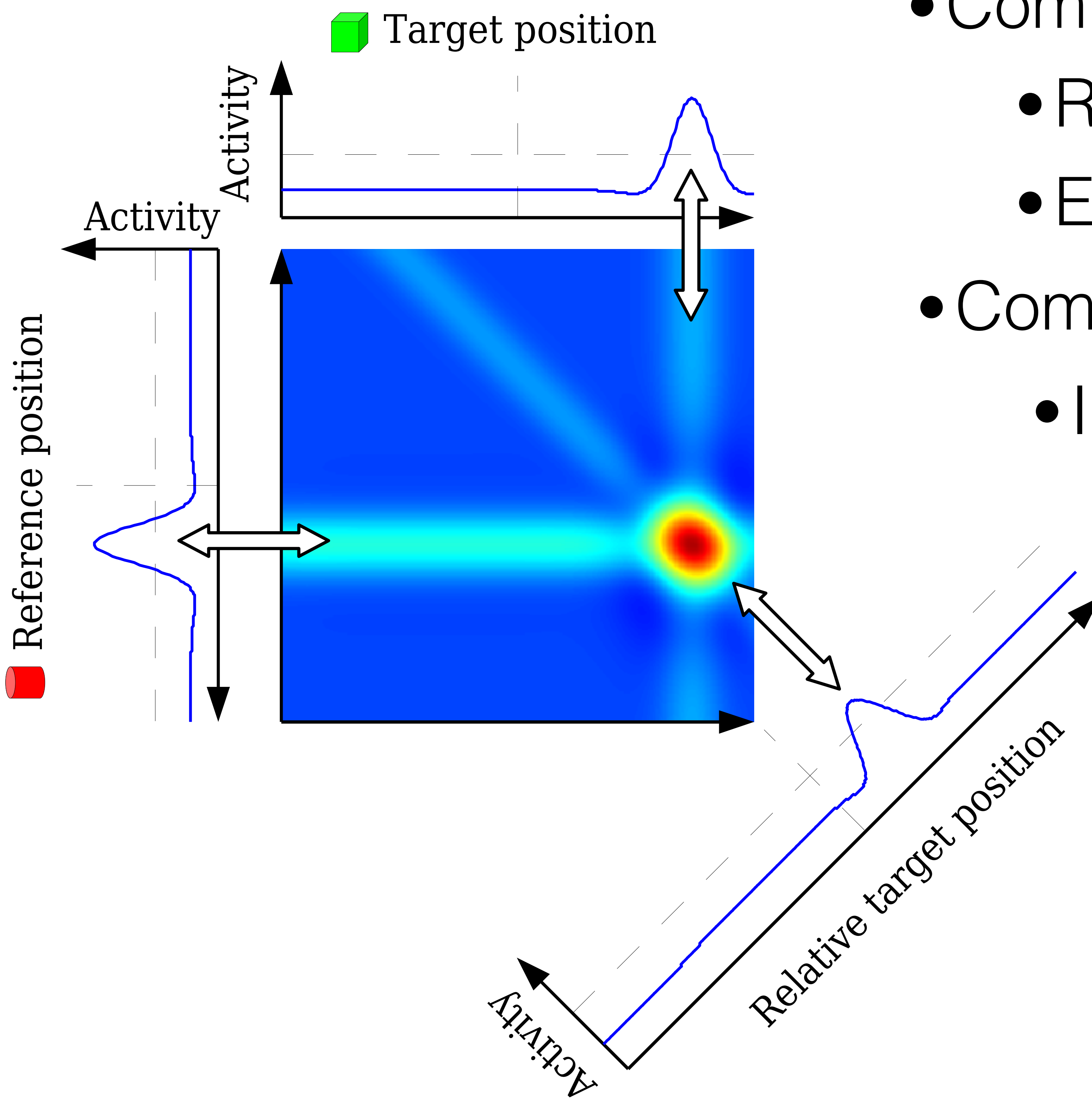
Neural ref. frame transformation:



ROLLS device

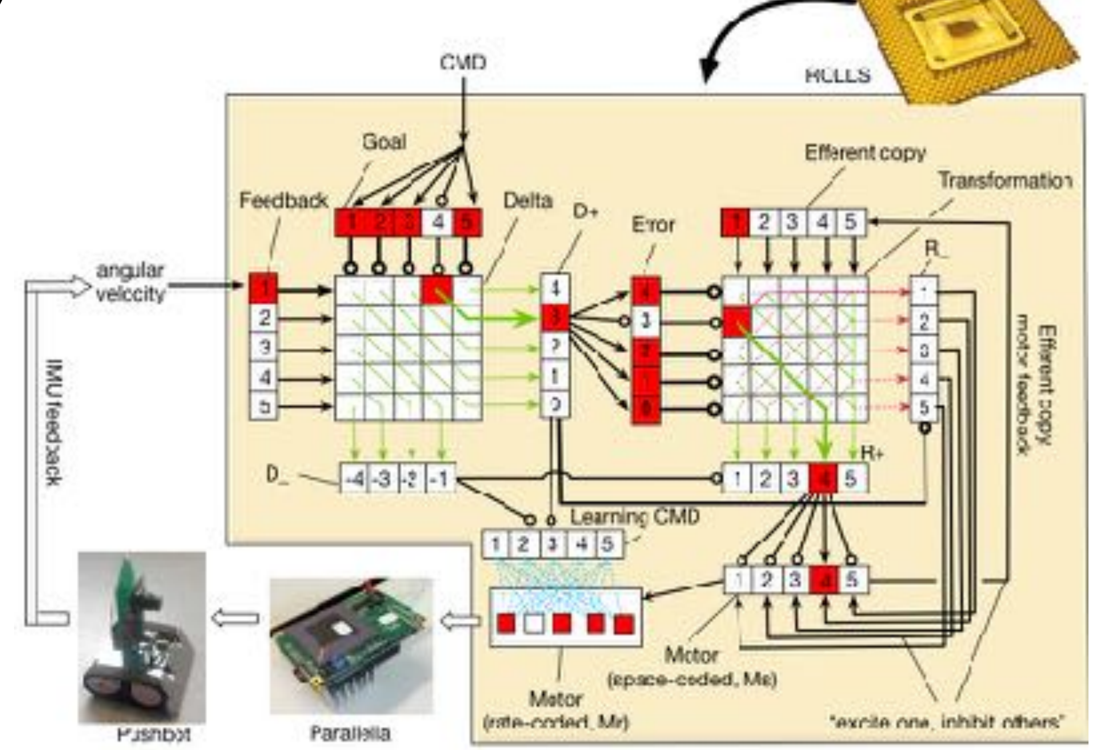


Neuronal coding of 3-way relations

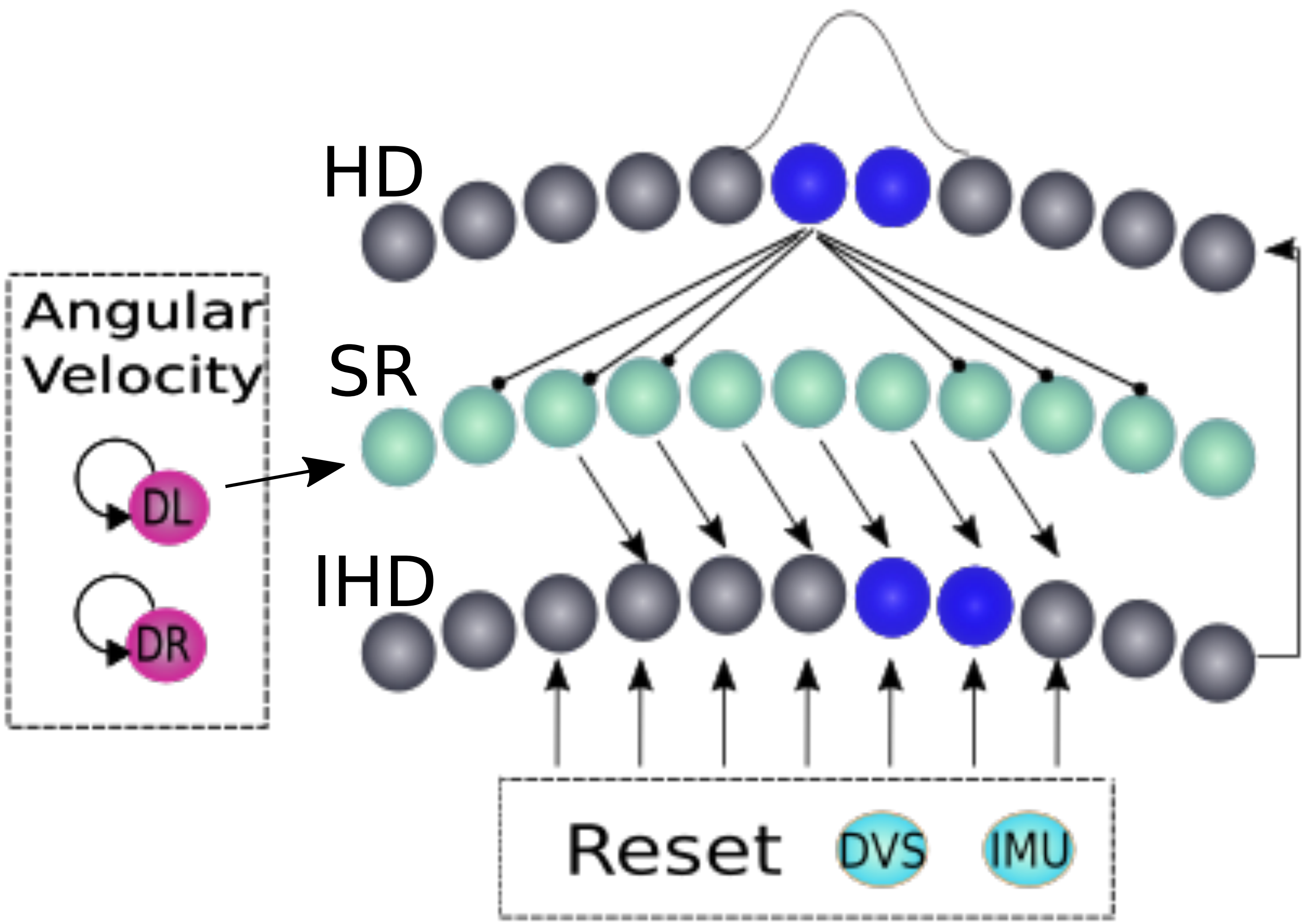


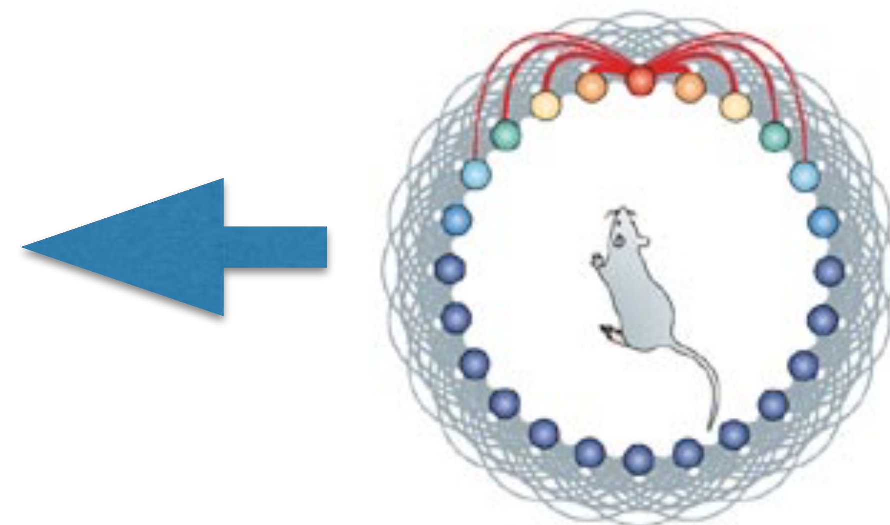
- Computing differences
  - Reference frame transform
  - Error estimation
- Computing sums
  - Integration

➡Control



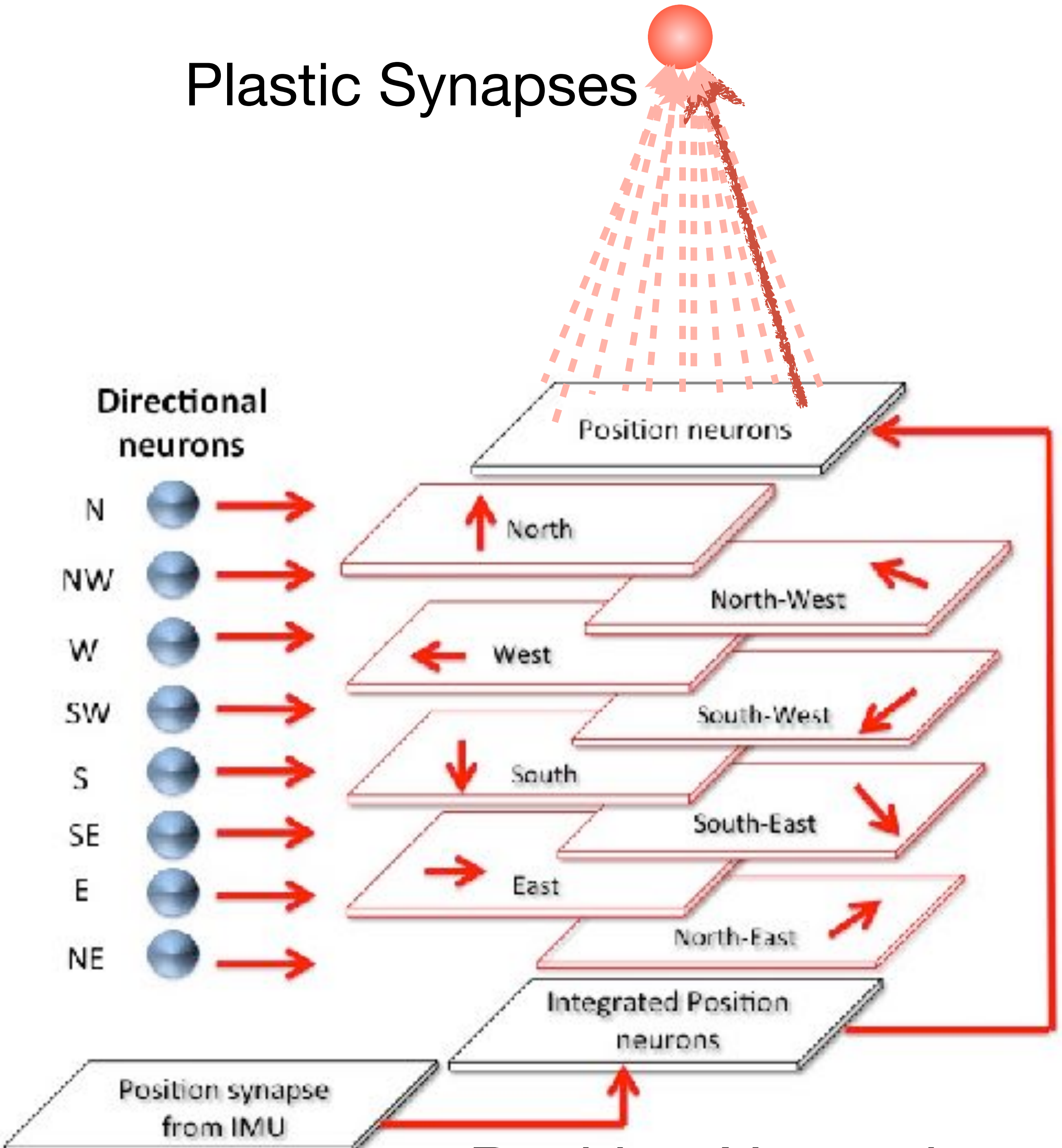
Neuromorphic SLAM: 1) Heading direction / orientation

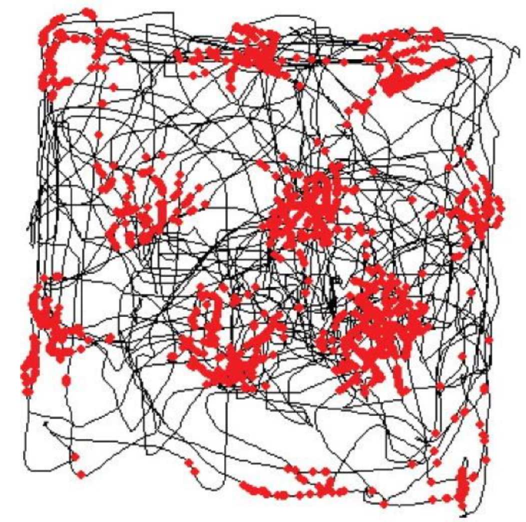




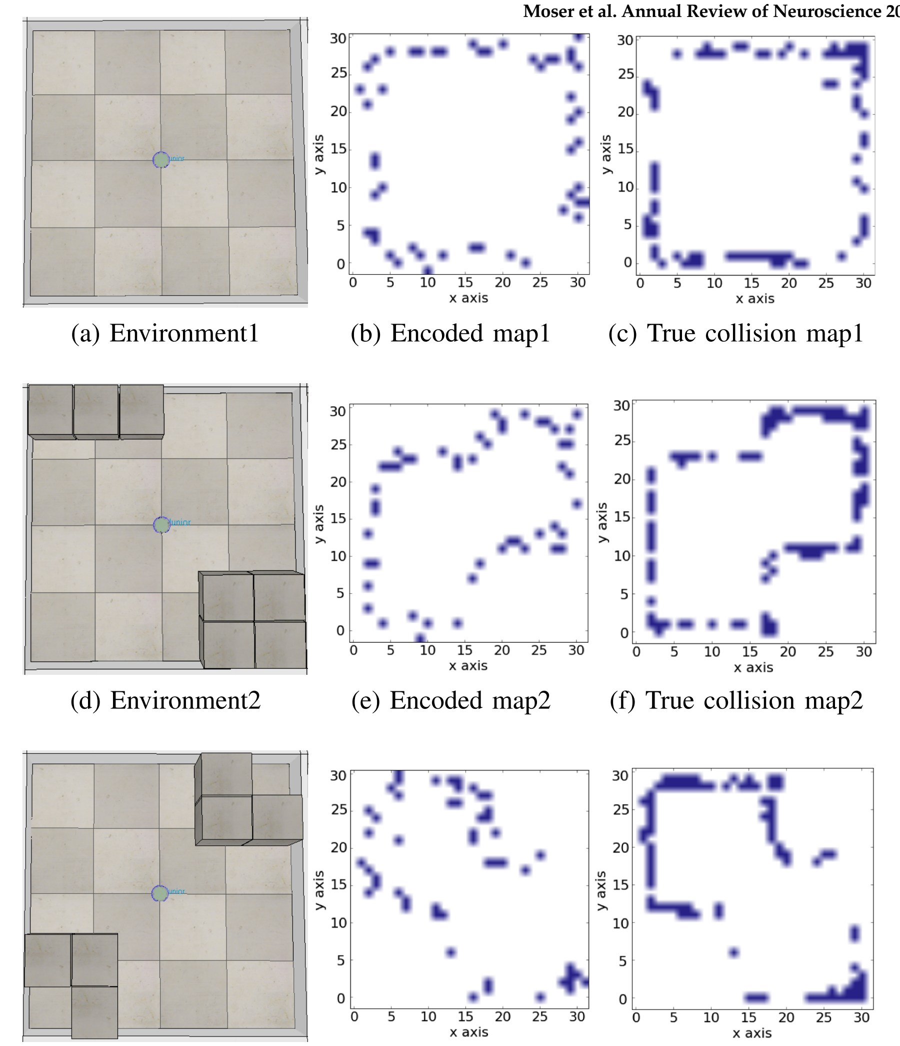
Kreiser, R.; Cartiglia, M. & Sandamirskaya, Y. A Neuromorphic approach to path integration: a head direction spiking neural network with visually-driven reset. IEEE Symposium for Circuits and Systems, ISCAS, **2018**

Neuromorphic SLAM: 2) Position, 2D map





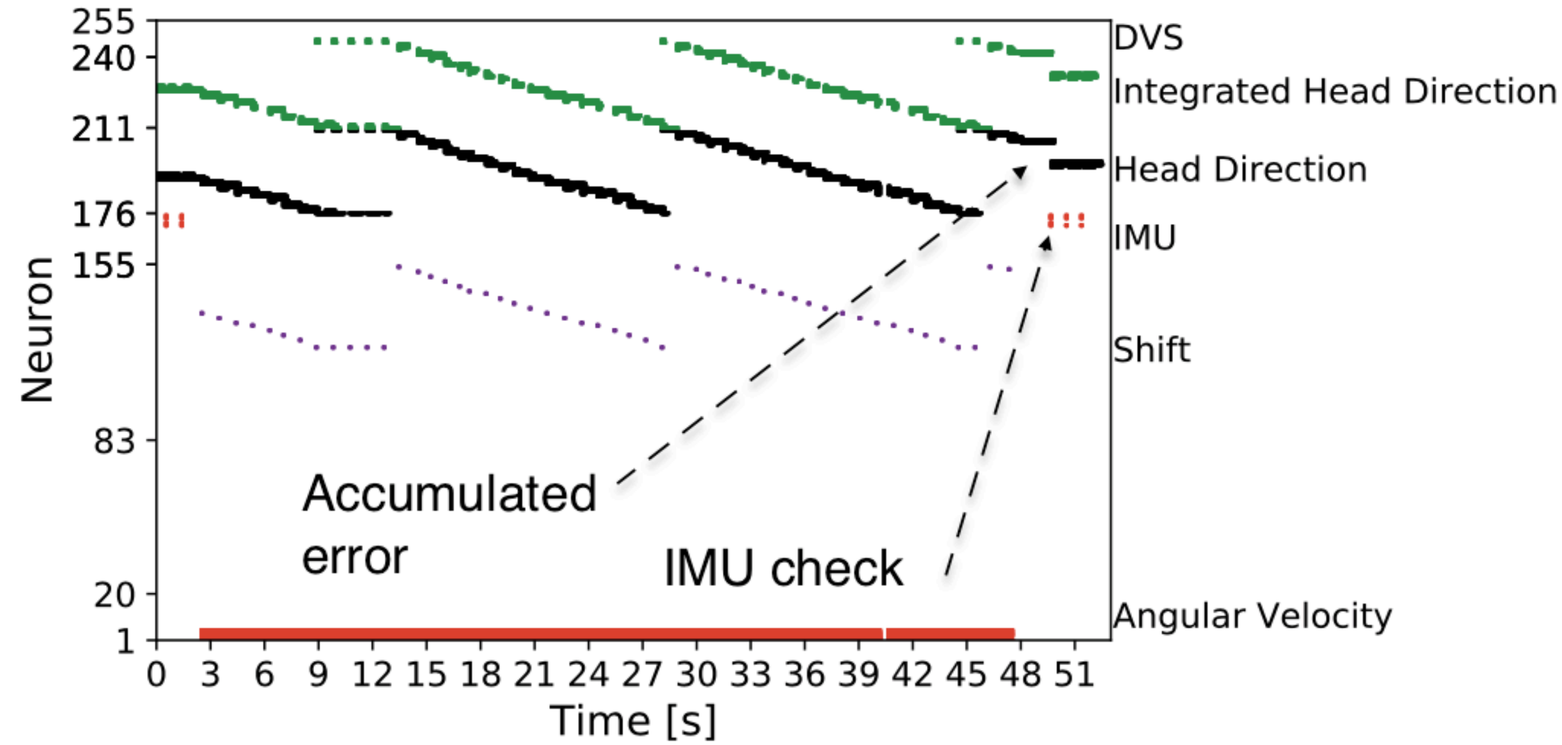
Moser et al. Annual Review of Neuroscience 2008



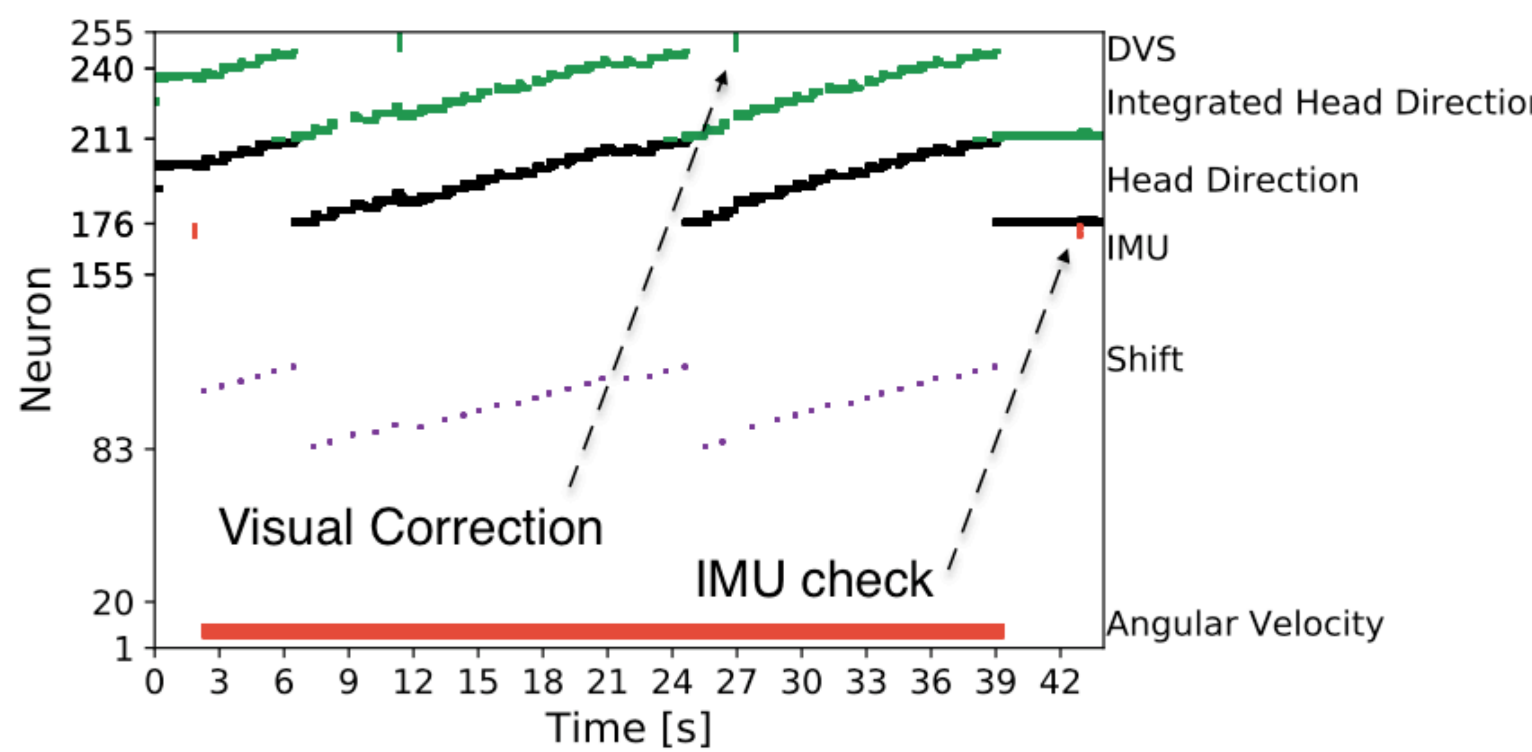
Kreiser, R.; Pienroj, P.; Renner, A. & Sandamirskaya, Y. Pose Estimation and Map Formation with Spiking Neural Networks: towards Neuromorphic SLAM. 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, **2018**

Neuromorphic SLAM: 3) Errors, sensor fusion

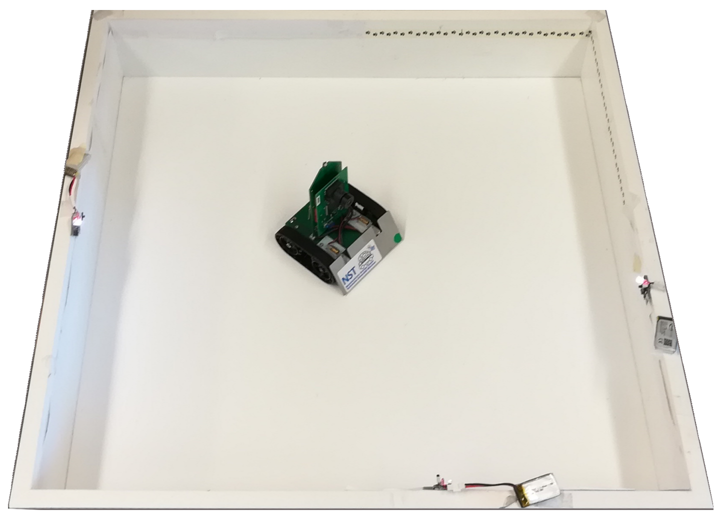
“Proprioception” only

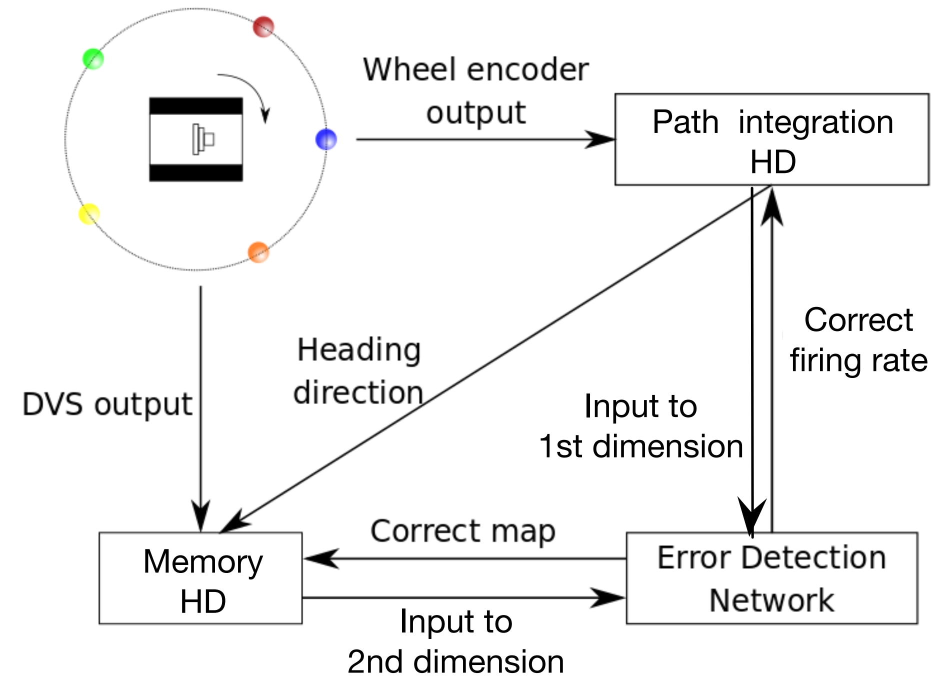


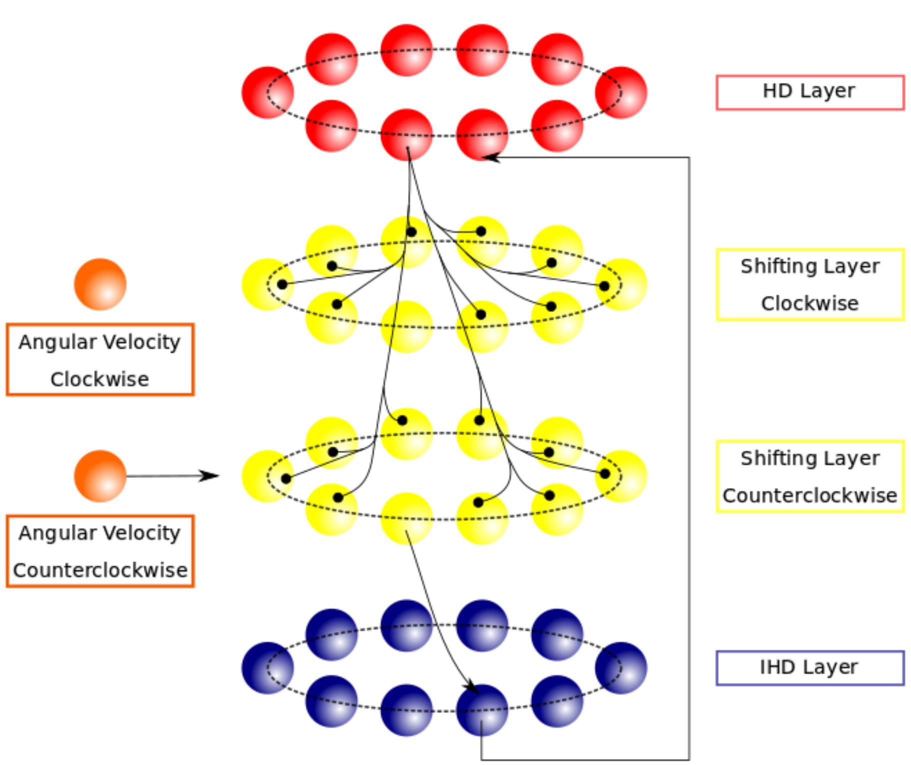
Correction using vision

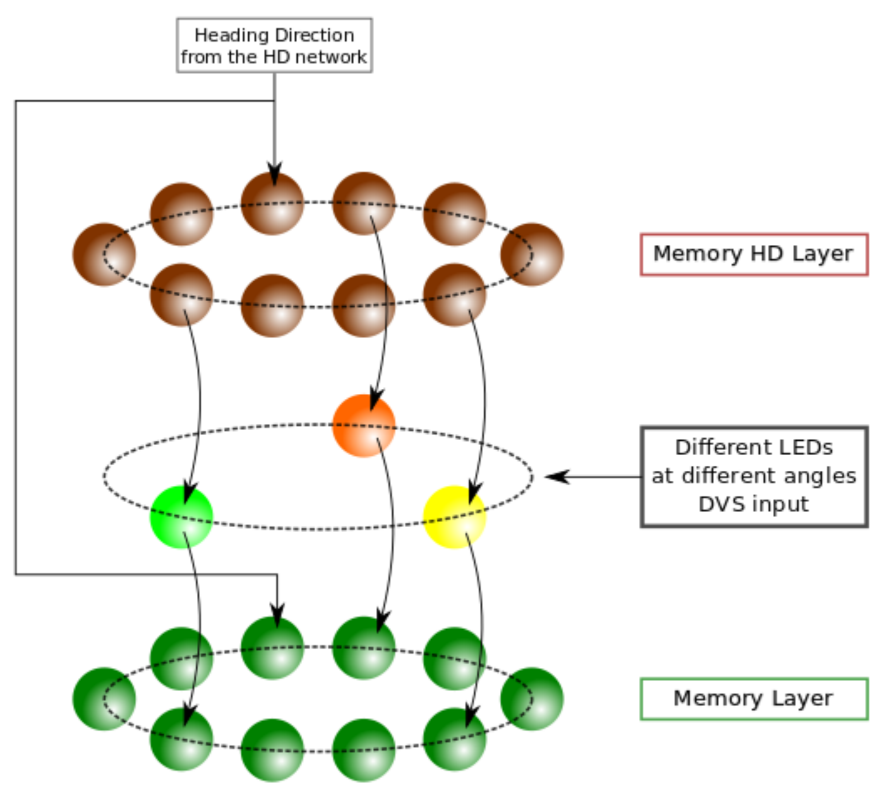


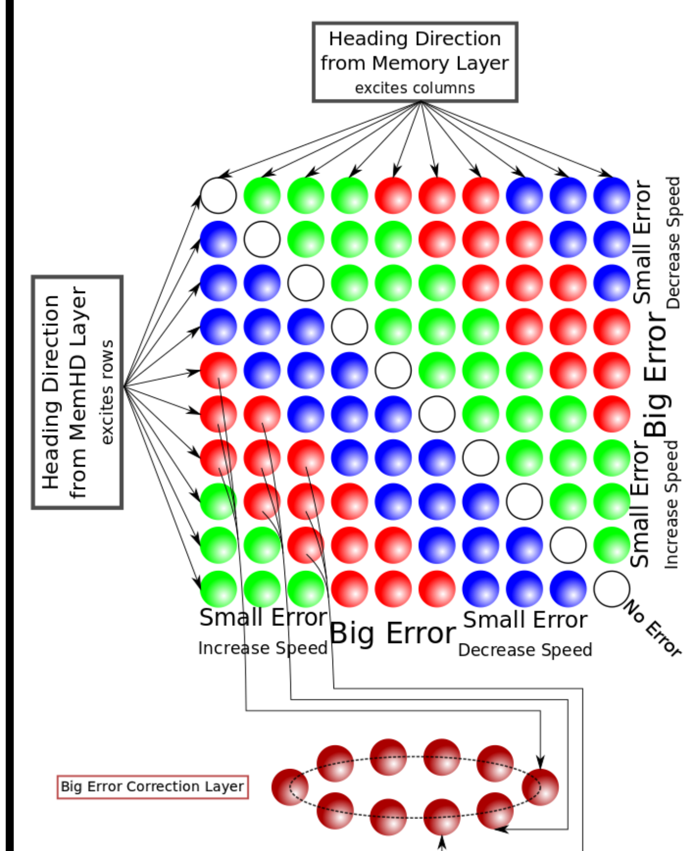
Neuromorphic SLAM: 4) Loop closure





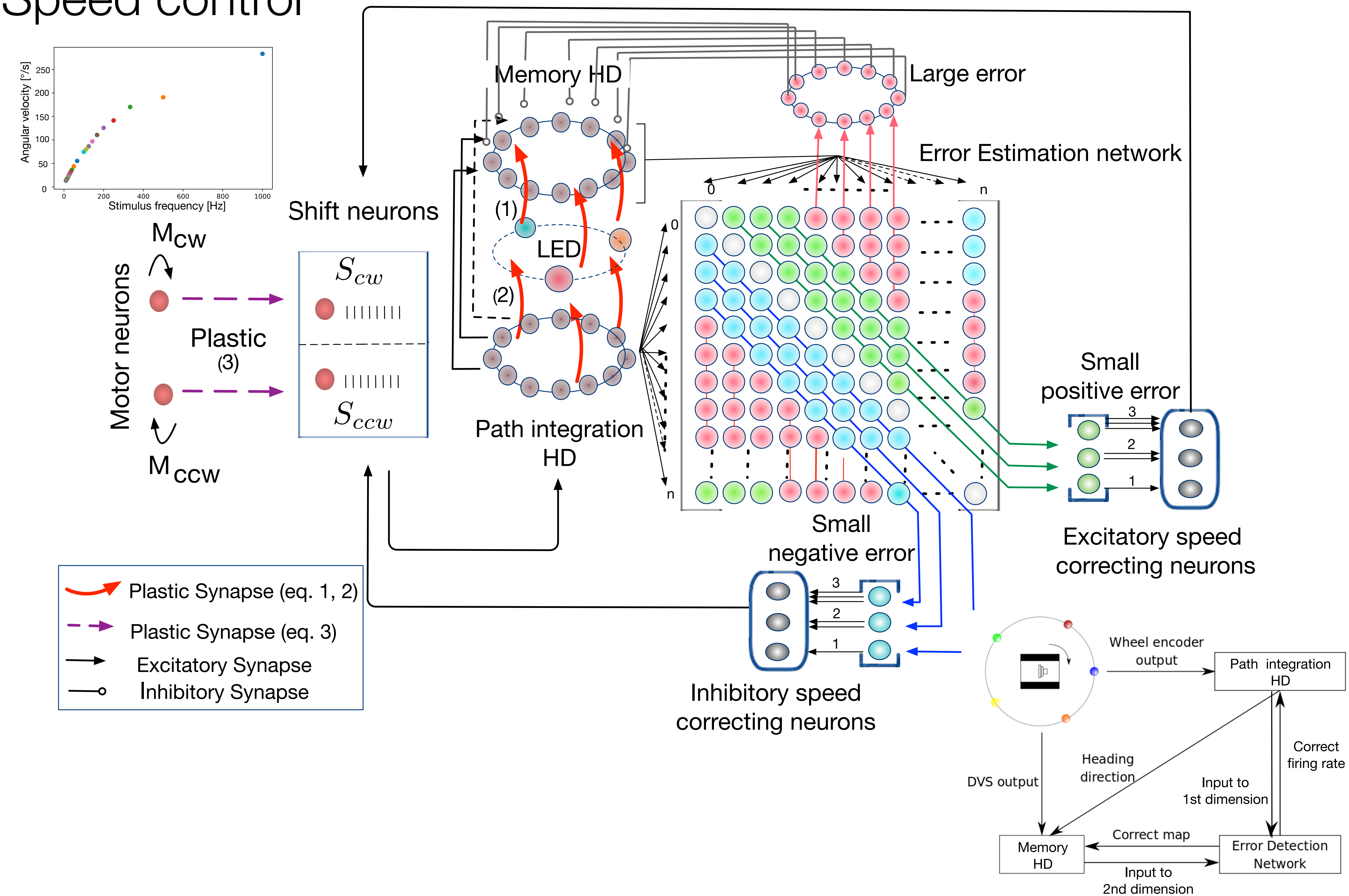




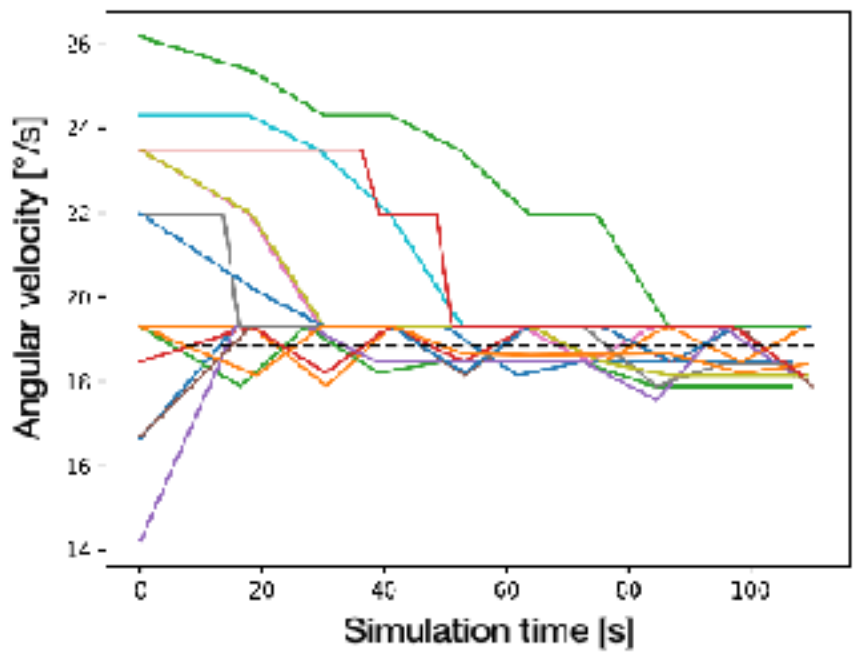


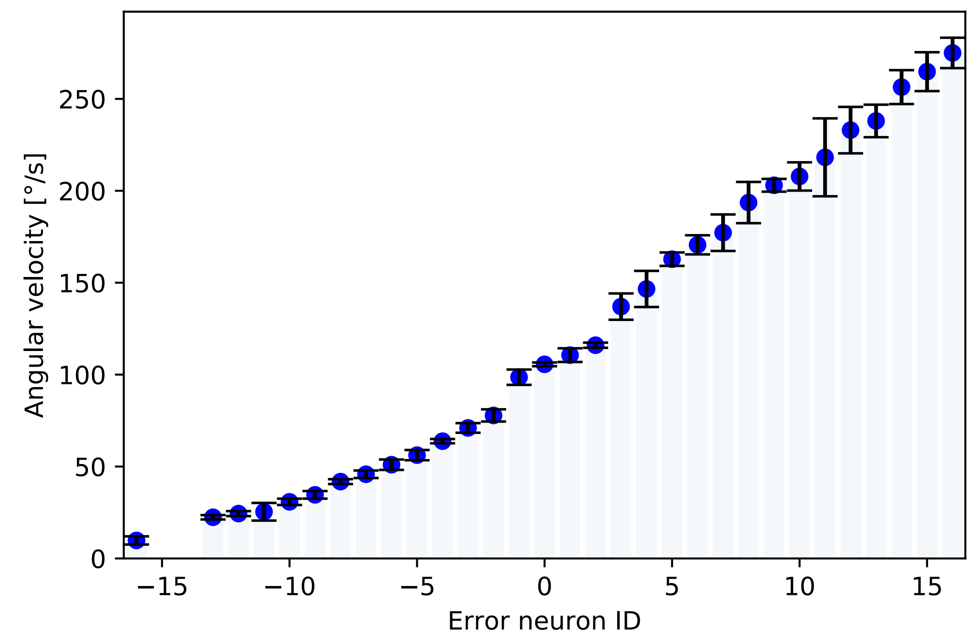
SLAM 4: Loop closure architecture

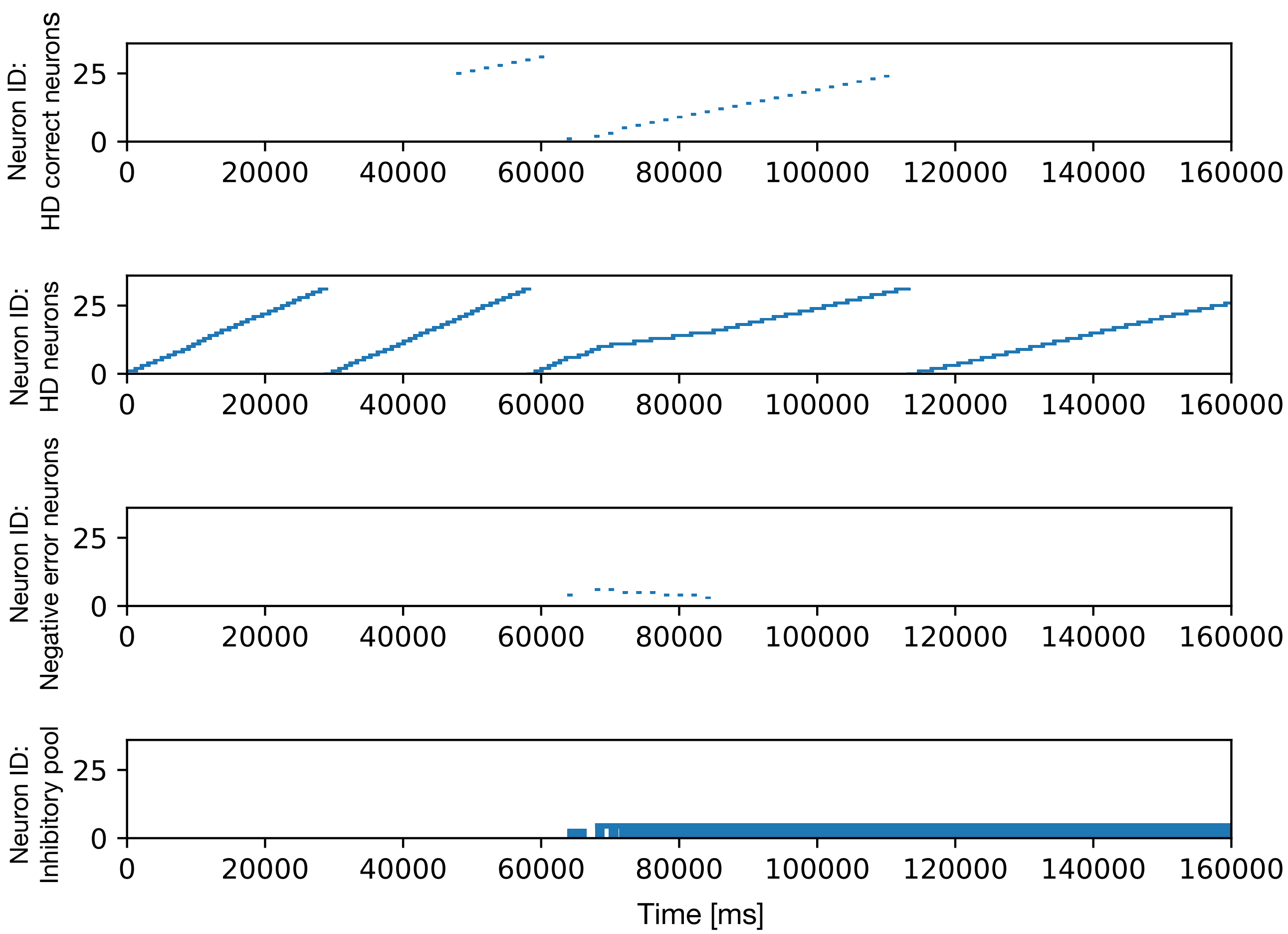
Speed control

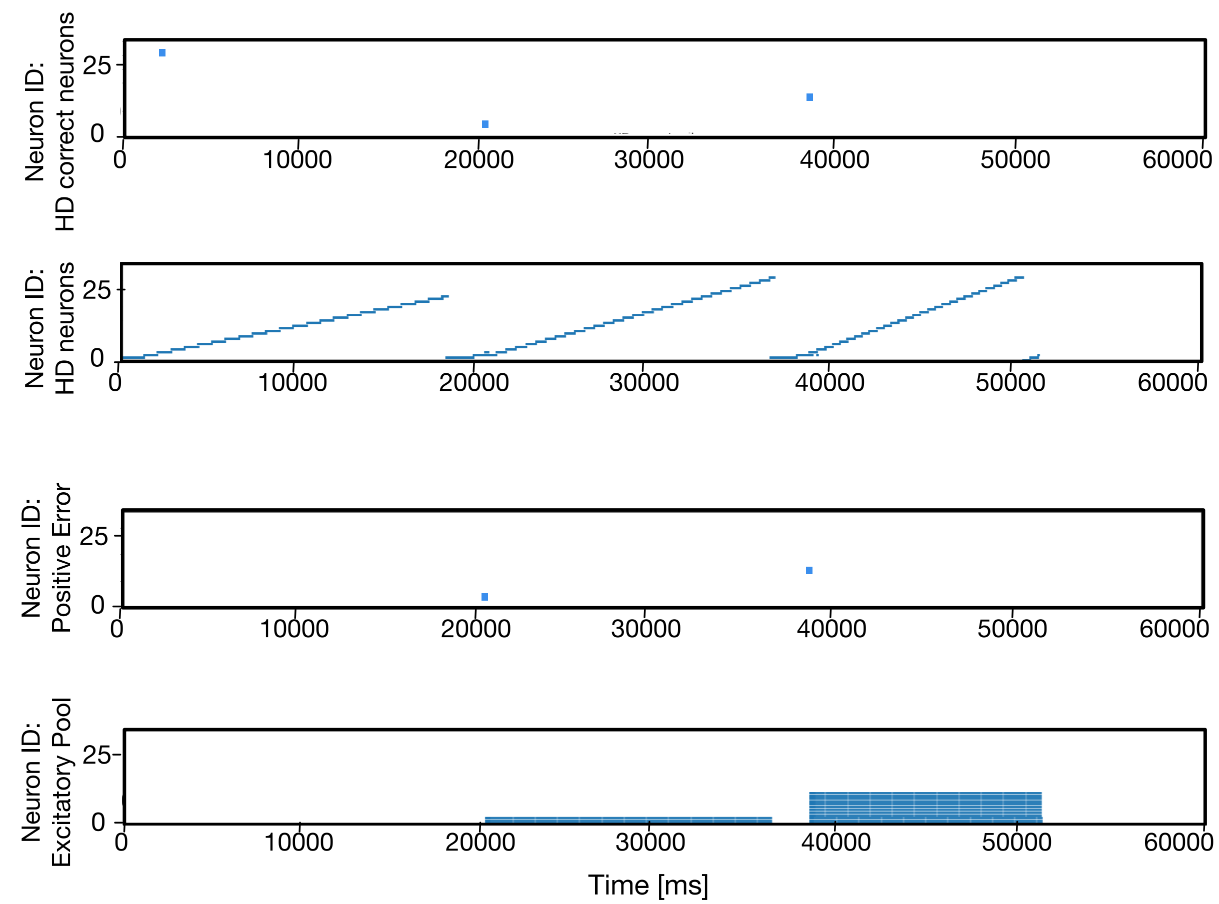


Neuromorphic SLAM: Results (calibration)



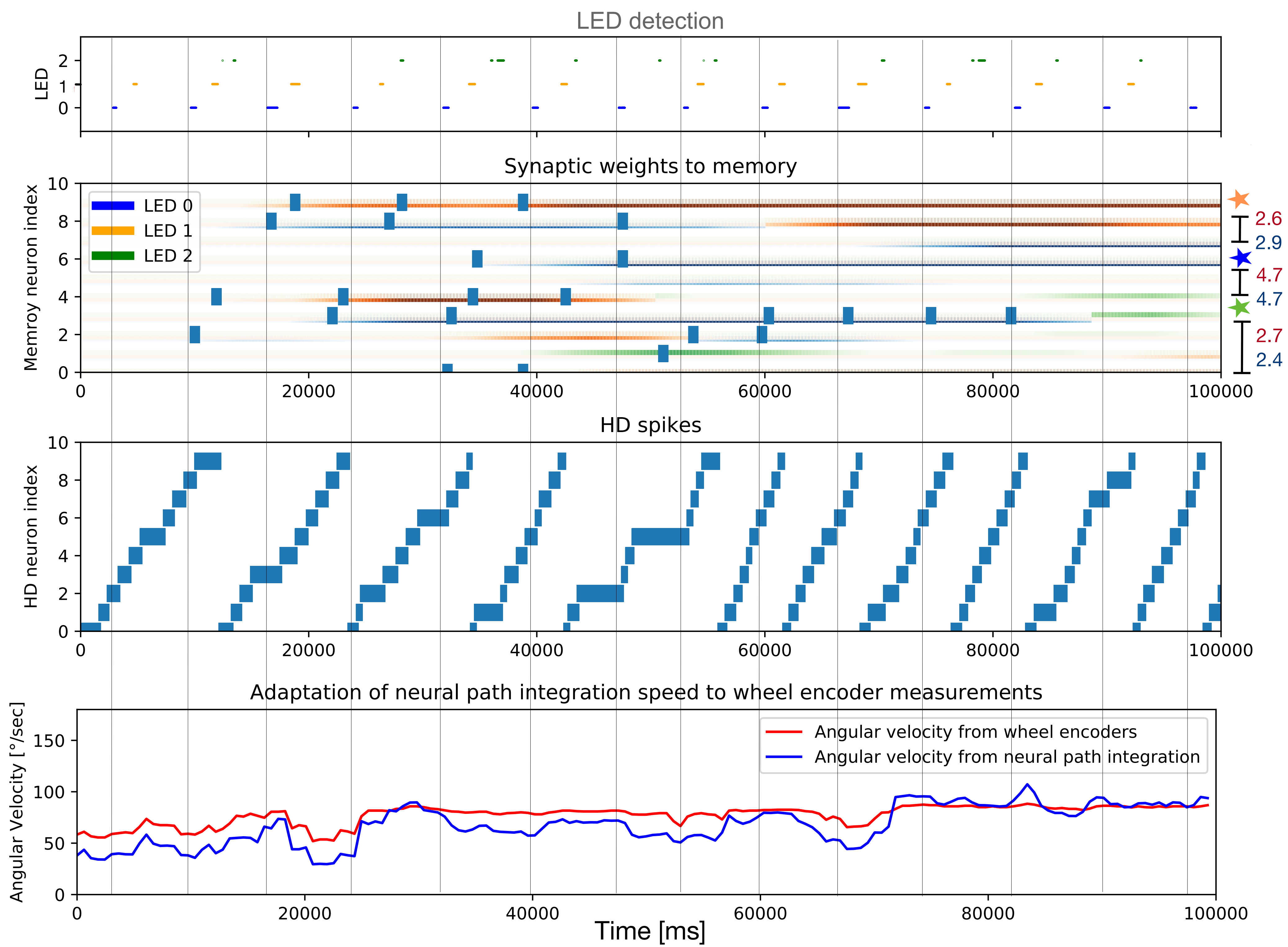






Kreiser et al, submitted to ICRA 2020

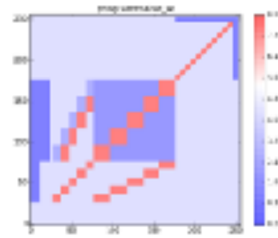
Neuromorphic SLAM: Results (+map formation)

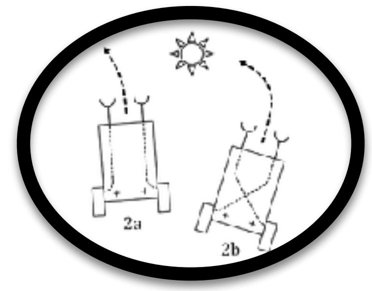


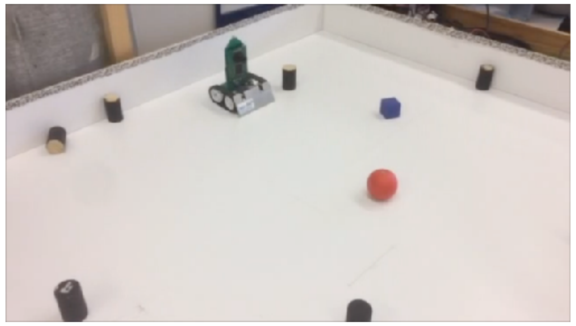
Overview of Neuromorphic **building blocks**

➡ Reactive loops

- attractors in a sensory-motor loop



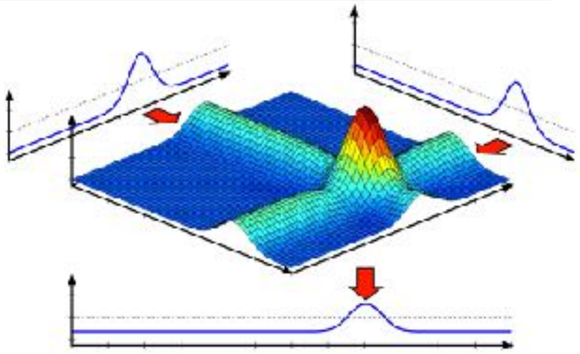




Milde et al 2017a,b; Kreiser et al 2018

➡ **Reference frame** transformations

- key for linking modalities

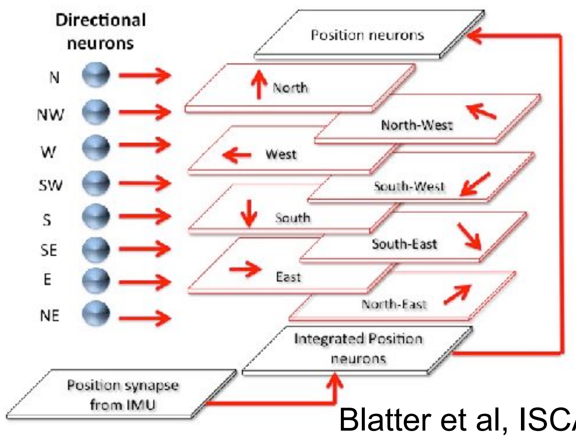


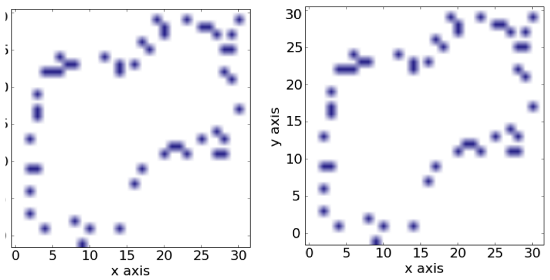
Blum et al 2017

➡ Pose estimation and map formation

- state estimation, building representations

Kreiser et al 2018, 2019a, b

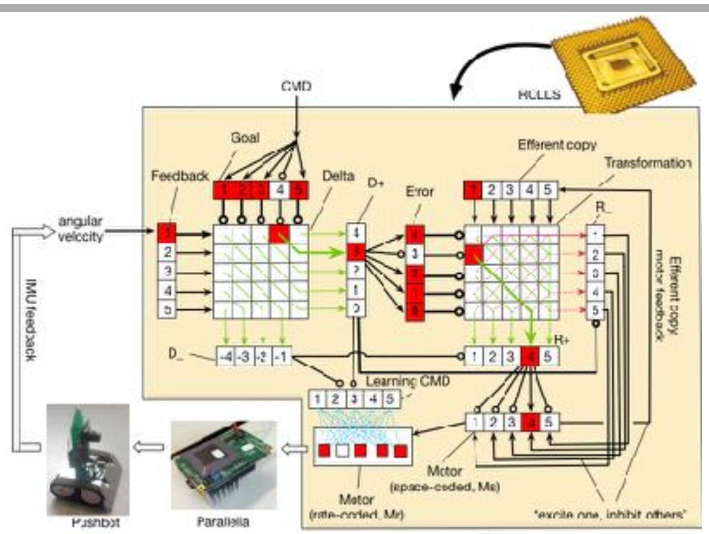


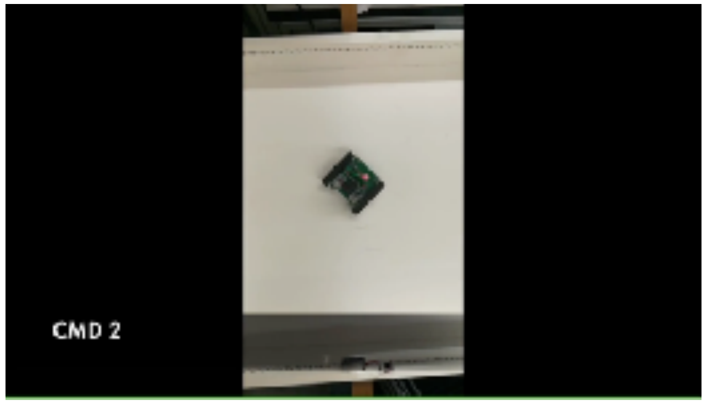


Blatter et al, ISCAS, under rev; Kreiser et al 2018a, b

➡ Adaptive motor control

- key element for adaptive behavior





Glatz et al, ICRA2019

Conclusion: We need to **redefine computing** to use neuromorphic hardware

`variable`

➡ neuronal population

- high-/low-dimensional, continuous or discrete (symbolic)
- adjustable resolution
- sensory, motor, abstract

To enable neuronally-inspired computing we need to work out its theory, framework, and tools

- can be adaptive

`input/output`

➡ interfaces to sensors and motors

`Operating System`

➡ a hierarchy of neuronal structures for particular task

Thank you!

- Marie Curie IF
- FET PROACT

- Ambizione
- Project coordination

- Forschungskredit
- GRC Grant

- Junior Group fellowship

MSc, BSc theses

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Tobias Storck
Christian Bell
Claudia Rudolph
Jianlin Lu
Ammar Bitar
Jonathan Müller
Kay Müller
Sebastian Glatz
Valery Metry
Alpha Renner
David Niederberger
Raphaela Kreiser

Semester theses

Alexander Dietmüller
Mario Blatter
Frédéric Debraine
Lukas Blässig
Lennard de Graf
Michel Frising
Zahra Farsijani
Michael Purcell
Viviane Yang
Davide Plozza
Damiano Steger
Nuria

Héctor Vazquez
Sebastian Glatz
Herman Blum
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Lin Jin
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Panin Pienroj
Paul Joseph
Nuria Armengol
Jozef Bucko
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