Technische Hochschule Nürnberg

Neural Control Systems

From mechanistics to neuromorphics

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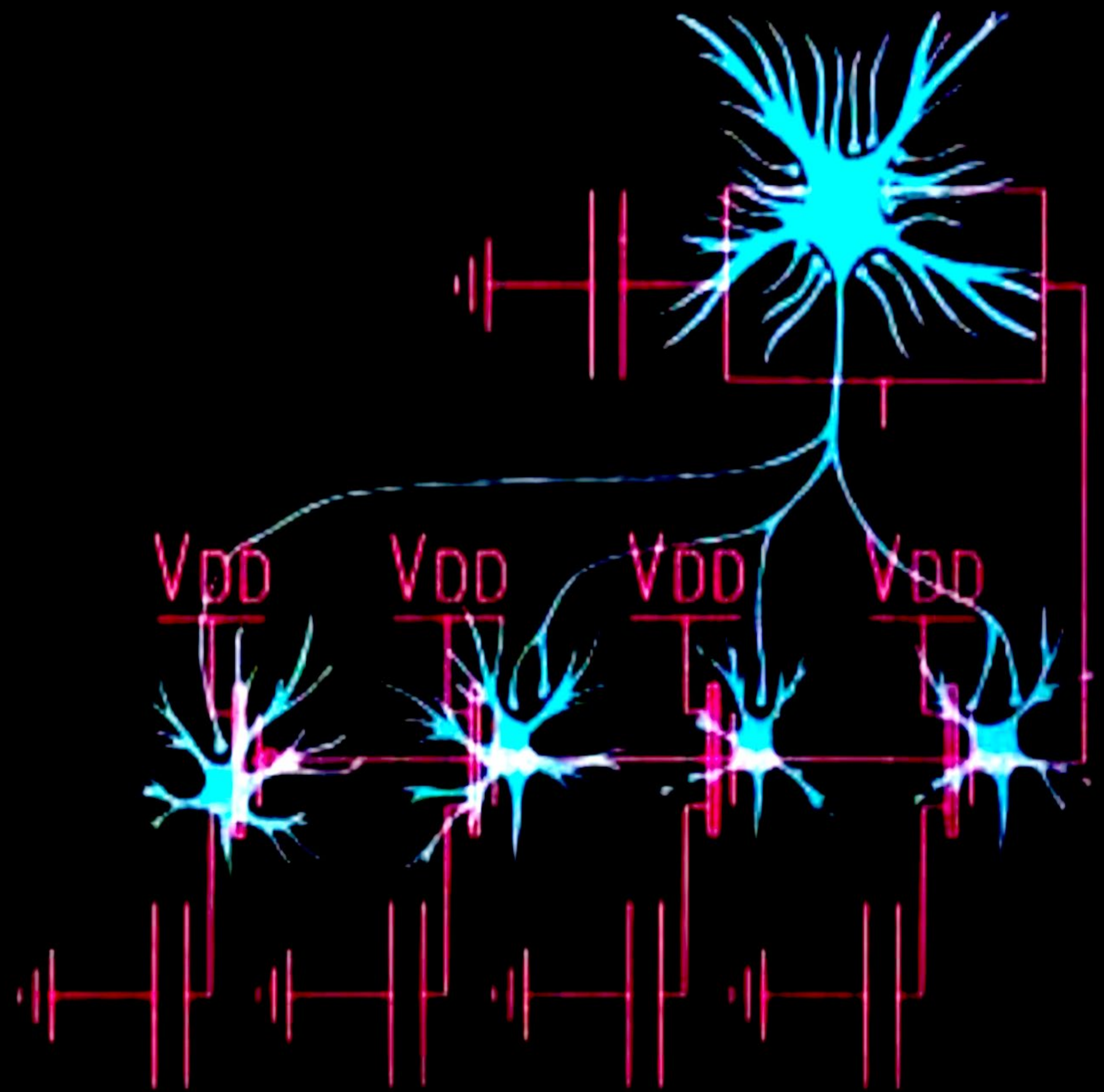
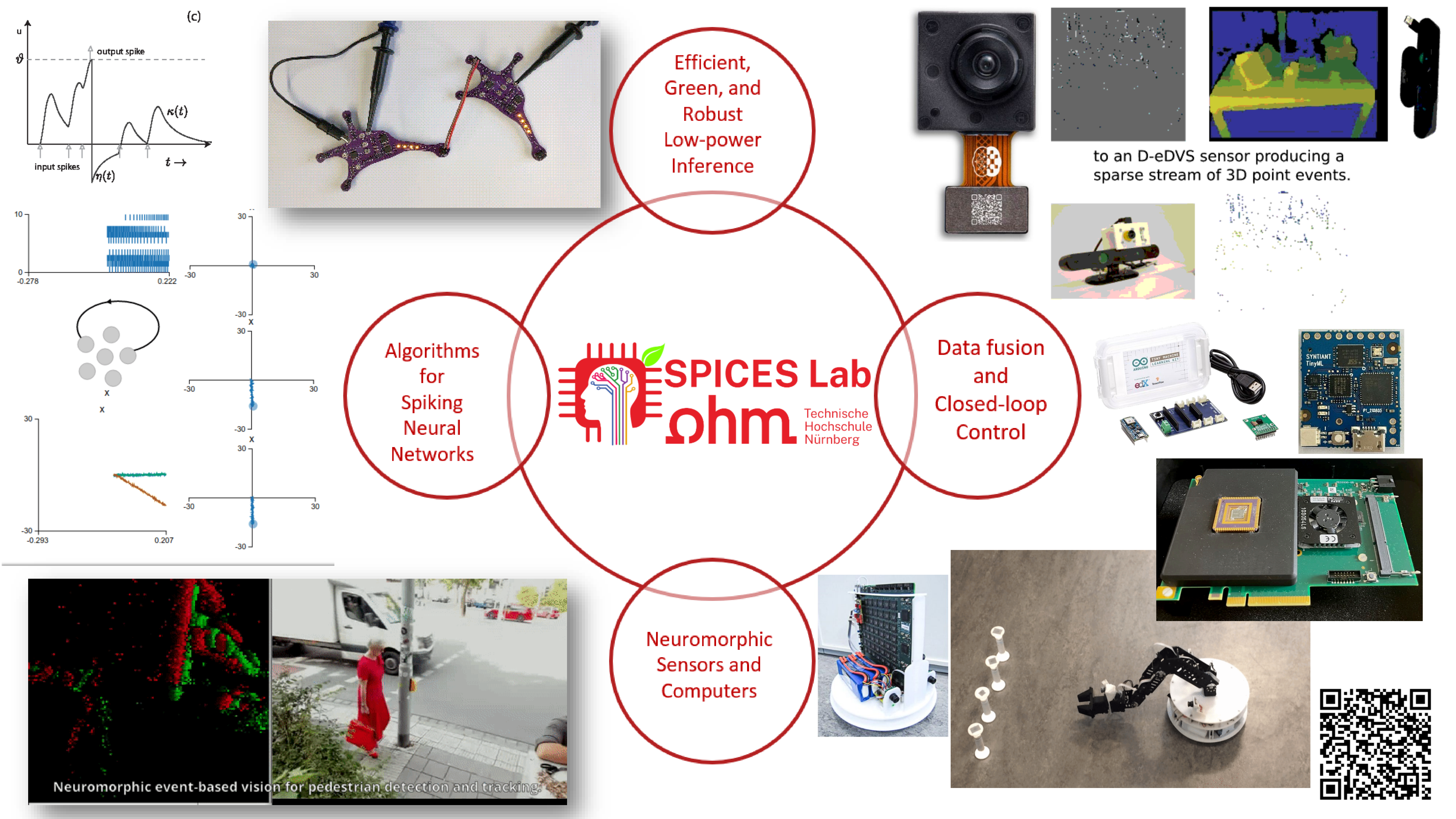
Technische Hochschule Nürnberg

Prof. Dr.-Ing. Cristian Axenie SMIEEE

Carver, Mead. *Analog VLSI and neural systems*. Addison-Wesley, 1989.




(c)
u
output spike
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Efficient, Green, and Robust Low-power Inference
to an D-eDVS sensor producing a sparse stream of 3D point events.
Algorithms for Spiking Neural Networks
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Data fusion and Closed-loop Control
Neuromorphic Sensors and Computers
Neuromorphic event-based vision for pedestrian detection and tracking.

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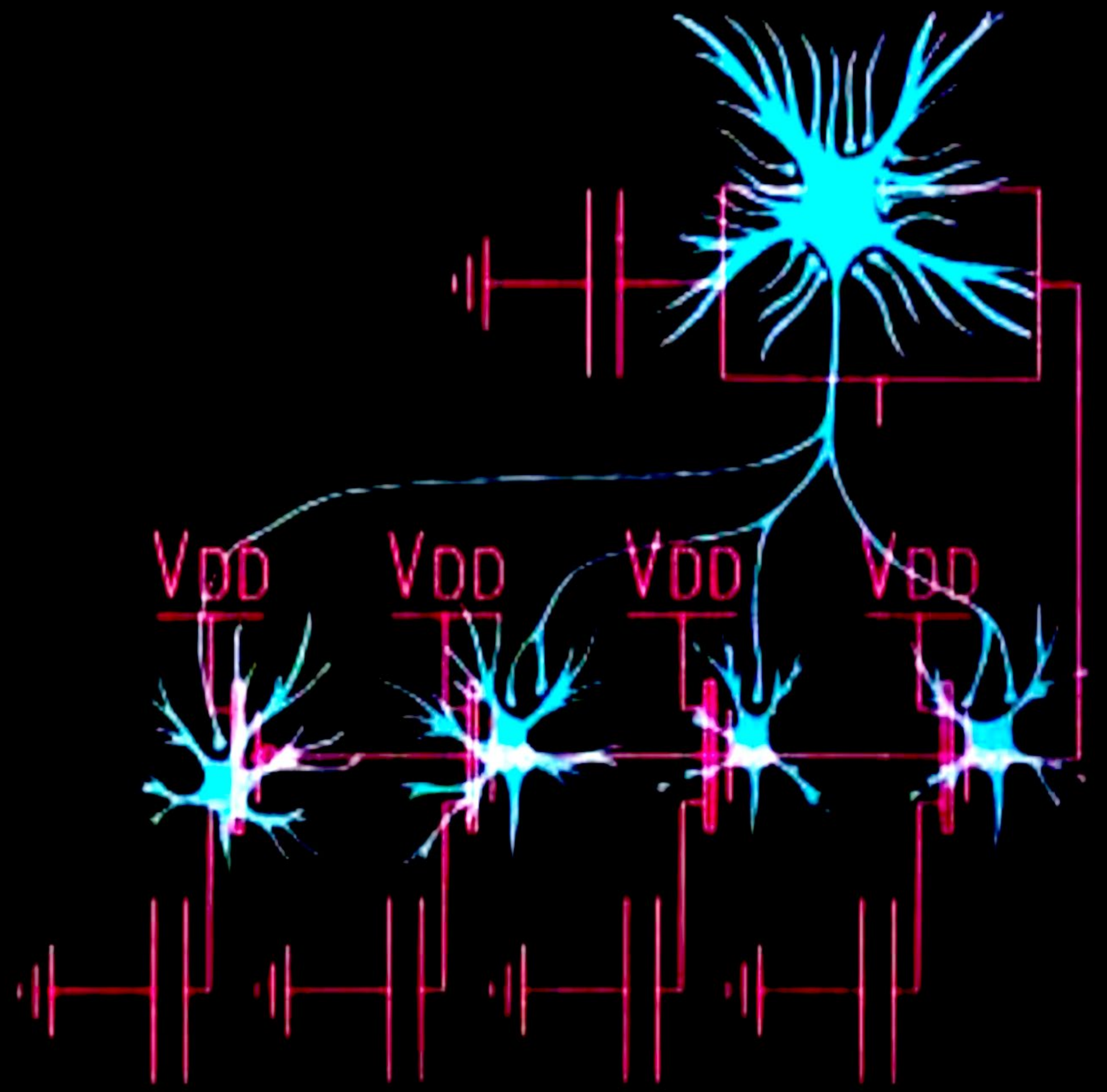
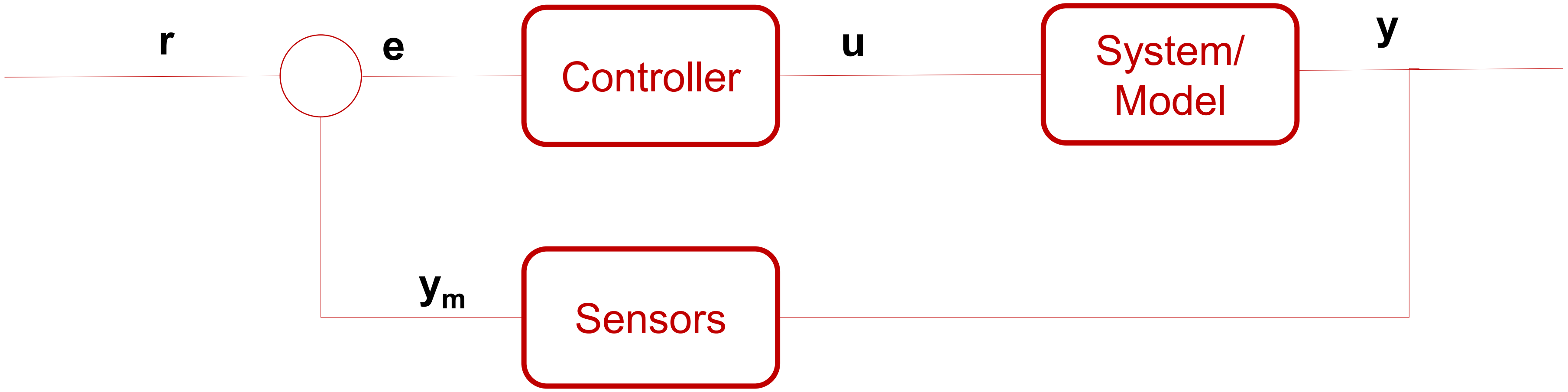
Neural Control Systems

Basics

Carver, Mead. *Analog VLSI and neural systems*. Addison-Wesley, 1989.

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Controller
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Sensors

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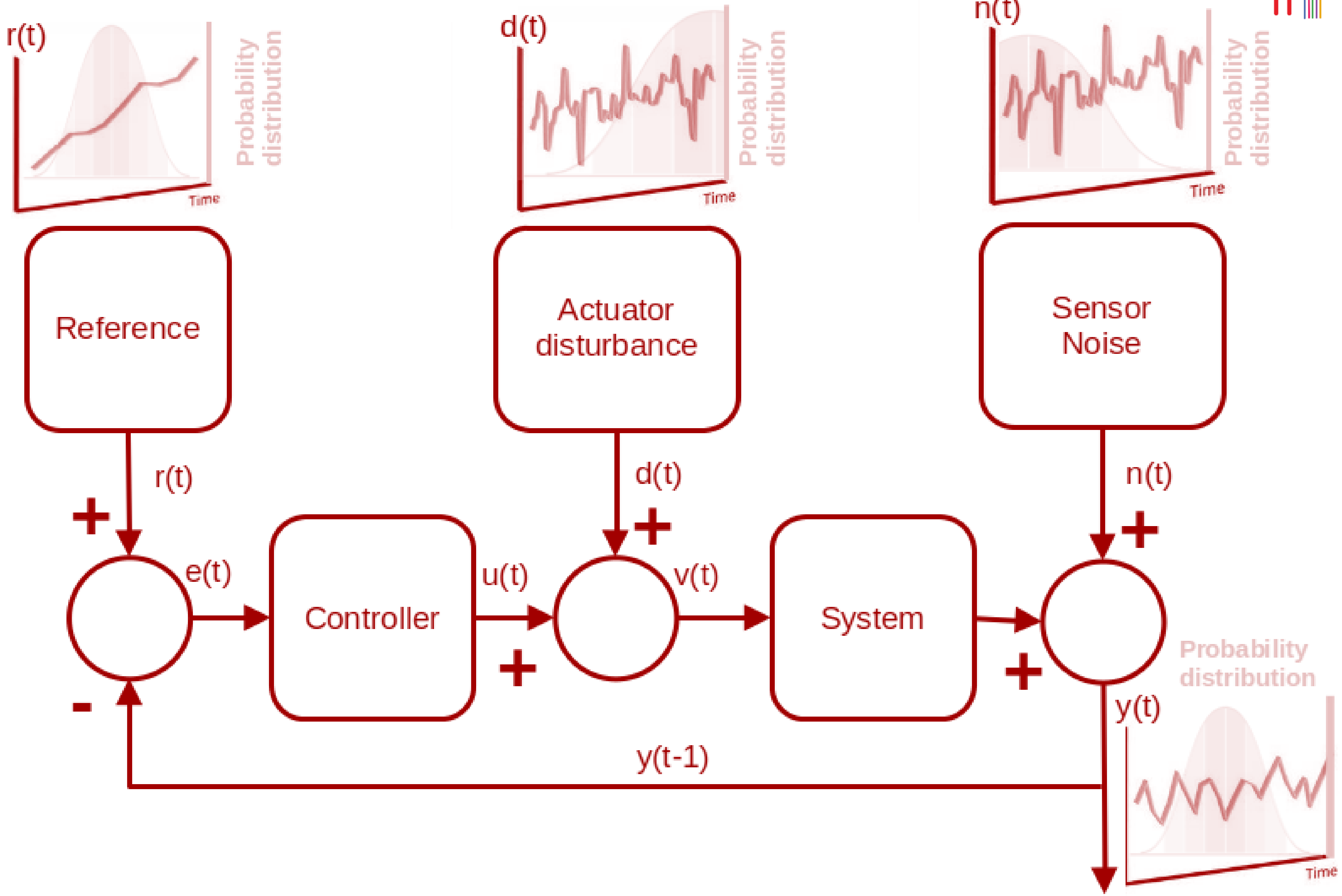

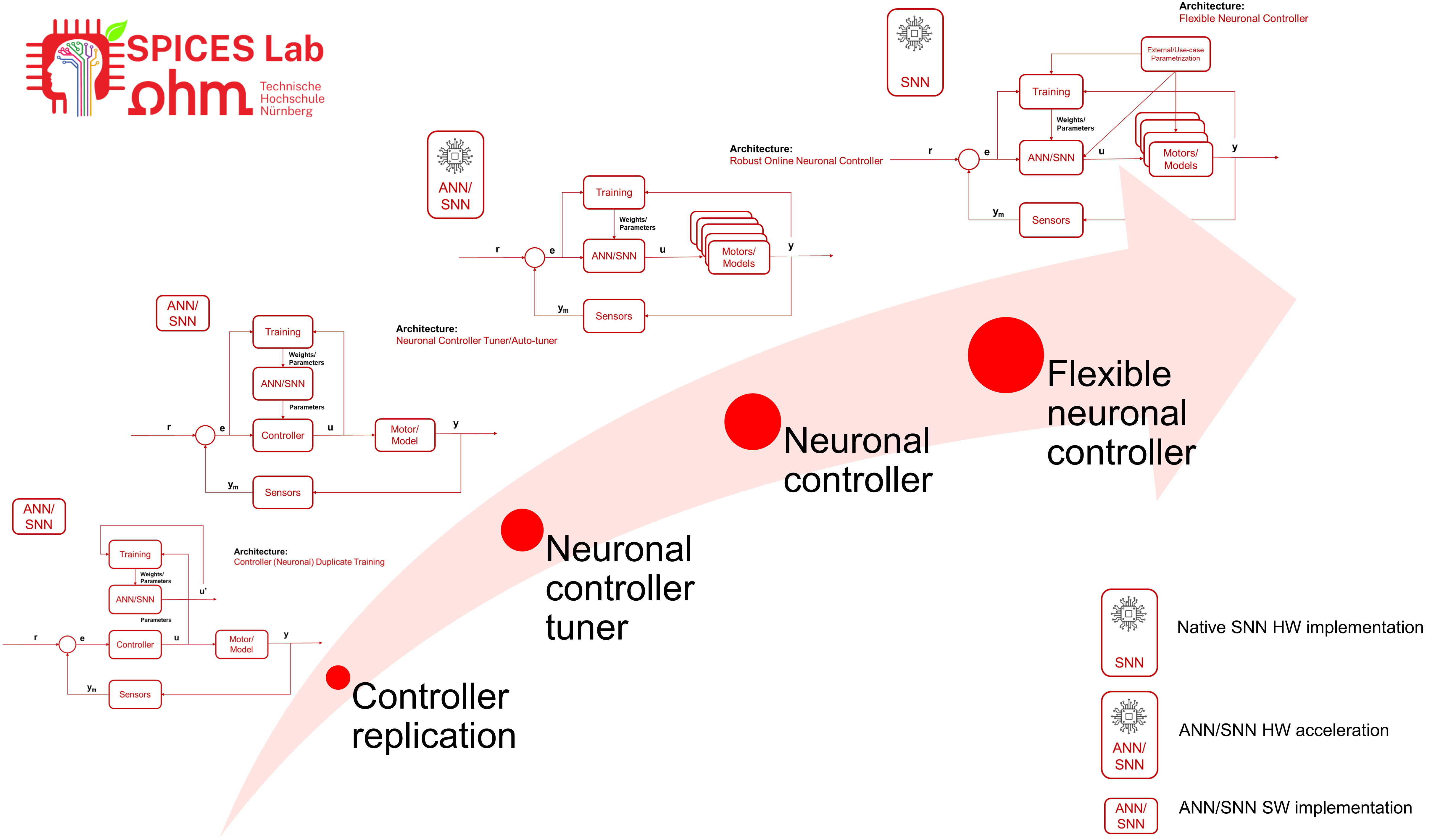
SPICES Lab
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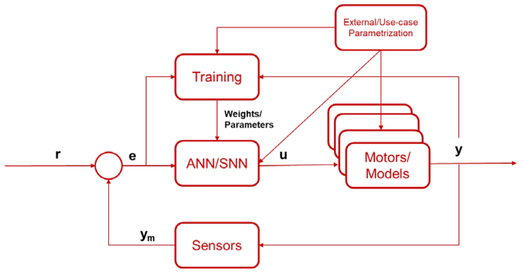
SNN
Architecture:
Flexible Neuronal Controller
External/Use-case Parametrization
Training
Weights/ Parameters
ANN/SNN
Motors/ Models
Sensors
r
e
u
y
y_m
ANN/ SNN
Architecture:
Robust Online Neuronal Controller
Training
Weights/ Parameters
ANN/SNN
Motors/ Models
Sensors
ANN/ SNN
Architecture:
Neuronal Controller Tuner/Auto-tuner
Training
Weights/ Parameters
ANN/SNN
Parameters
Controller
Motor/ Model
Sensors
ANN/ SNN
Architecture:
Controller (Neuronal) Duplicate Training
Training
Weights/ Parameters
ANN/SNN
u'
Parameters
Controller
Motor/ Model
Sensors
Controller replication
Neuronal controller tuner
Neuronal controller
Flexible neuronal controller
SNN
Native SNN HW implementation
ANN/ SNN
ANN/SNN HW acceleration
ANN/ SNN
ANN/SNN SW implementation

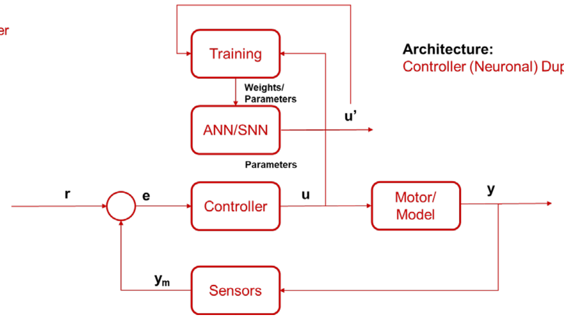
Neuronal Controller Specification/Requirements

- Controller optimization
- Closed-loop optimization
- Flexible controller and loop optimization

Architecture:
Flexible Neuronal Controller



Architecture:
Controller (Neuronal) Duplicate Training



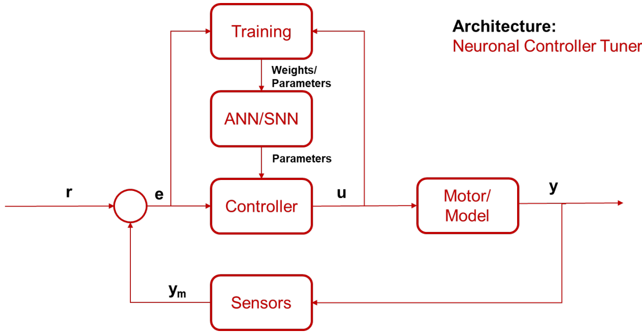
Neuronal Controller Implementation

SNN

ANN/ SNN

ANN/ SNN

Architecture:
Neuronal Controller Tuner/Auto-tuner



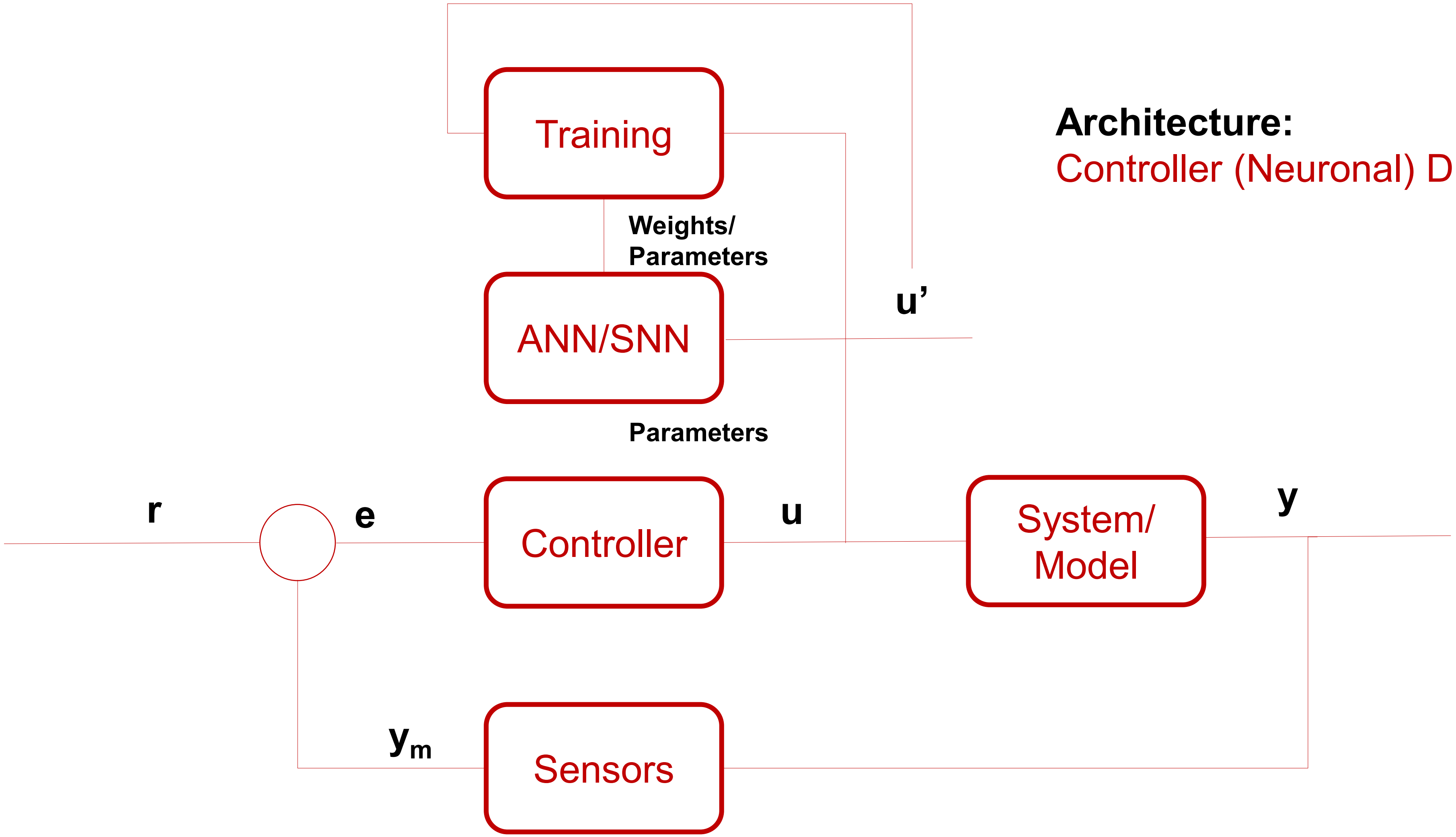
Neuronal Controller Use-cases

SNN — Native SNN HW implementation

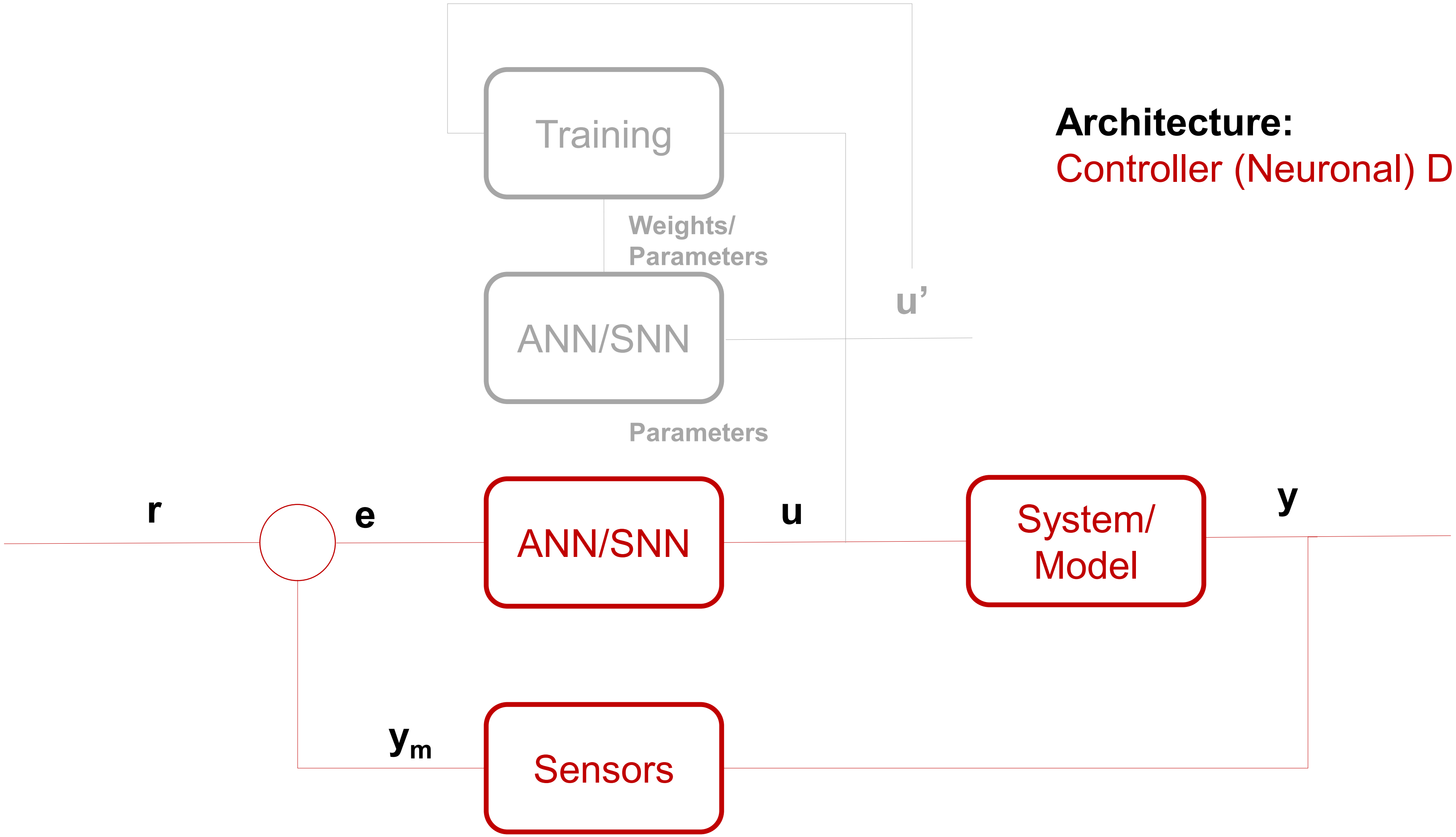
ANN/ SNN — ANN/SNN HW acceleration

ANN/ SNN — ANN/SNN SW implementation

Architecture:
Controller (Neuronal) Duplicate Training



Architecture:
Controller (Neuronal) Duplicate Training



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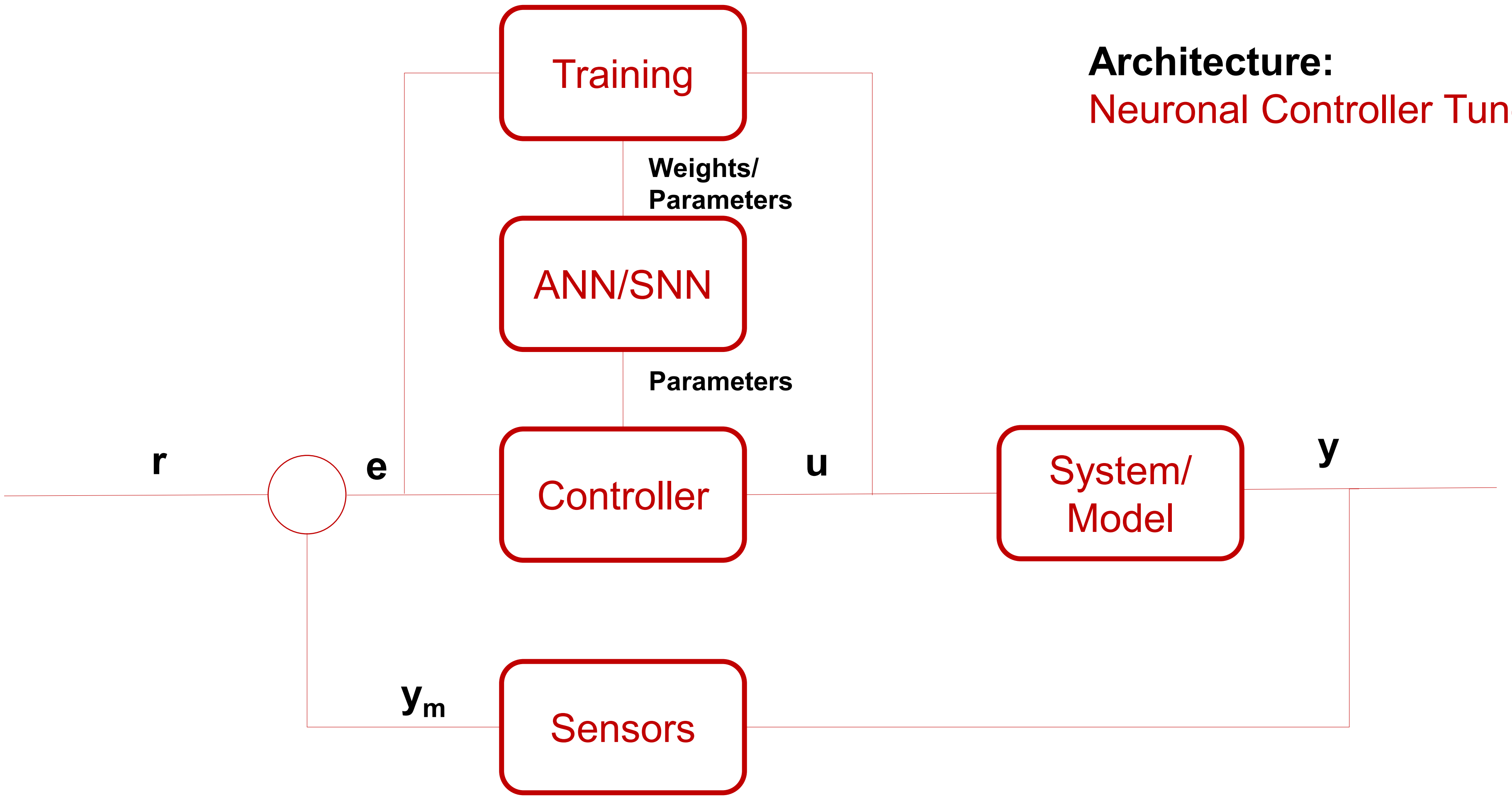
Architecture:
Neuronal Controller Tuner/Auto-tuner



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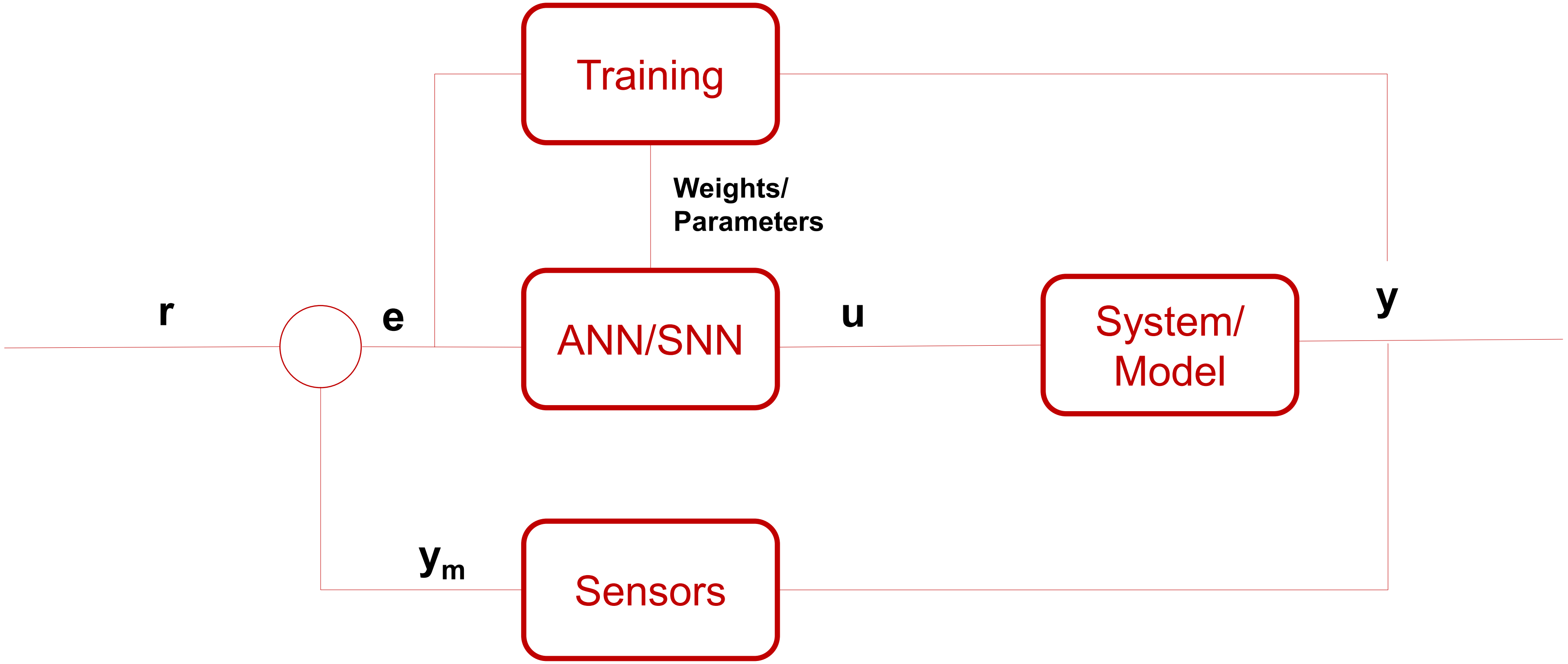
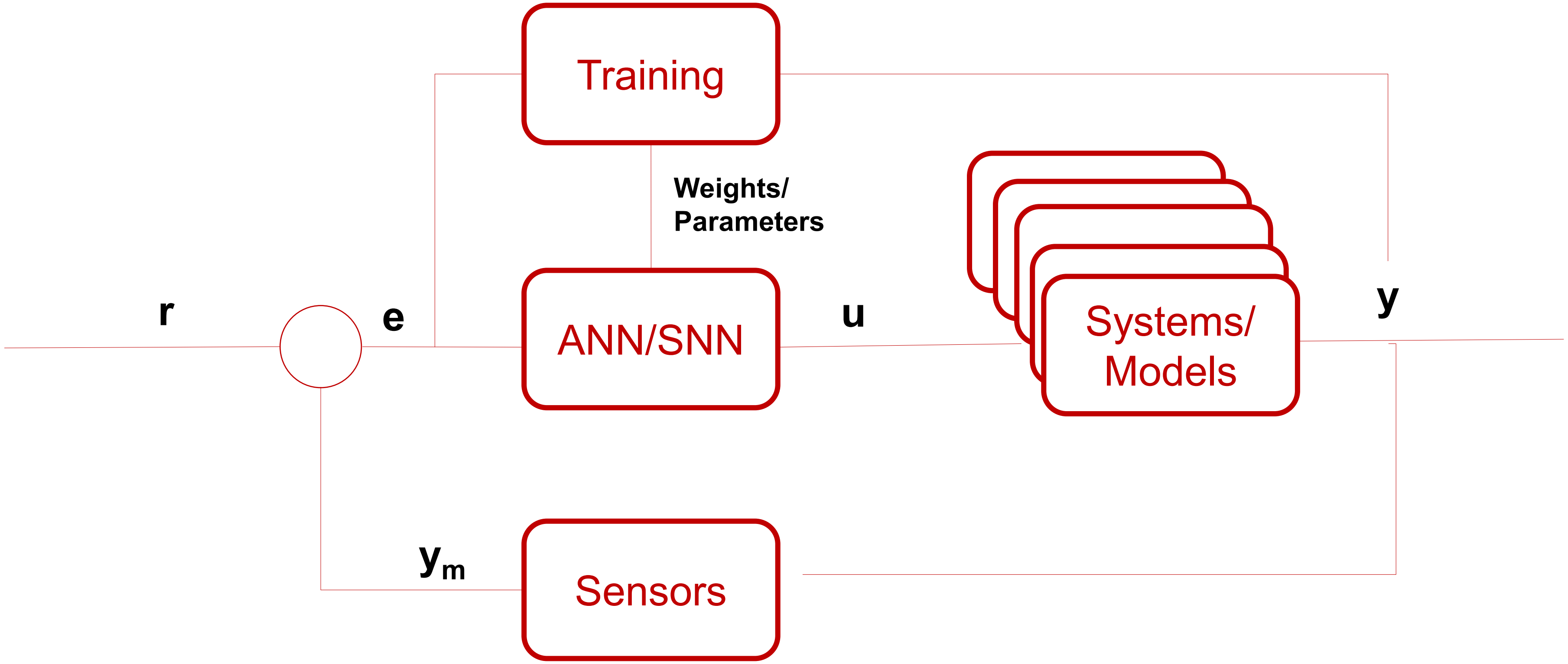
Architecture:
Online Neuronal Controller



Architecture:
Robust Online Neuronal Controller



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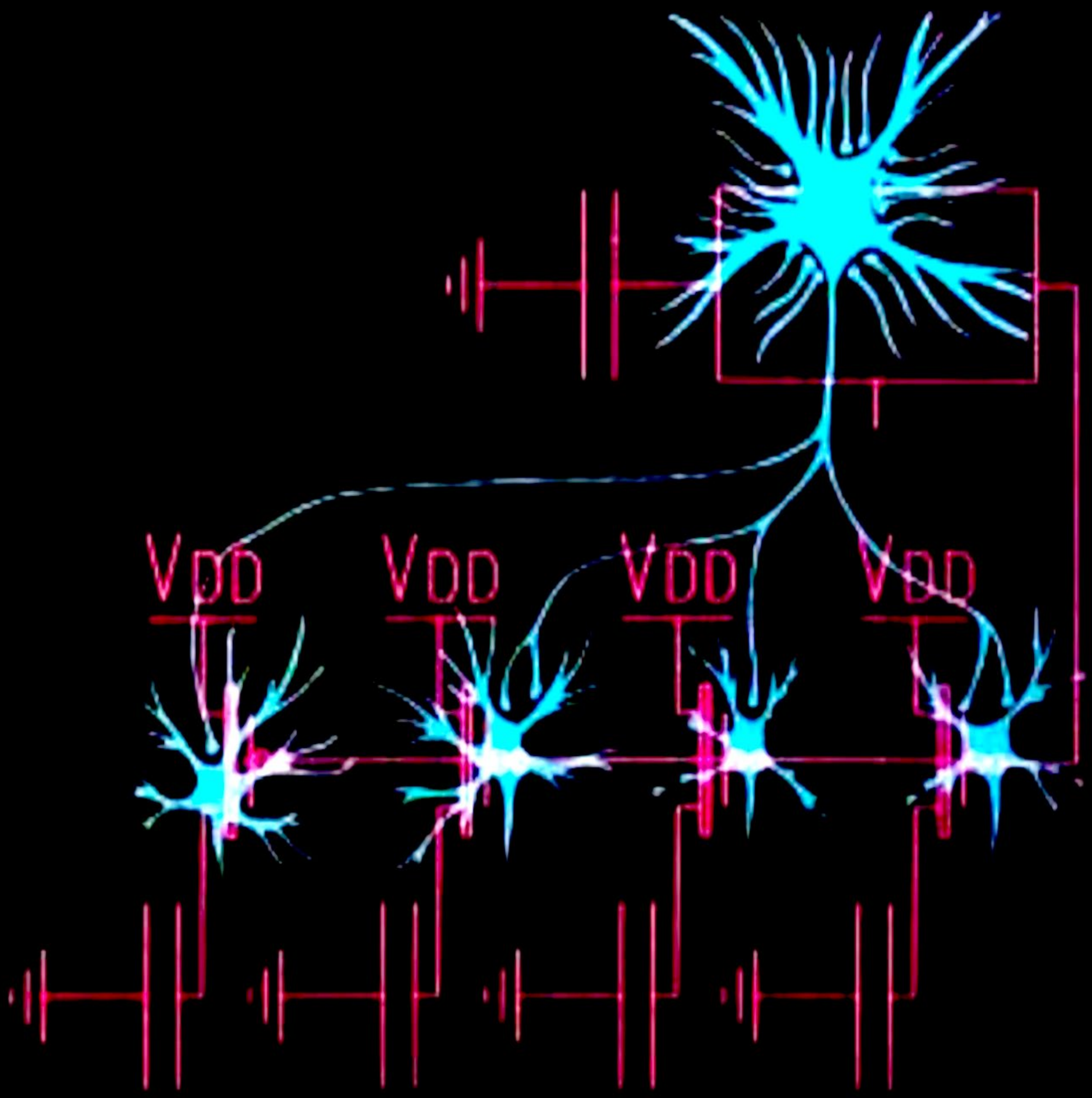
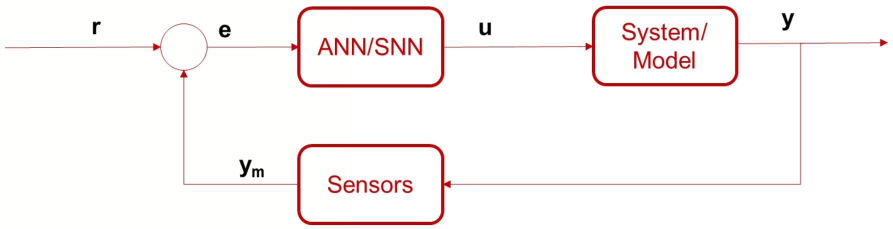
Neural Control Systems

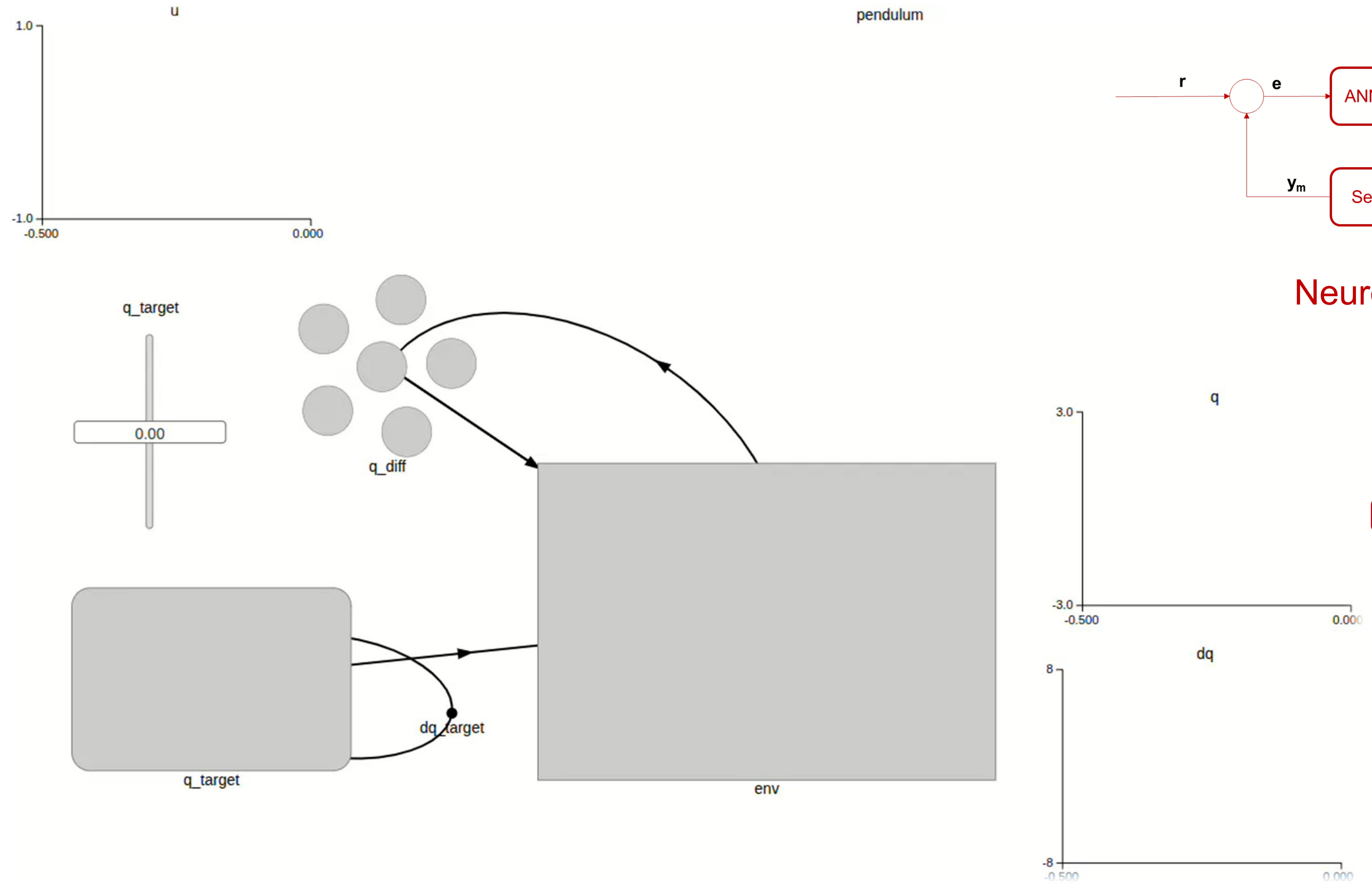
Canonical testbench

Carver, Mead. *Analog VLSI and neural systems*. Addison-Wesley, 1989.



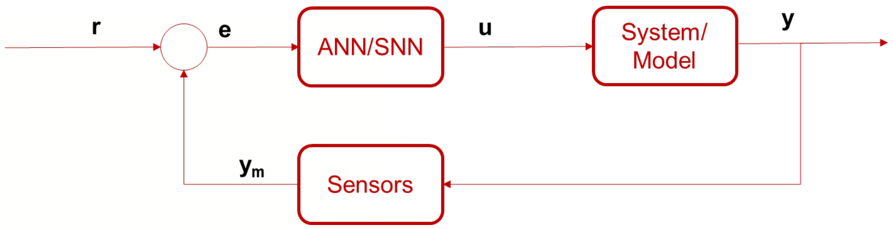


Neuronal P Controller

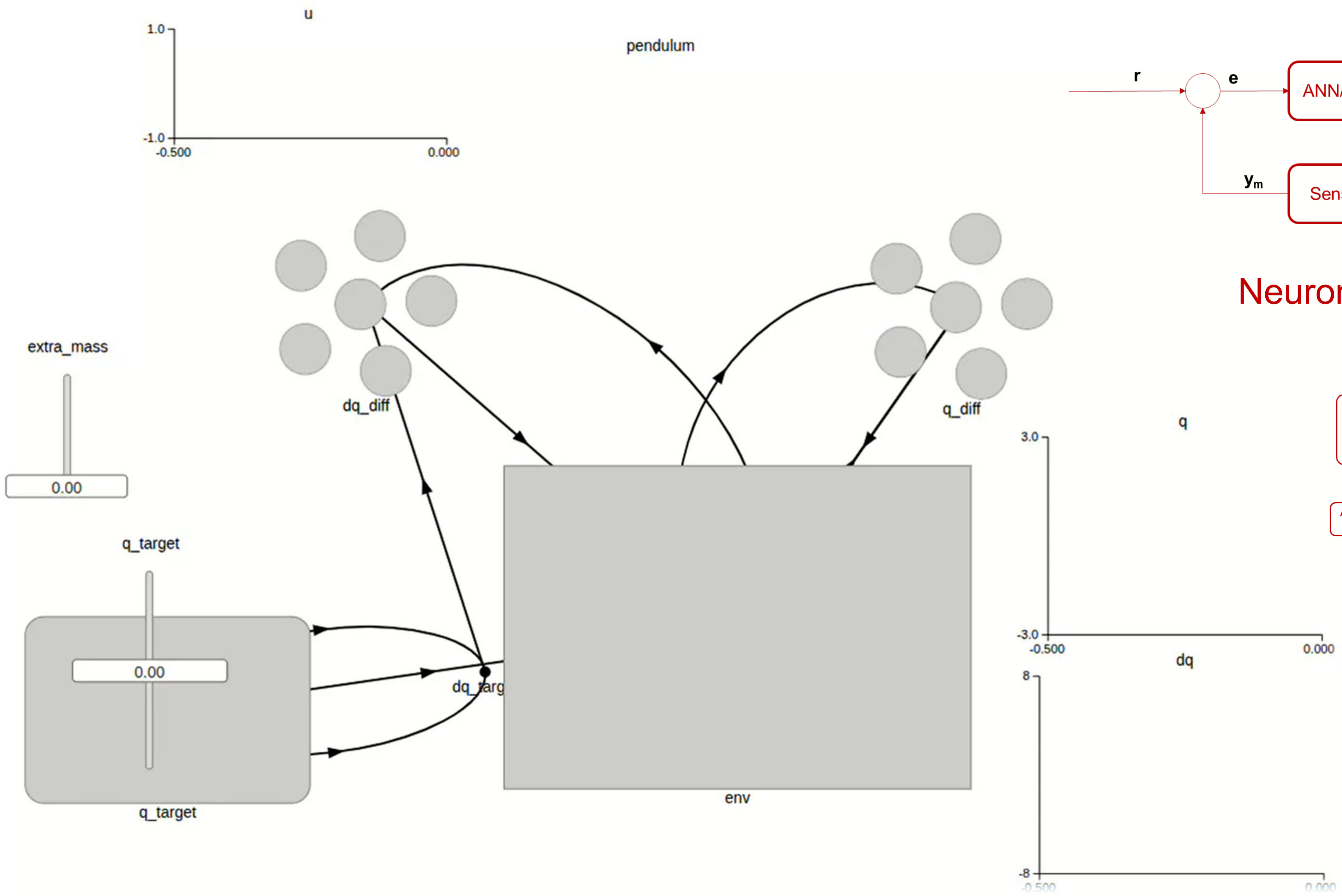


SNN — Native SNN HW implementation

ANN/SNN — ANN/SNN SW implementation



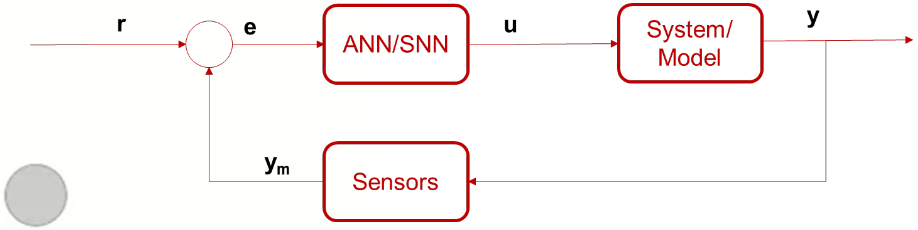
Neuronal PD Controller



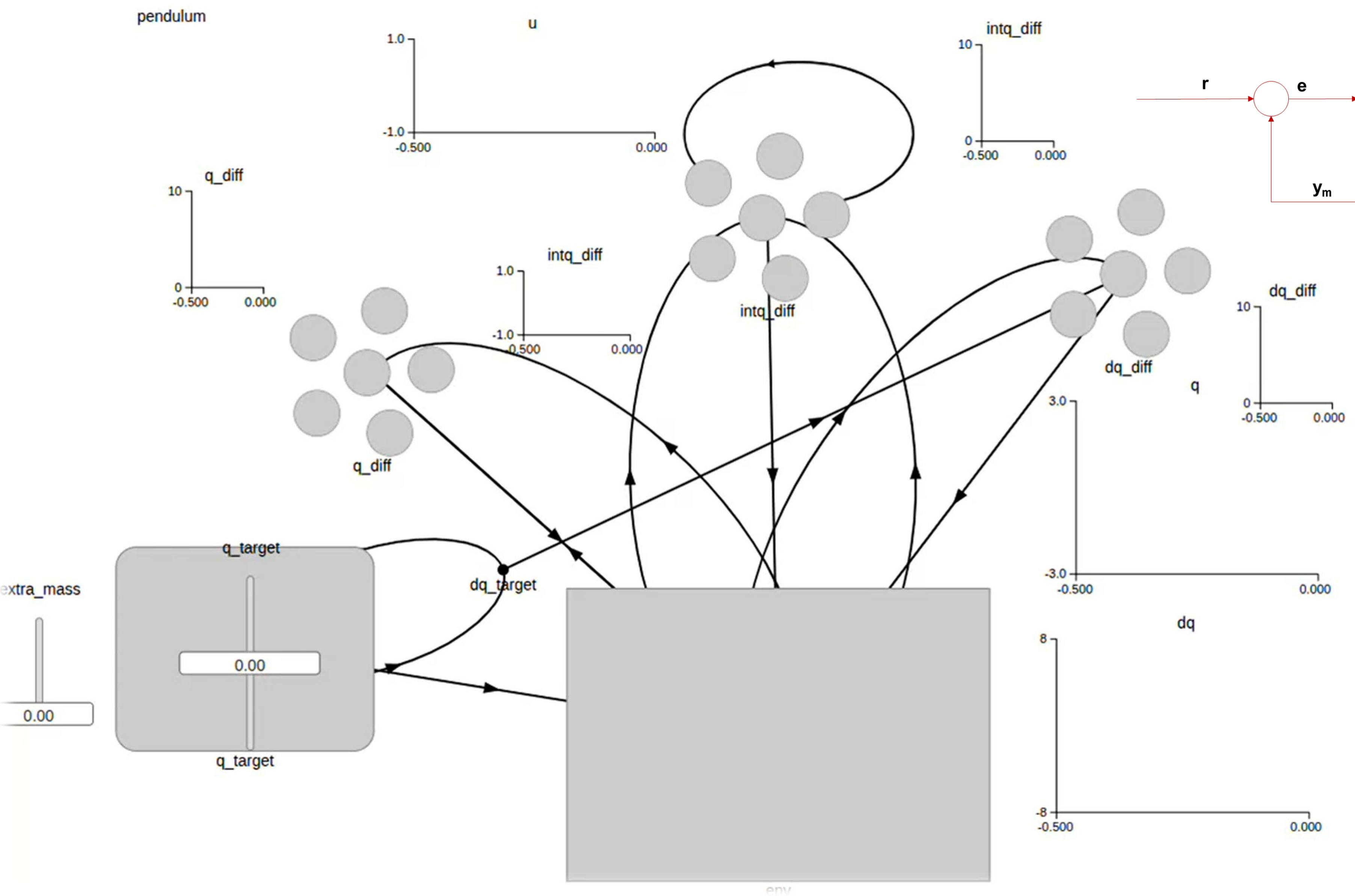
SNN — Native SNN HW implementation

ANN/SNN — ANN/SNN SW implementation

Nengo



Neuronal PID Controller



SNN Native SNN HW implementation

ANN/ SNN ANN/SNN SW implementation

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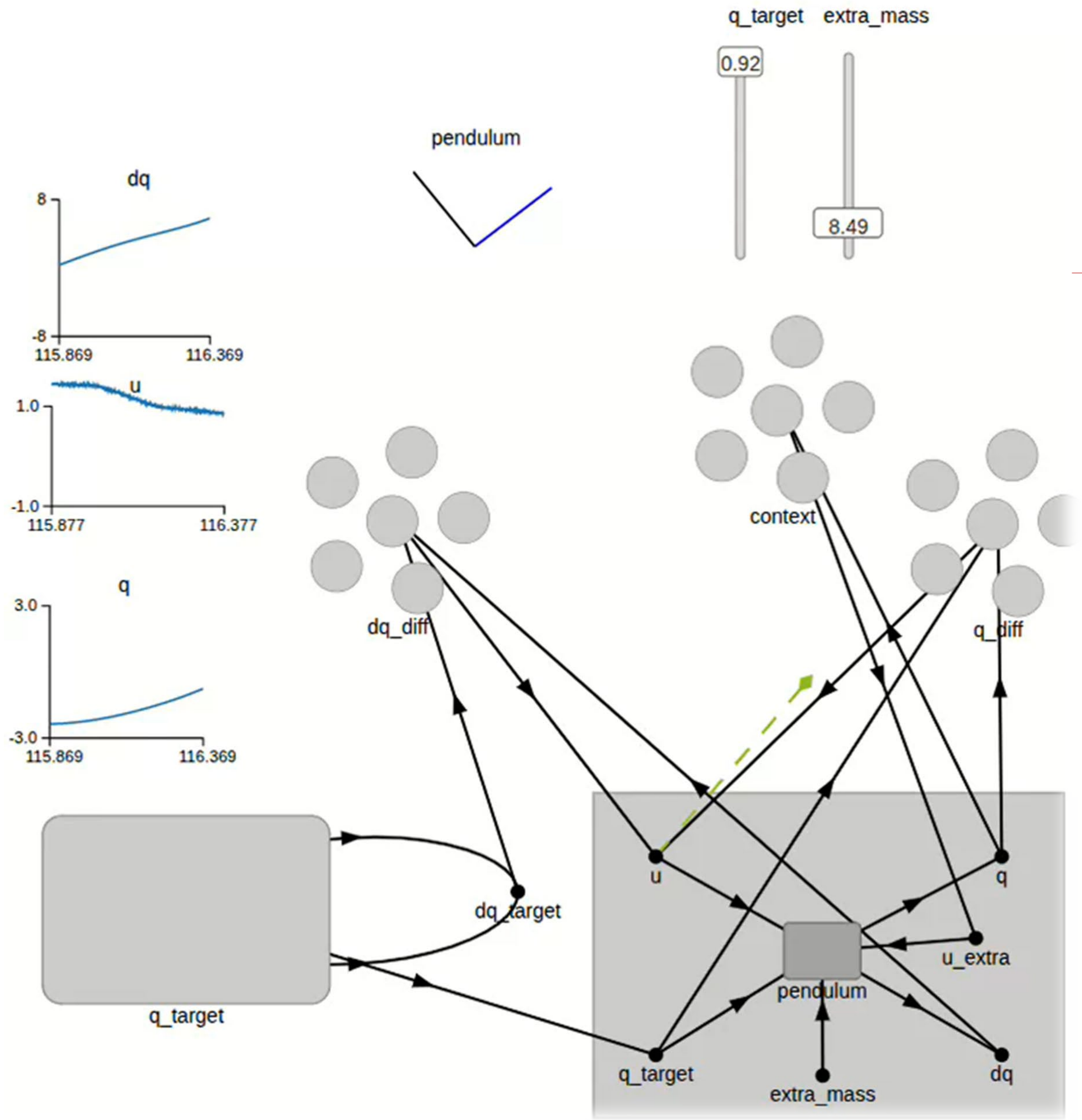
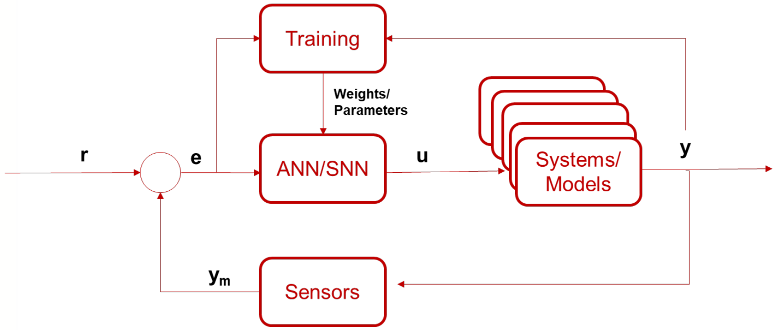


Architecture:
Robust Online Neuronal Controller



Learning
PD Controller

SNN Native SNN HW implementation

ANN/SNN ANN/SNN SW implementation

Nengo

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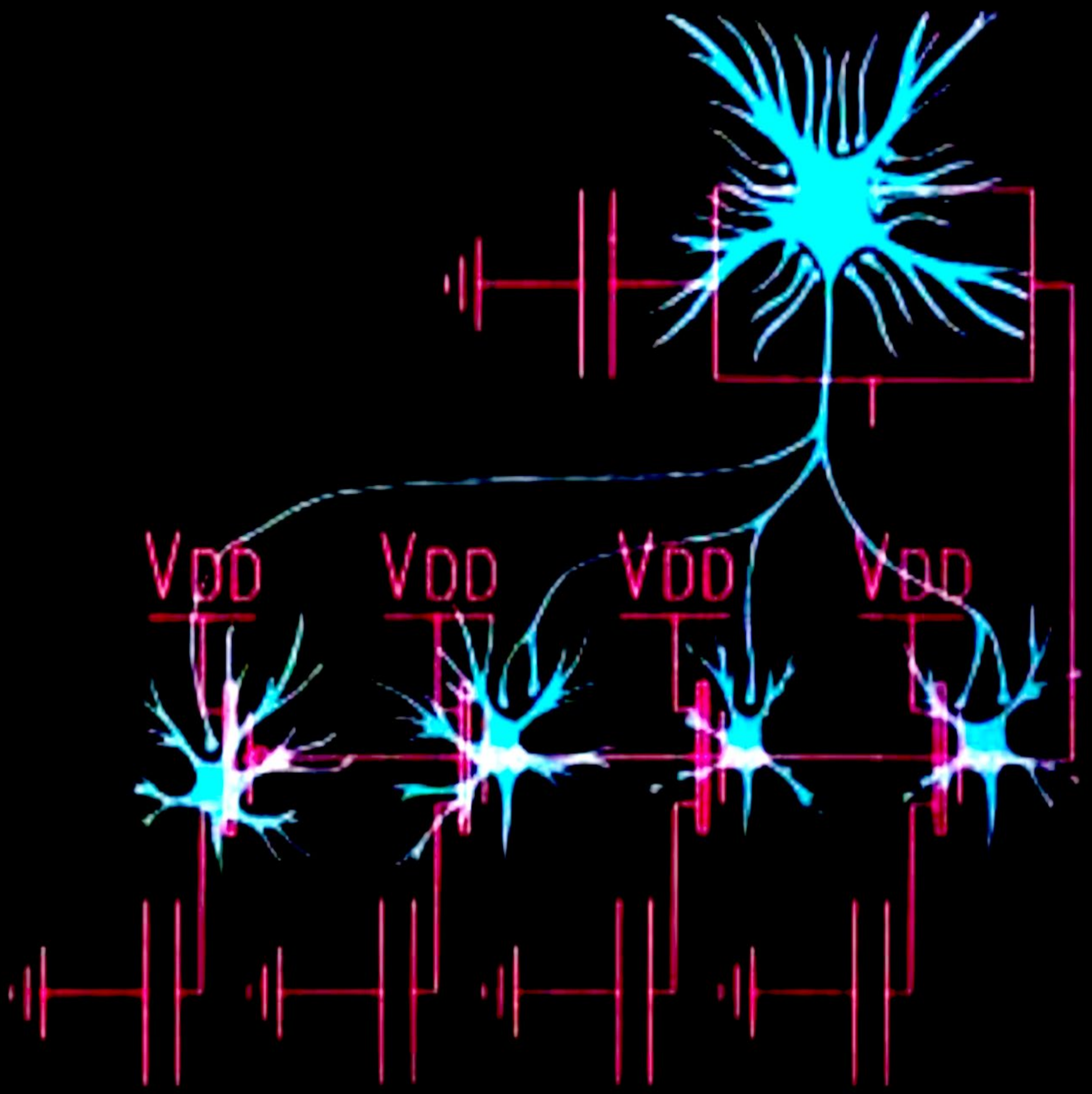
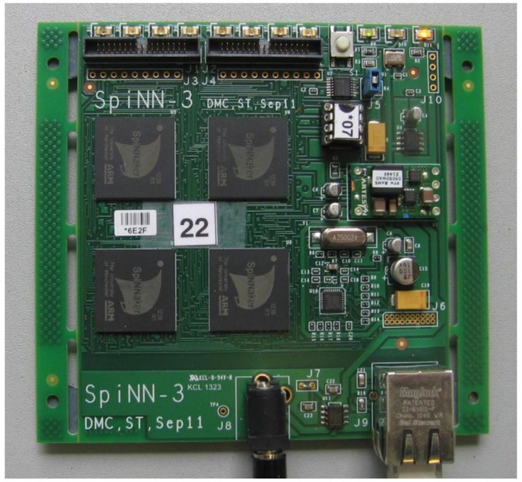
Neural Control Systems

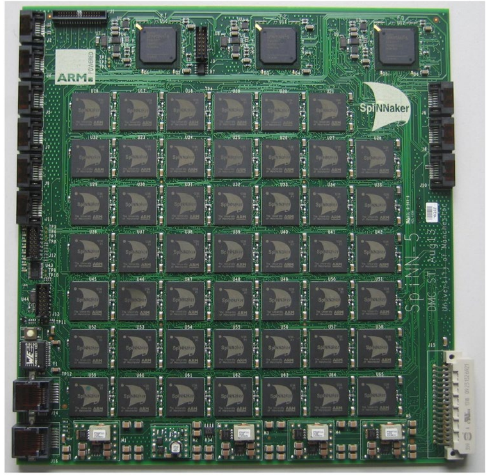
Robotics

Carver, Mead. *Analog VLSI and neural systems*. Addison-Wesley, 1989.

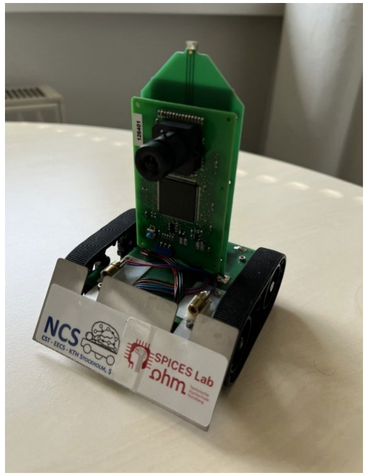


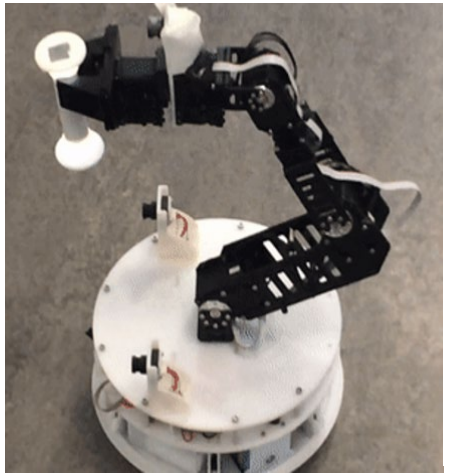
Neuromorphic HW

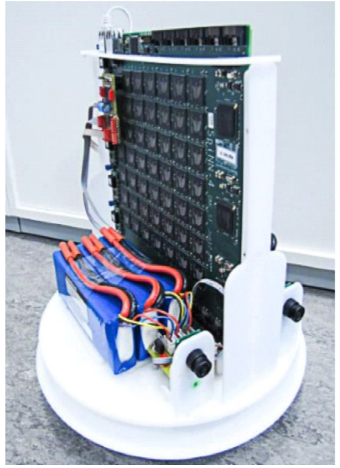


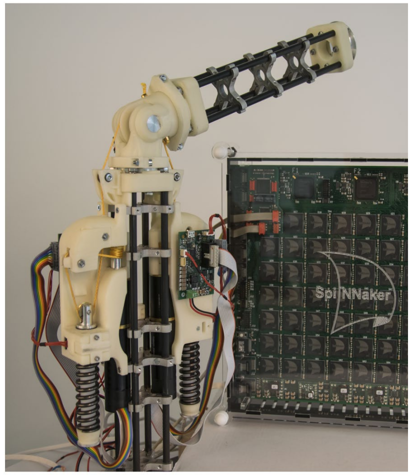


Robotic platforms



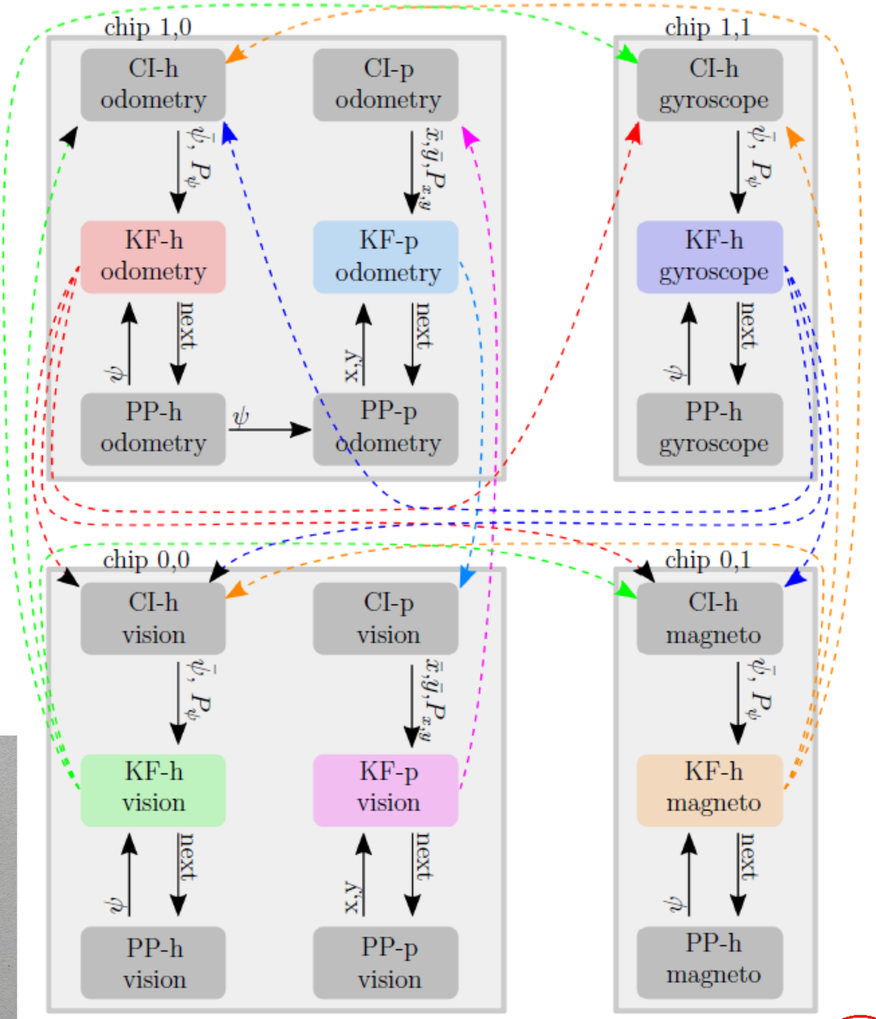




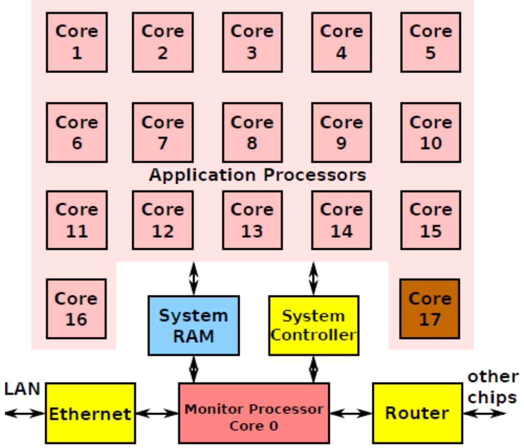


Native SNN HW implementation

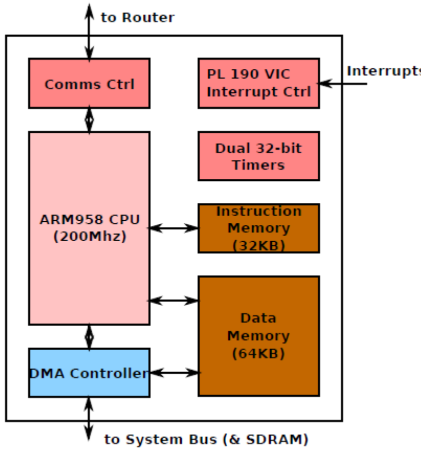
Sensory information:
G – integrated gyroscope with 3 components (G_x, G_y, G_z)
A – net acceleration with 3 components (A_x, A_y, A_z)
M – magnetic field intensity with 3 components (M_x, M_y, M_z)

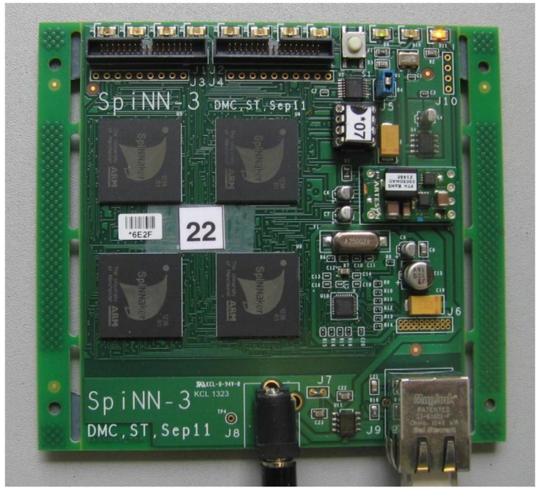


chip

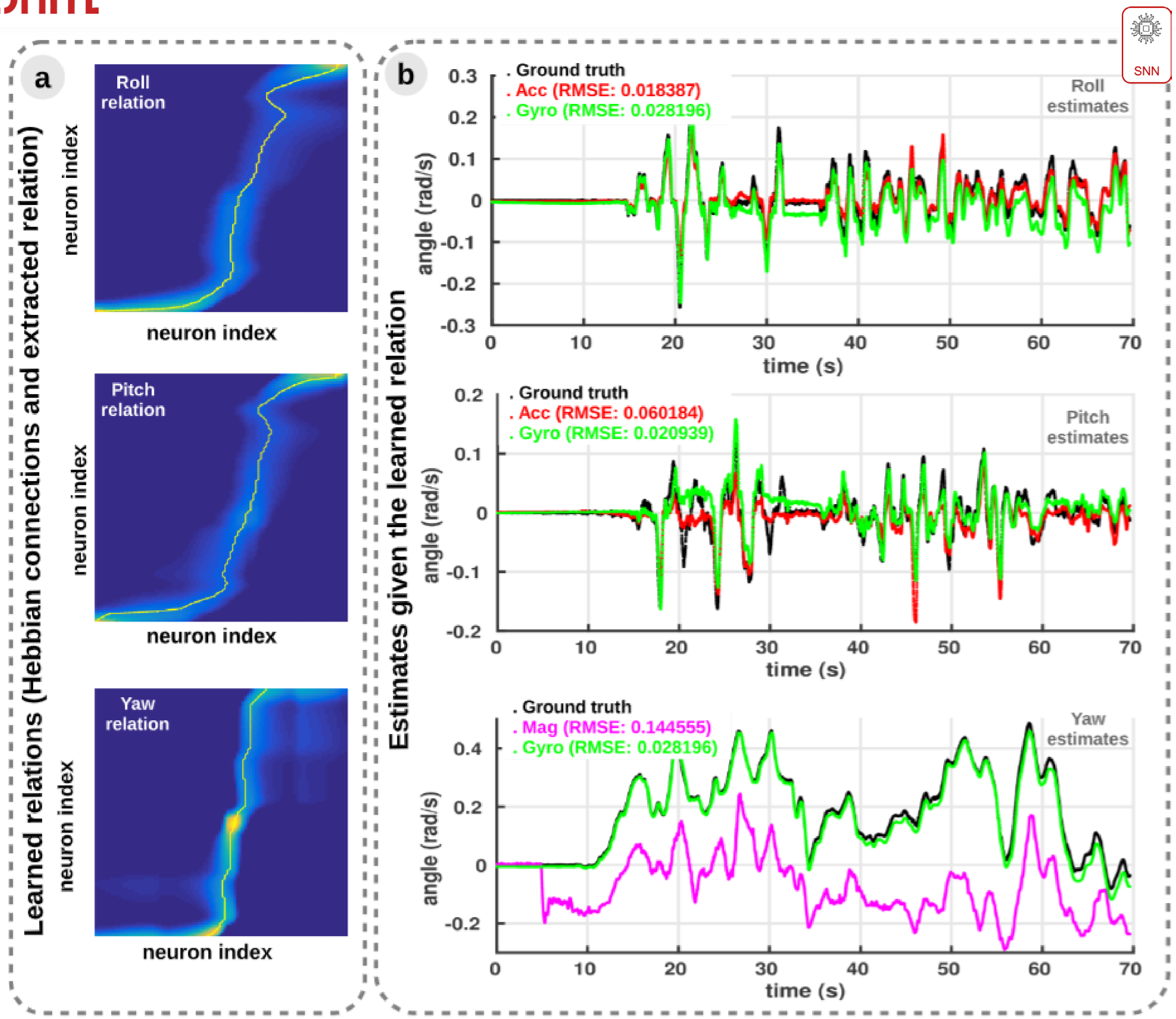


core





Covariance Intersection heading/position:
Kalman filter heading/position:
Preprocessor heading/position:
Communication via System-BUS
Communication via Multicast packages



Native SNN HW implementation

Sensory information:

G – integrated gyroscope
with 3 components (G_x, G_y, G_z)

A – net acceleration
with 3 components (A_x, A_y, A_z)

M – magnetic field intensity
with 3 components (M_x, M_y, M_z)

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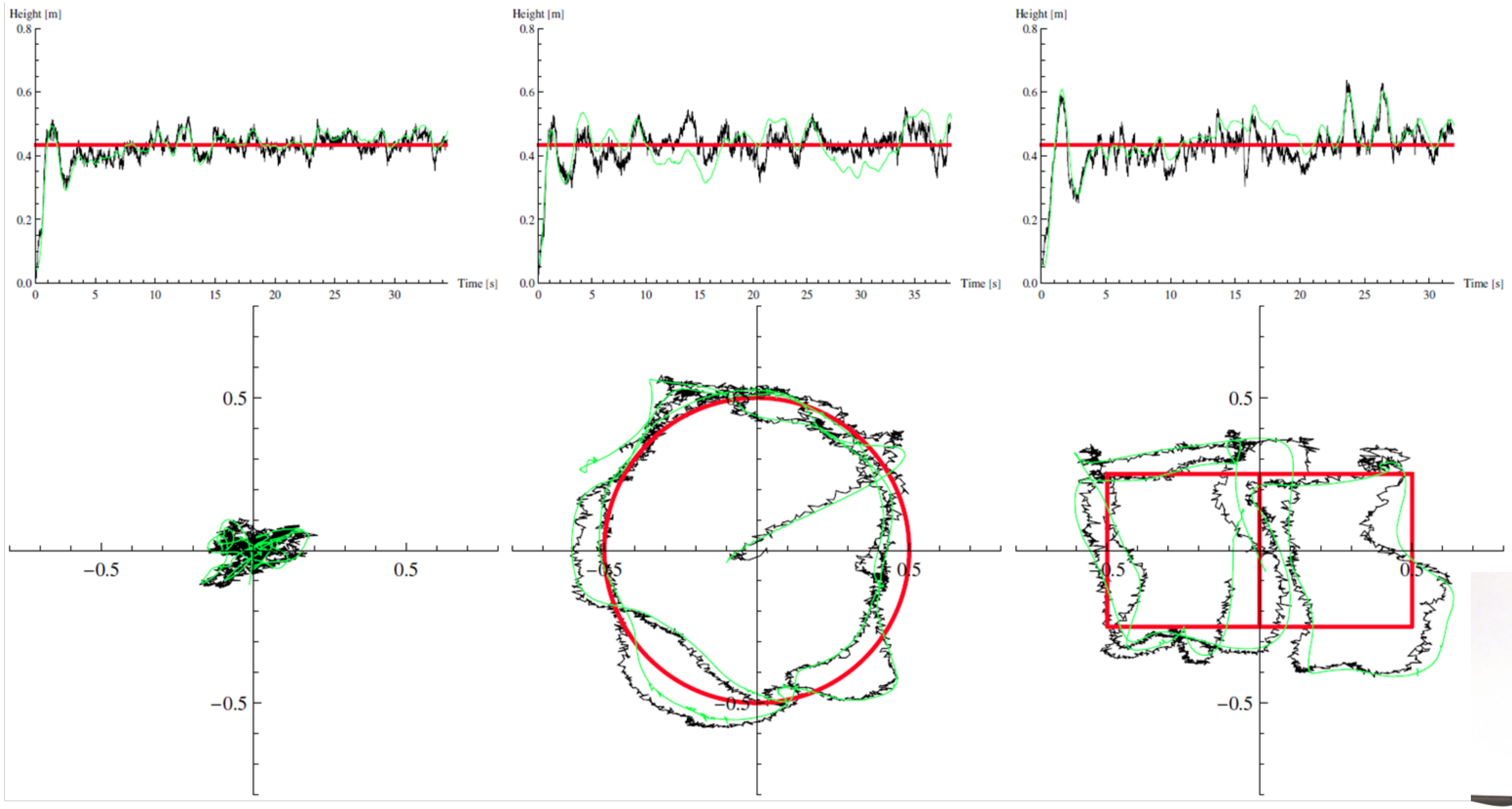

Evaluation against ground truth: desired trajectory

eb-3DSLAM and control

ext. tracker (OptiTrack Flex13)

SPICE Net

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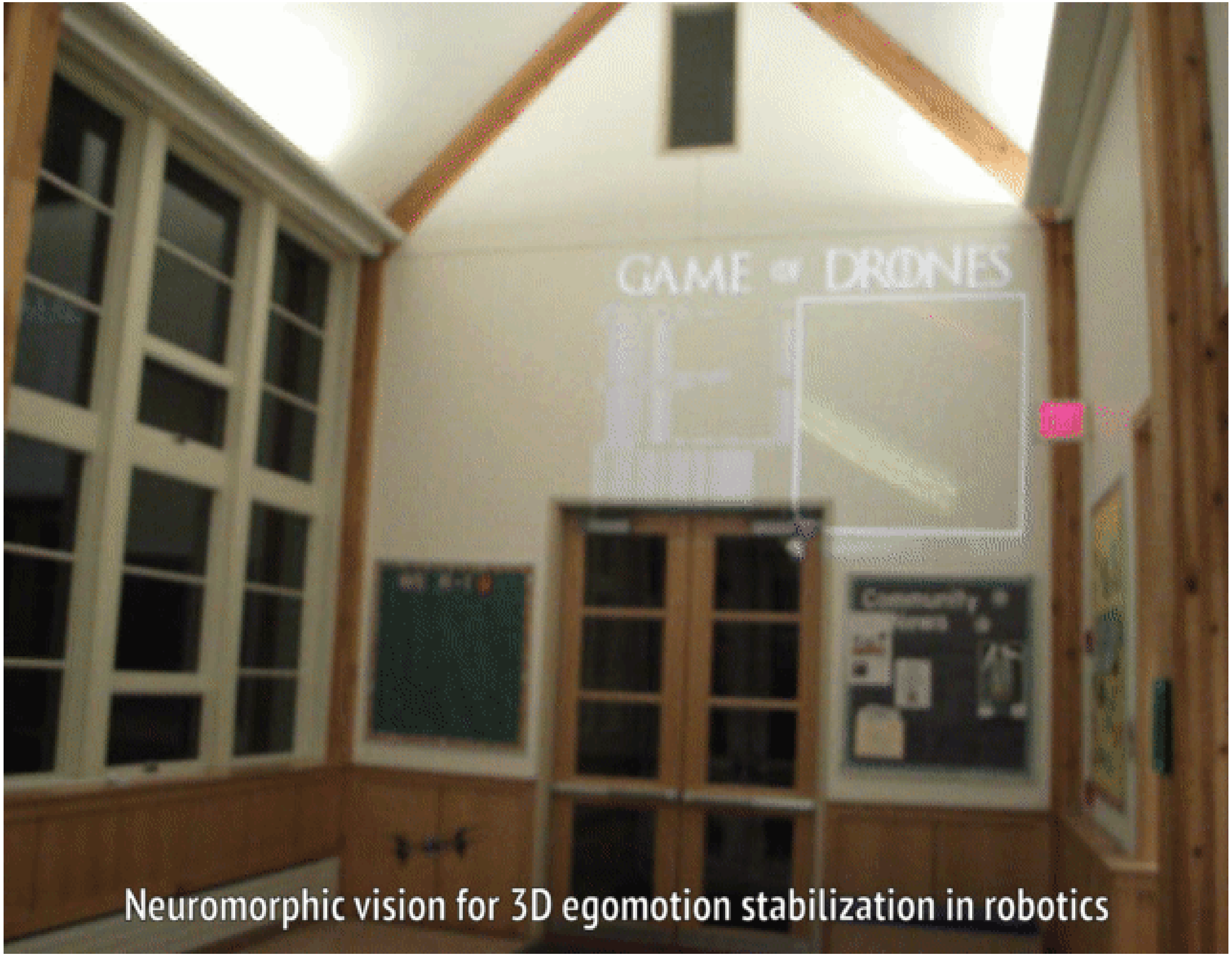

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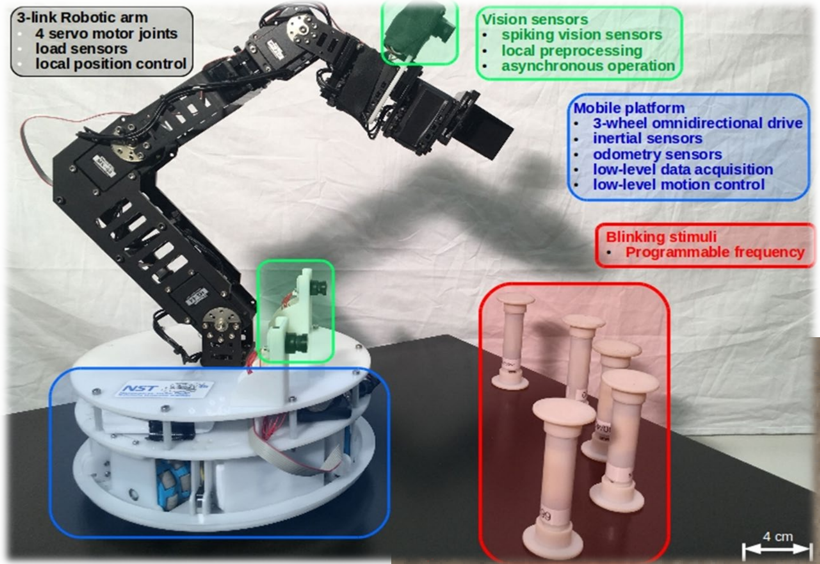
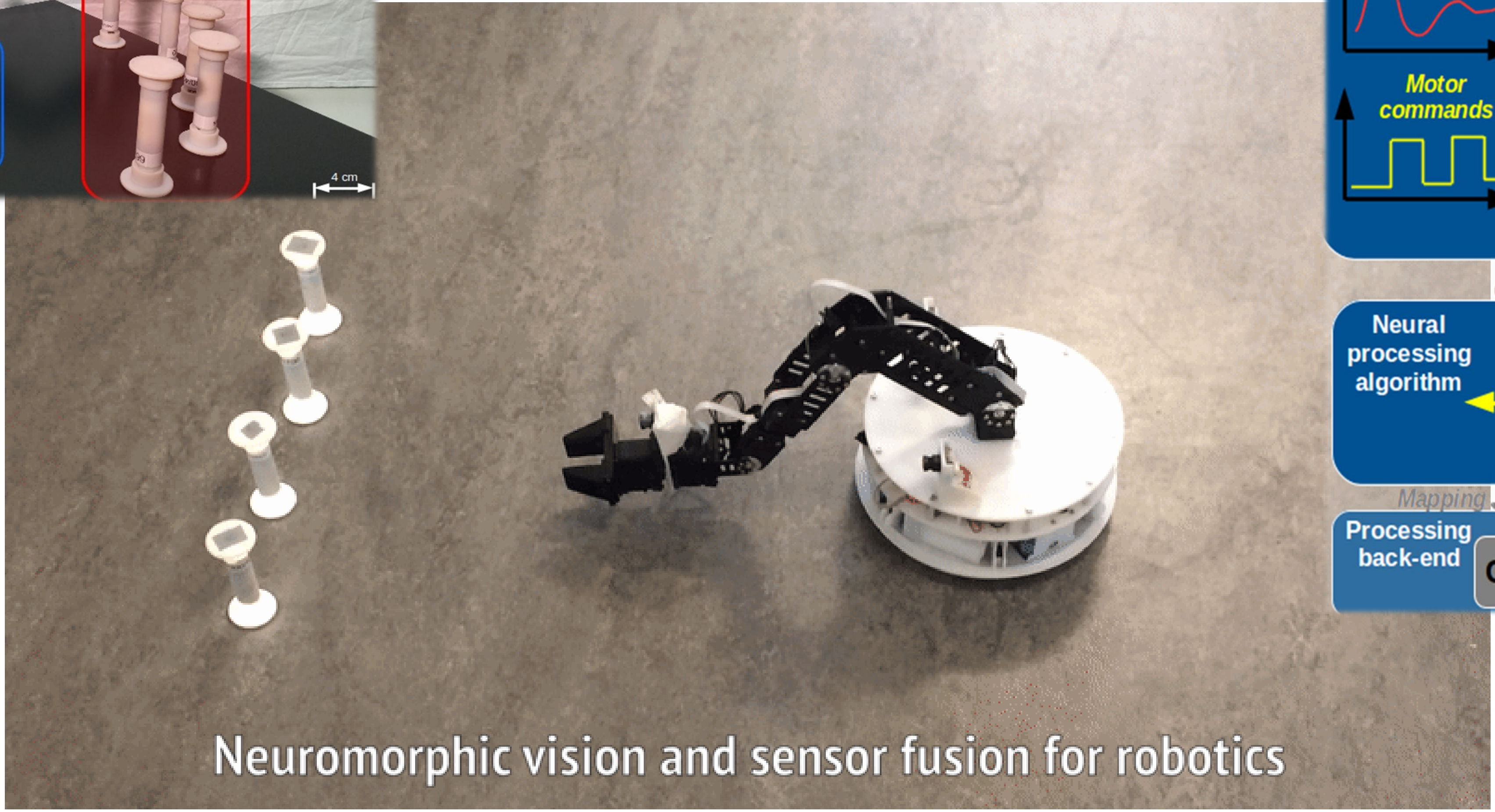
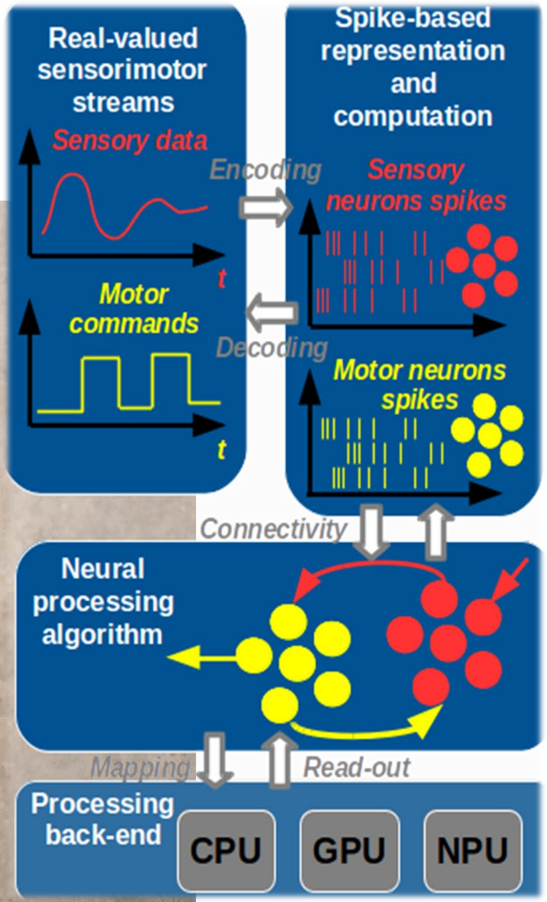
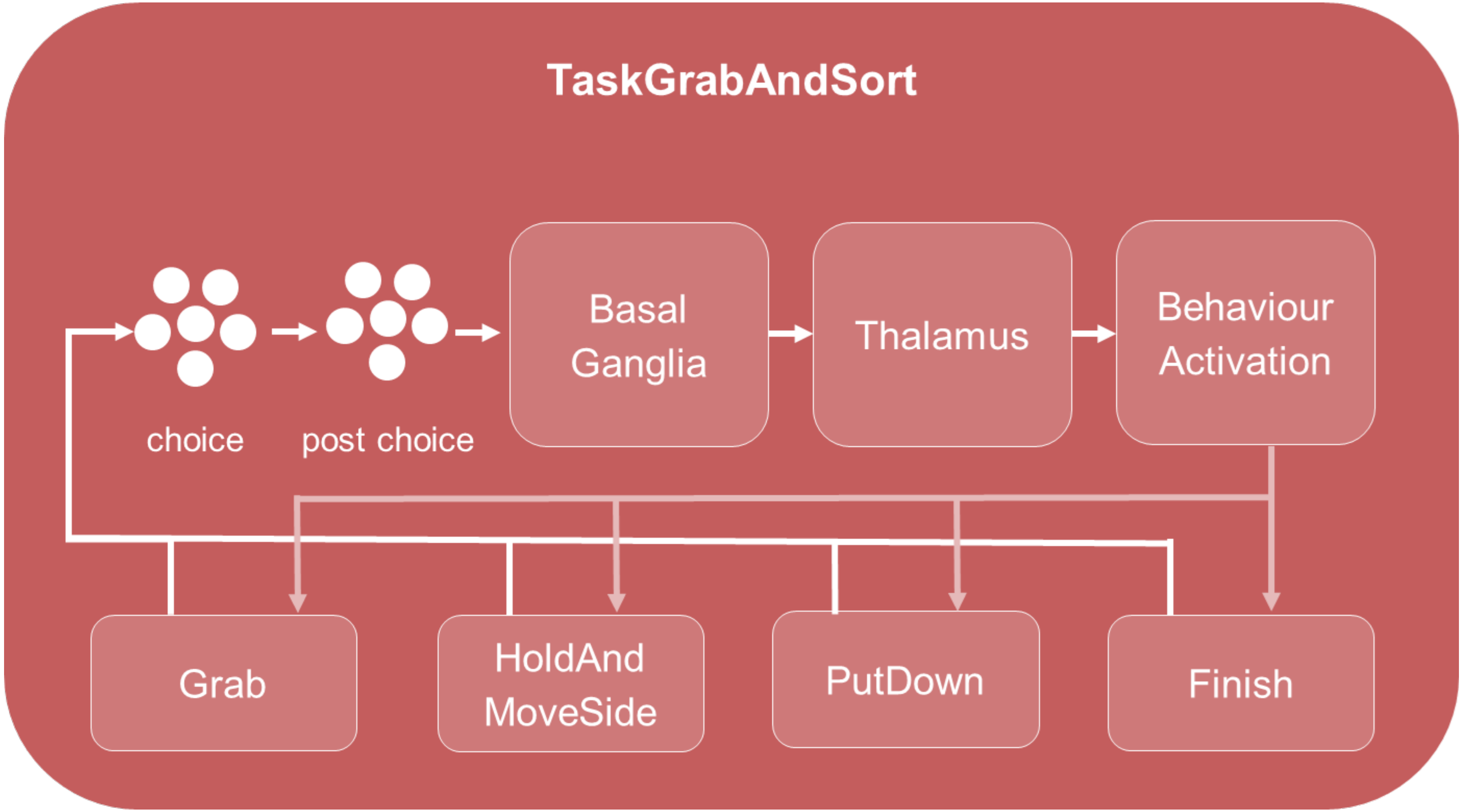
ANN/SNN HW acceleration








TaskGrabAndSort
choice
post choice
Basal Ganglia
Thalamus
Behaviour Activation
Grab
HoldAnd MoveSide
PutDown
Finish

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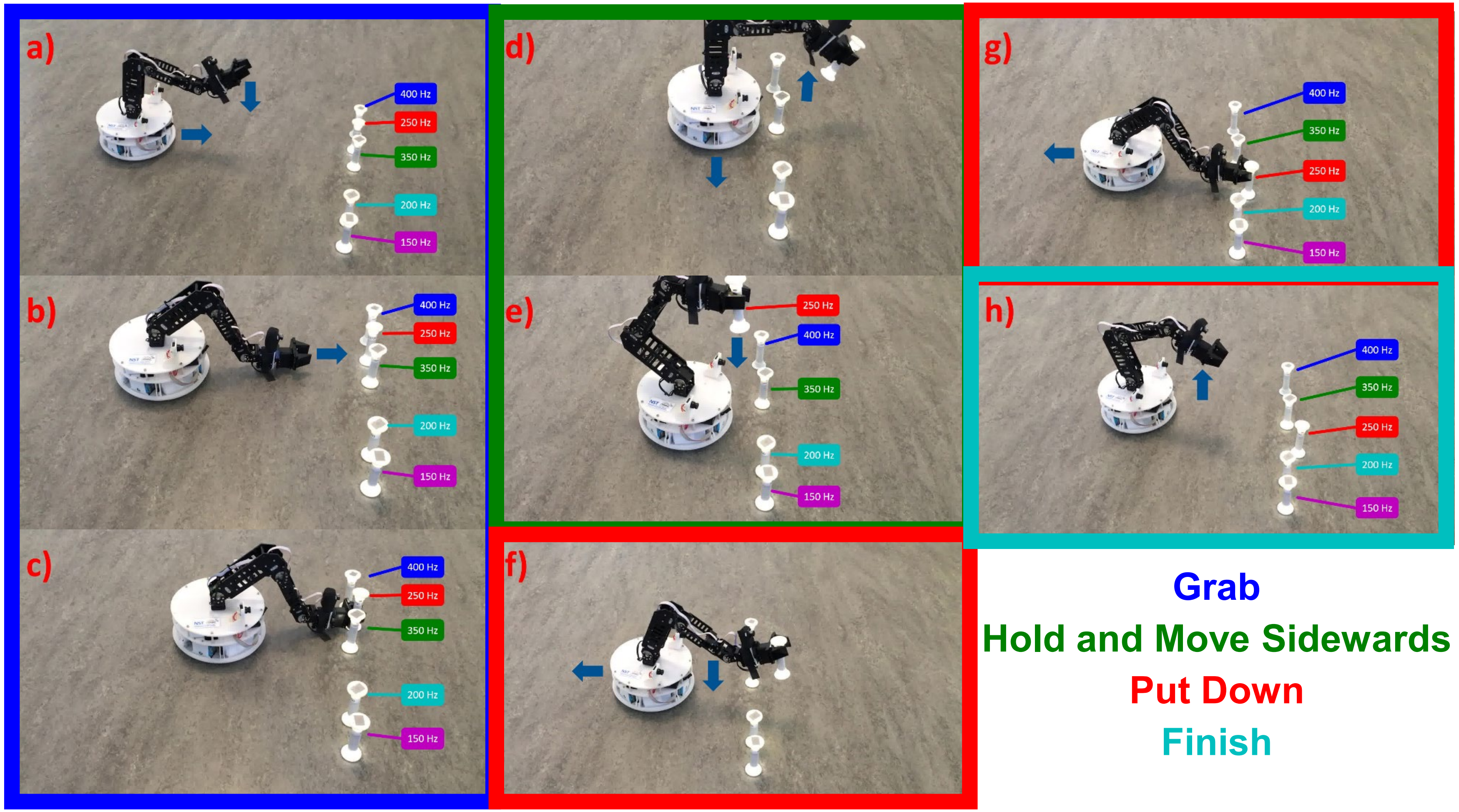
ANN/SNN

ANN/SNN HW acceleration

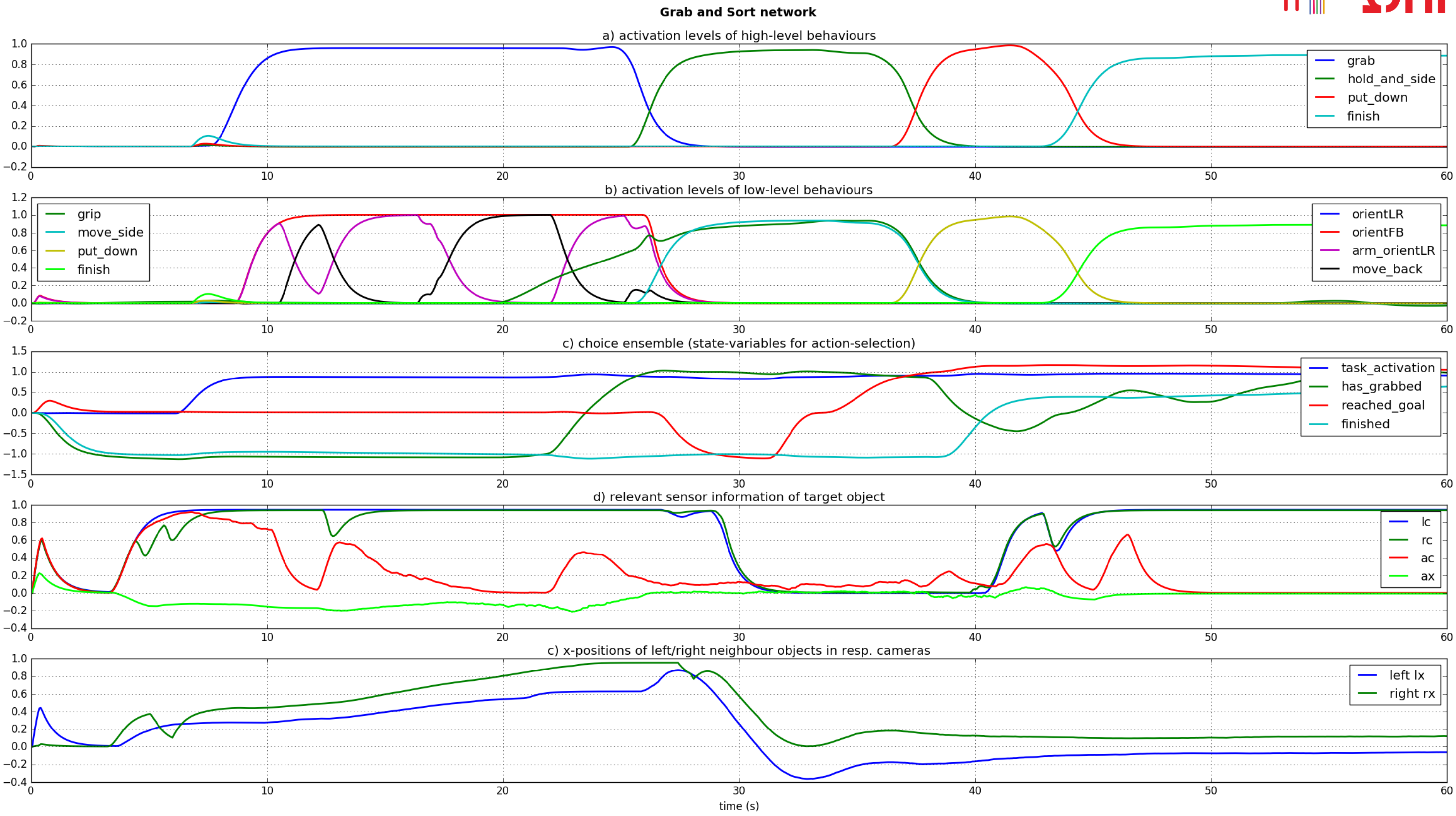


Grab

Hold and Move Sidewards

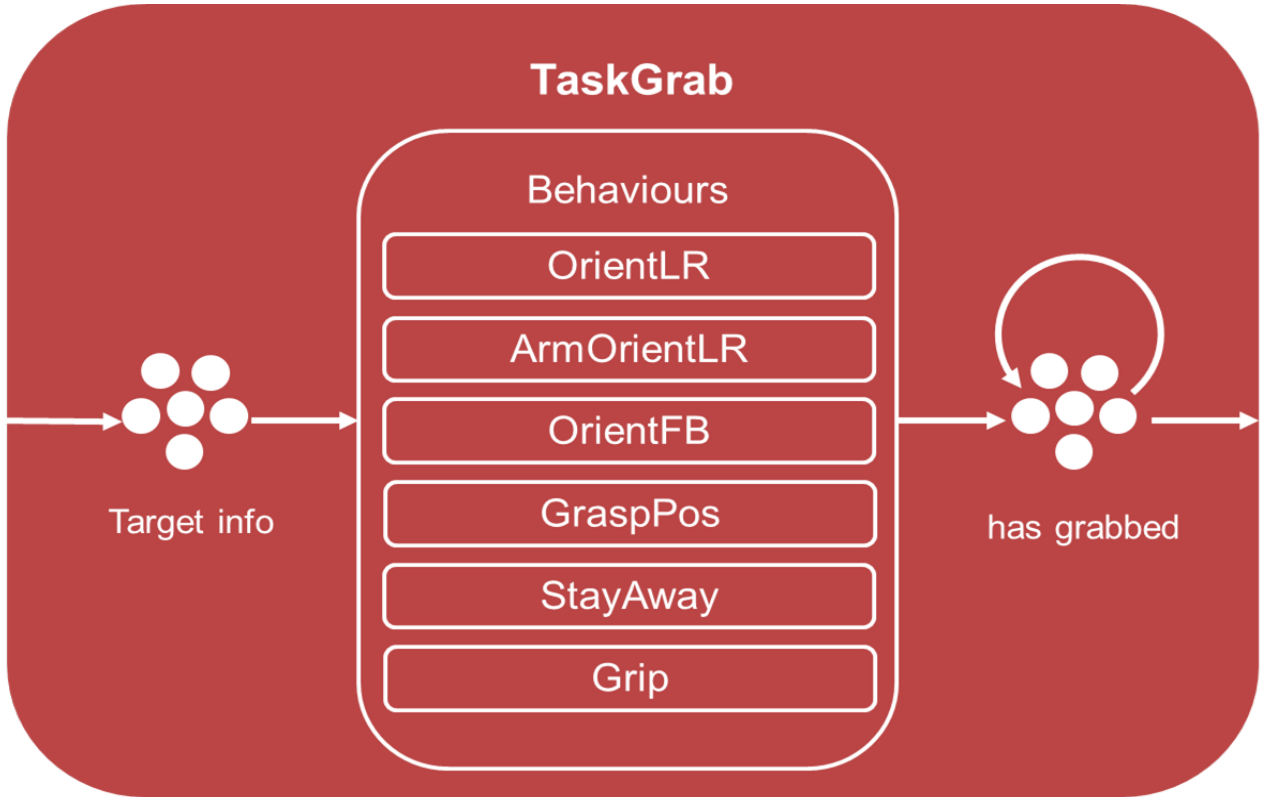
Put Down

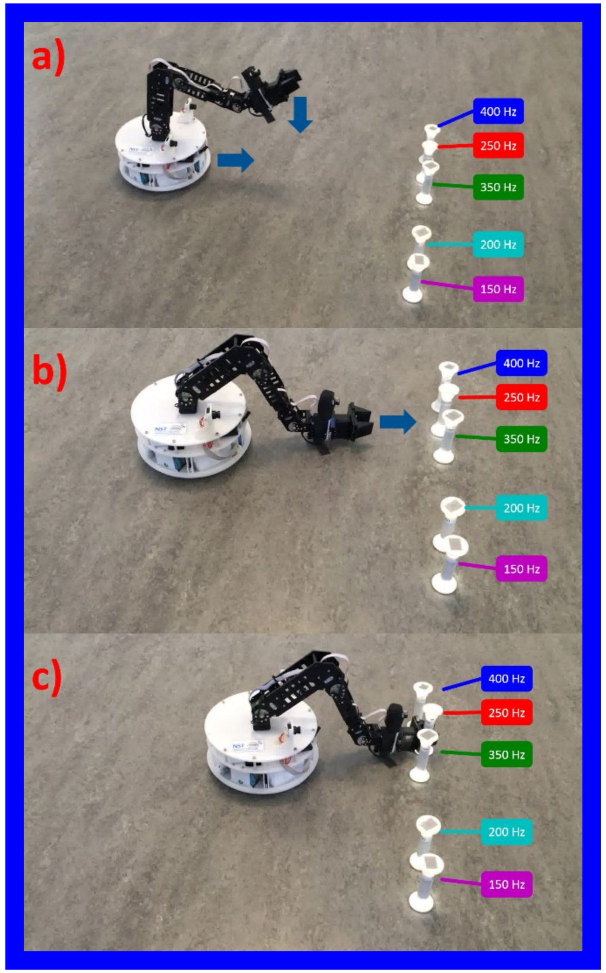
Finish

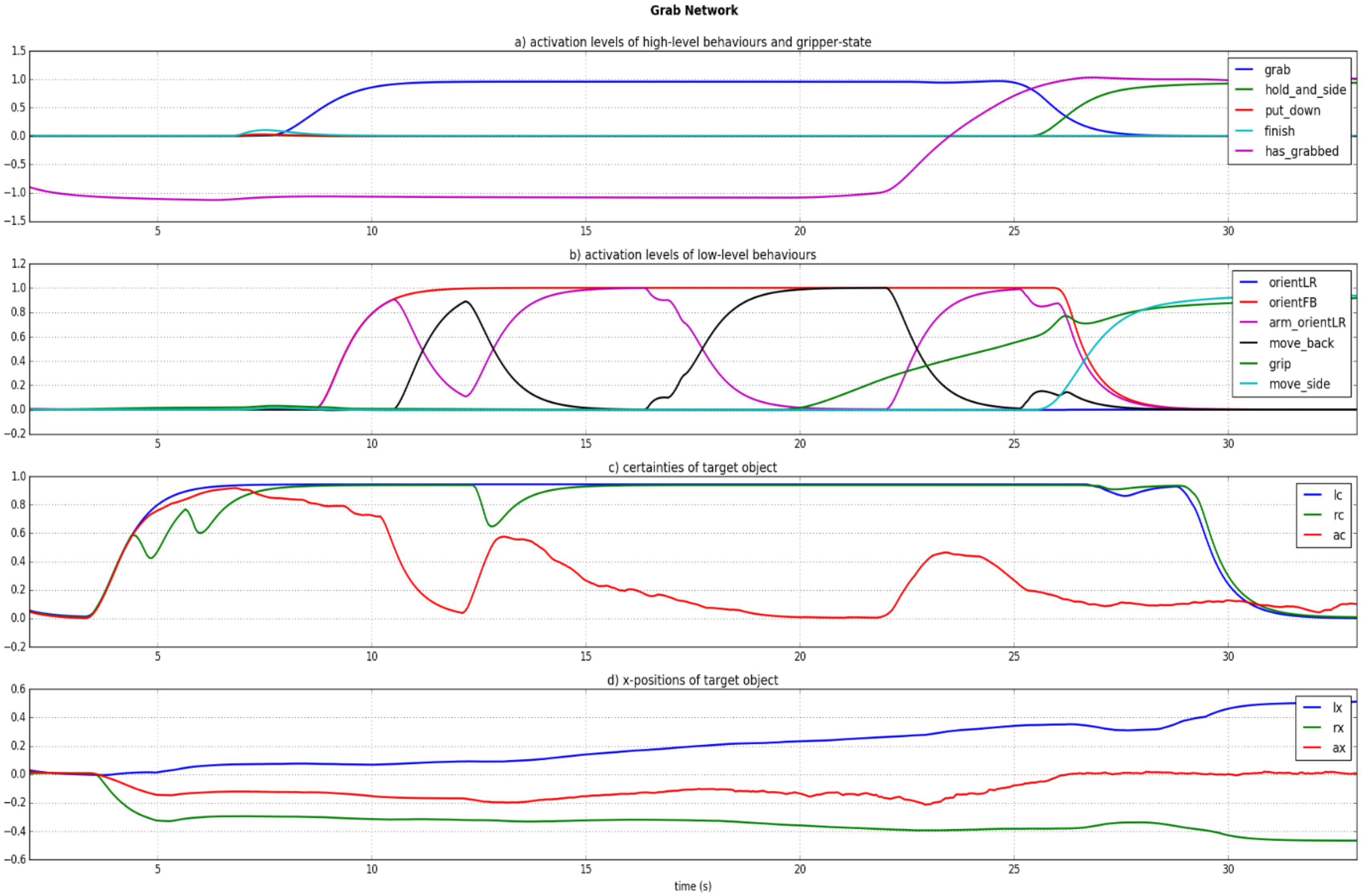

Grab and Sort network
a) activation levels of high-level behaviours
grab
hold_and_side
put_down
finish
b) activation levels of low-level behaviours
grip
move_side
put_down
finish
orientLR
orientFB
arm_orientLR
move_back
c) choice ensemble (state-variables for action-selection)
task_activation
has_grabbed
reached_goal
finished
d) relevant sensor information of target object
lc
rc
ac
ax
c) x-positions of left/right neighbour objects in resp. cameras
left lx
right rx
time (s)

- **TargetInfo**: sensory information of target
- **OrientLR**: use x-position of the target in all three cameras to control the rotation of the platform to face object
- **ArmOrientLR**: same as OrientLR, but using only arm retina for close-up control
- **OrientFB**: use disparity to control forward/backward motion
- **GraspPos**: moves arm from resting to grasping position
- **StayAway**: move backwards
- **Grip**: close the gripper
- **Has grabbed**: memory of closed gripper

*→**TaskGrab**: find object and grab it*

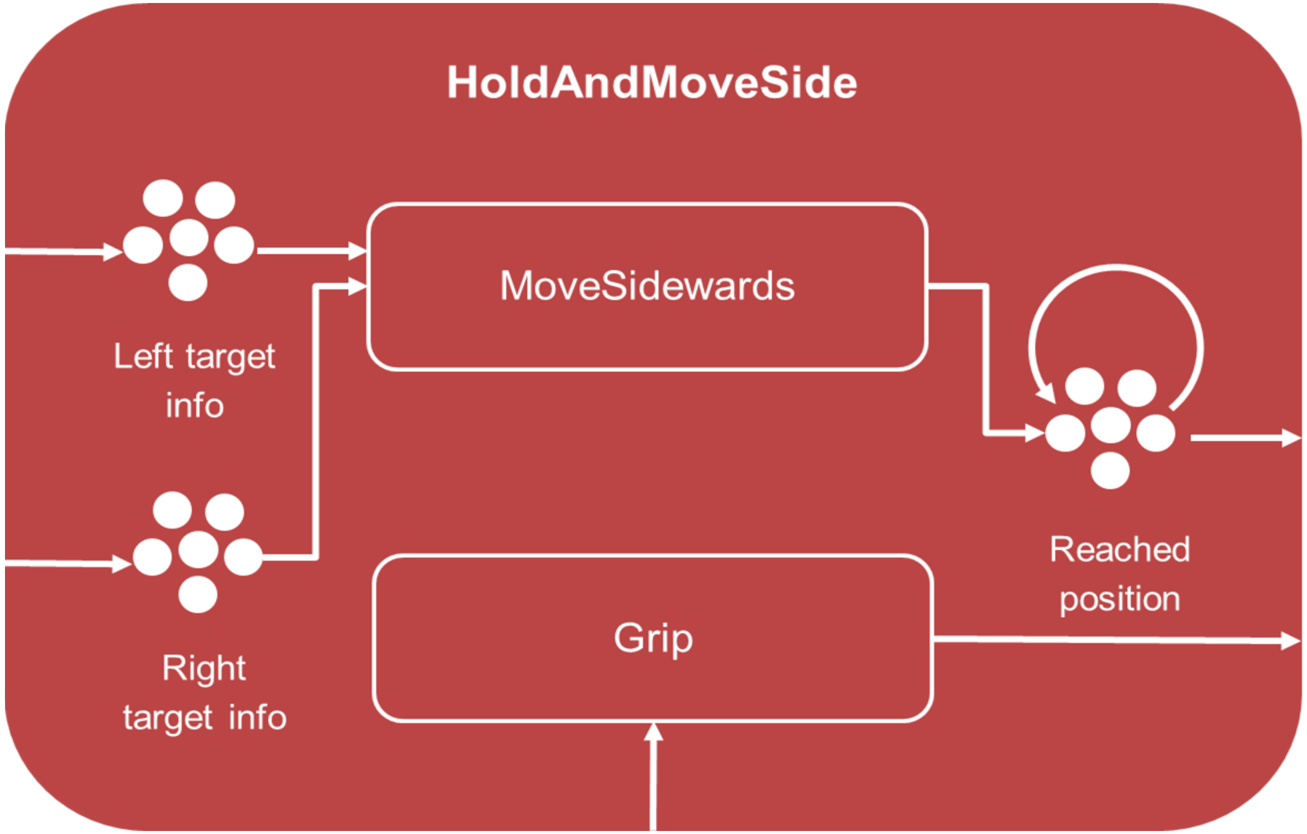


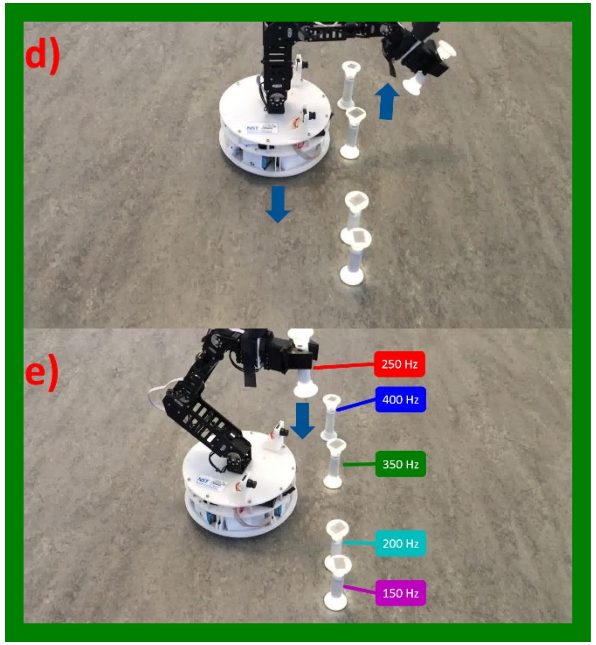

a)
400 Hz
250 Hz
350 Hz
200 Hz
150 Hz
b)
400 Hz
250 Hz
350 Hz
200 Hz
150 Hz
c)
400 Hz
250 Hz
350 Hz
200 Hz
150 Hz


Grab Network
a) activation levels of high-level behaviours and gripper-state
grab
hold_and_side
put_down
finish
has_grabbed
b) activation levels of low-level behaviours
orientLR
orientFB
arm_orientLR
move_back
grip
move_side
c) certainties of target object
lc
rc
ac
d) x-positions of target object
lx
rx
ax
time (s)

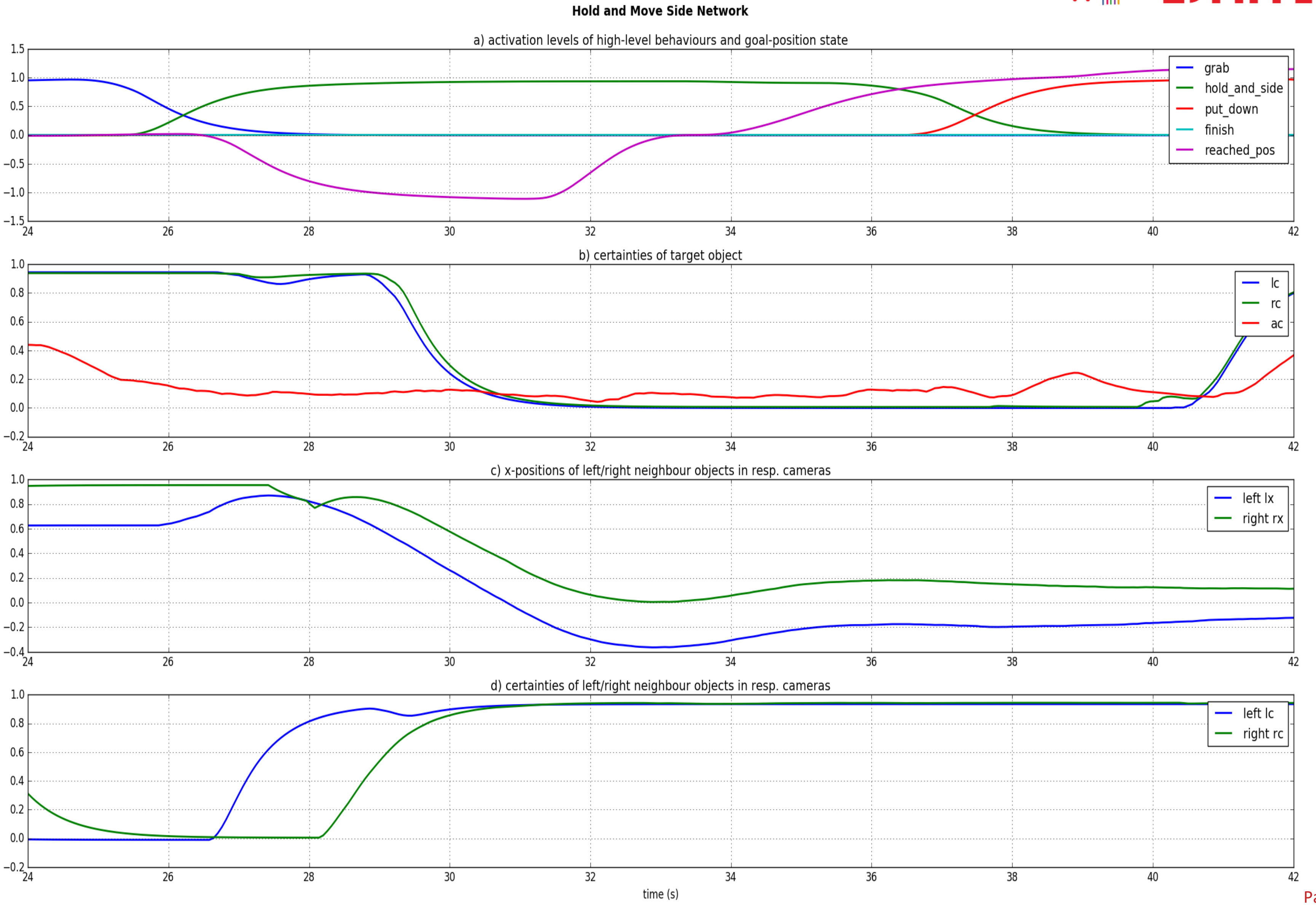
- **Left/right Target Info**: sensory information of left/right neighbor or target object
- **MoveSidewards**: use the mean value of the lateral positions of the left resp. right neighbor in the left resp. right base camera as an estimation of the center between the neighbor objects and move there
- **Grip**: keep the gripper closed
- **Reached position**: memory integrating evidence once goal position is reached

→***HoldAndMoveSide****: hold the object while approaching the goal position for putting down the target object*



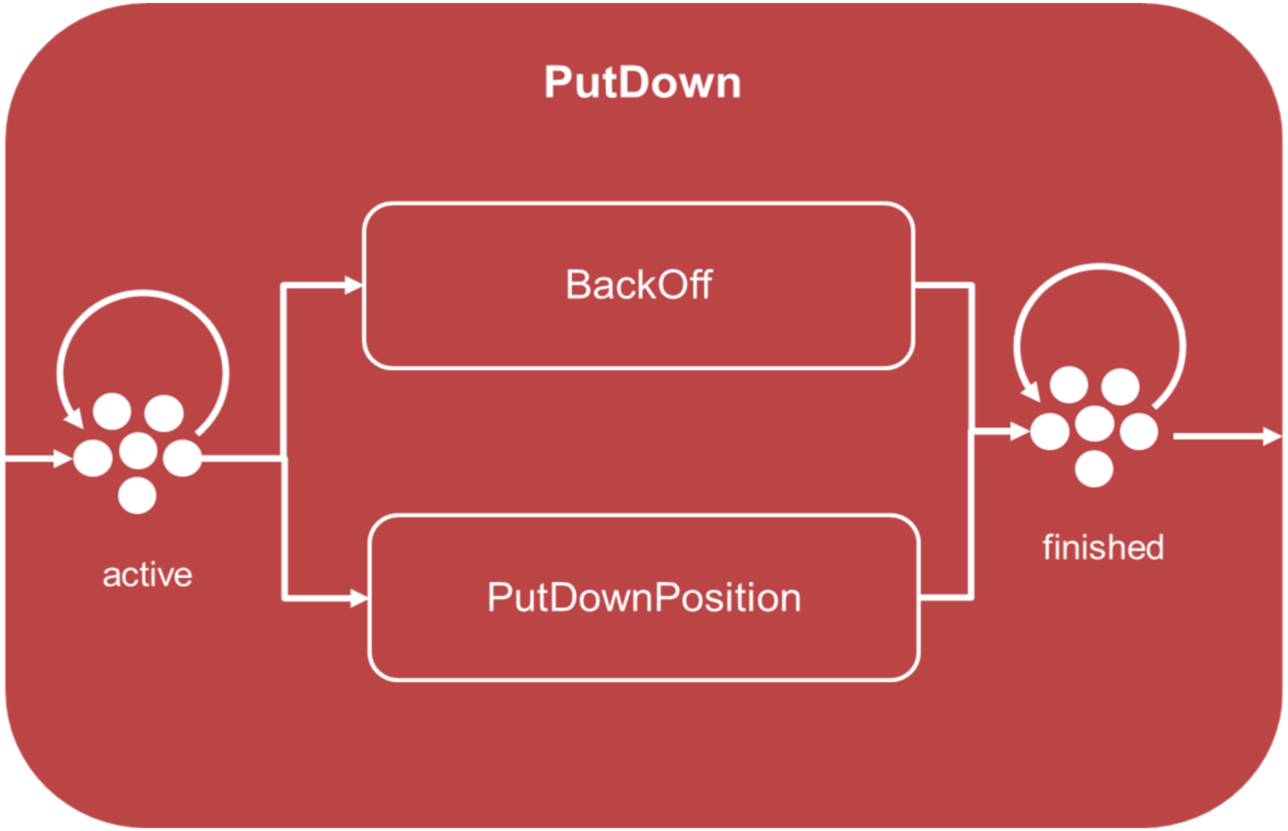


d)
e)
250 Hz
400 Hz
350 Hz
200 Hz
150 Hz



Hold and Move Side Network
a) activation levels of high-level behaviours and goal-position state
grab
hold_and_side
put_down
finish
reached_pos
b) certainties of target object
lc
rc
ac
c) x-positions of left/right neighbour objects in resp. cameras
left lx
right rx
d) certainties of left/right neighbour objects in resp. cameras
left lc
right rc
time (s)

- **Active**: memory integrating evidence when this behaviour is initally activated
- **PutDownPosition**: move the arm to a position suitable for releasing an object
- **BackOff**: move slightly backwards
- **Finished**: memory integrating evidence of the PutDown task being completed



→**PutDown**: move the arm from holding position to put-down position, openthe gripper and move the base slightly backwards to ensure smooth and safe placement of the target object

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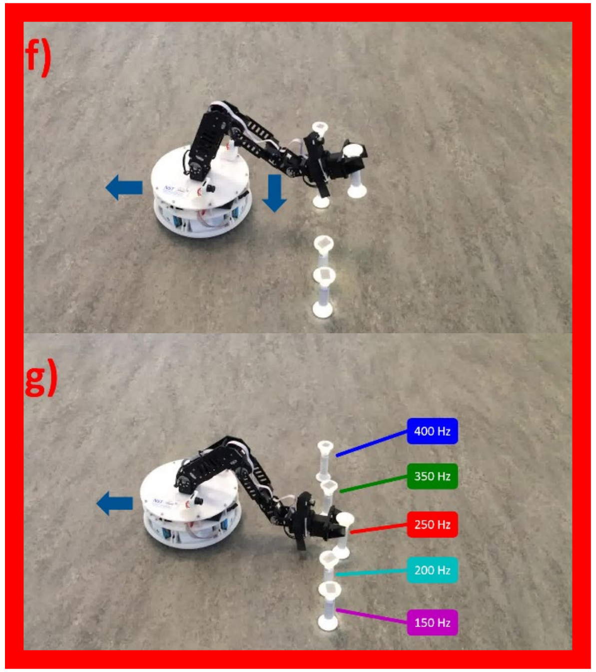
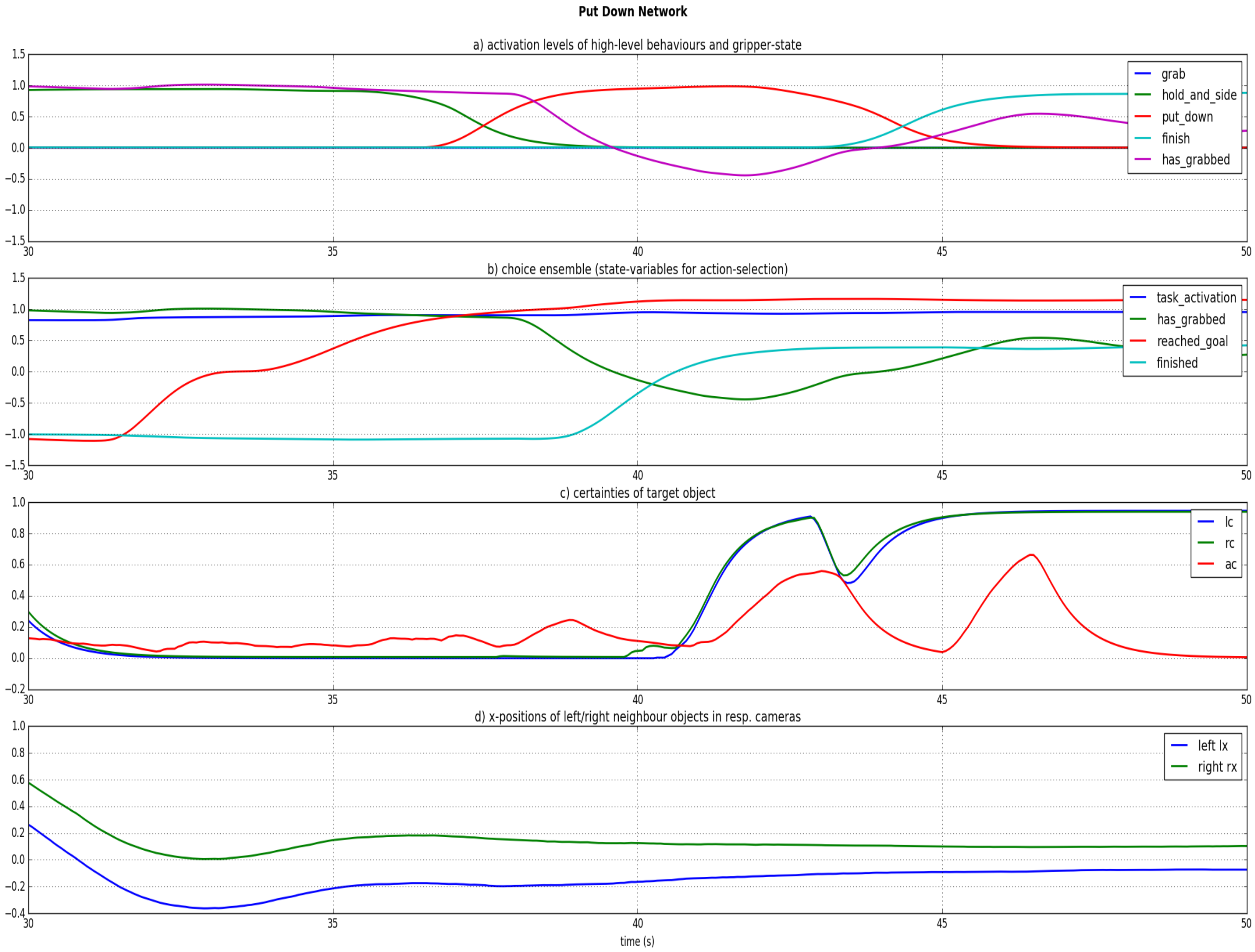
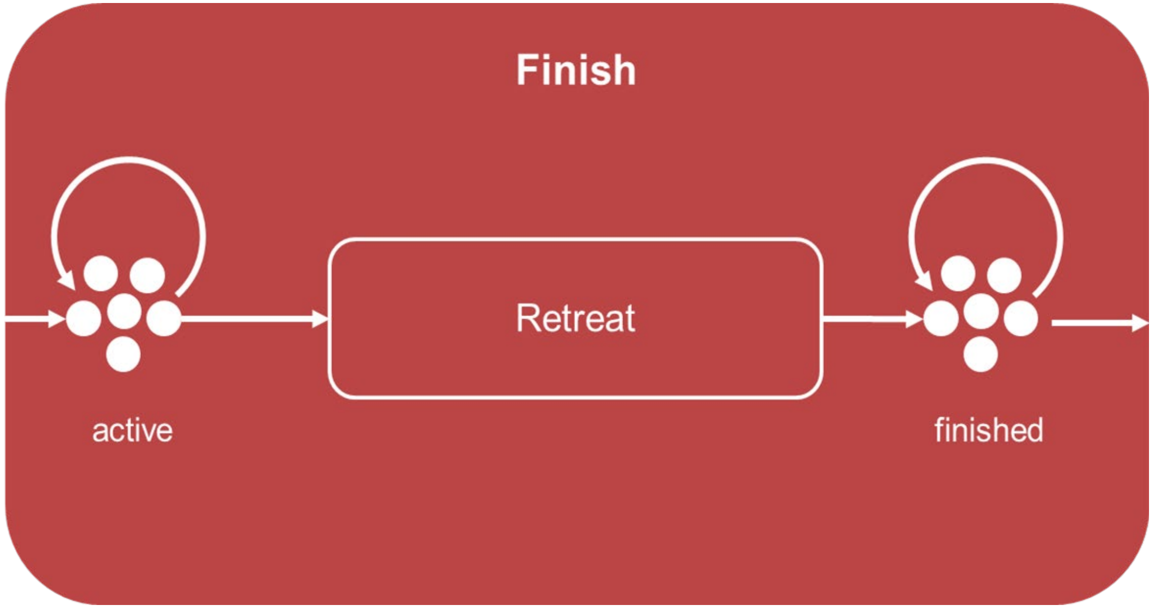


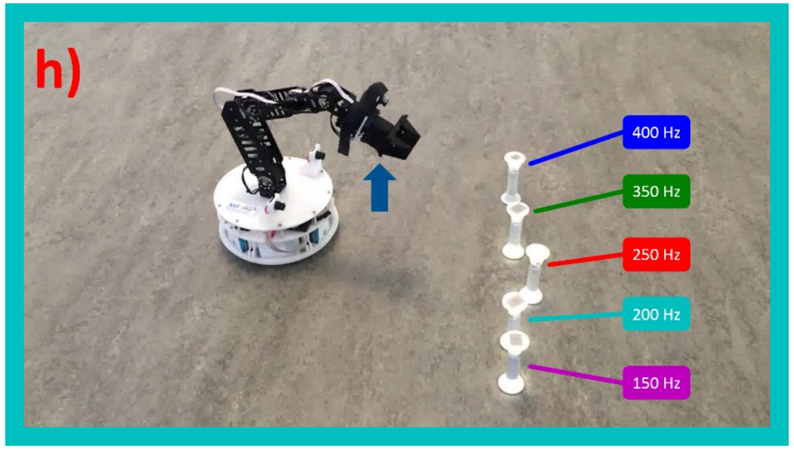


- **Active**: memory integrating evidence when this behaviour is initally activated
- **Retreat**: move slightly backwards
- **Finished**: memory integrating evidence of the PutDown task being completed



→**Finish**: back off from the manipulated objects and stop after some time

Implicitly by **deactivating all other behaviors** the arm moves to back resting position automatically, which indicates that the whole sequence of tasks is completed



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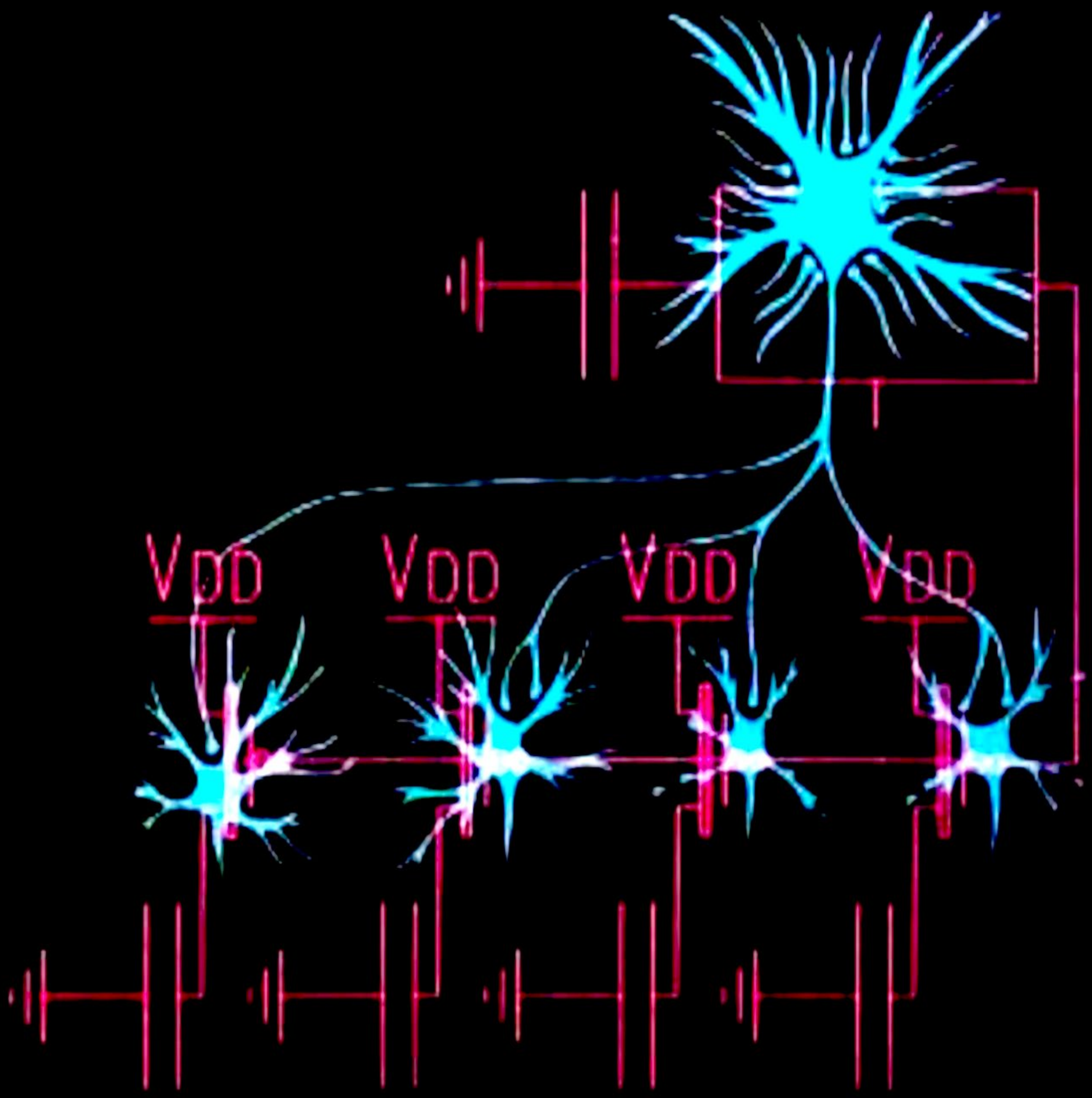
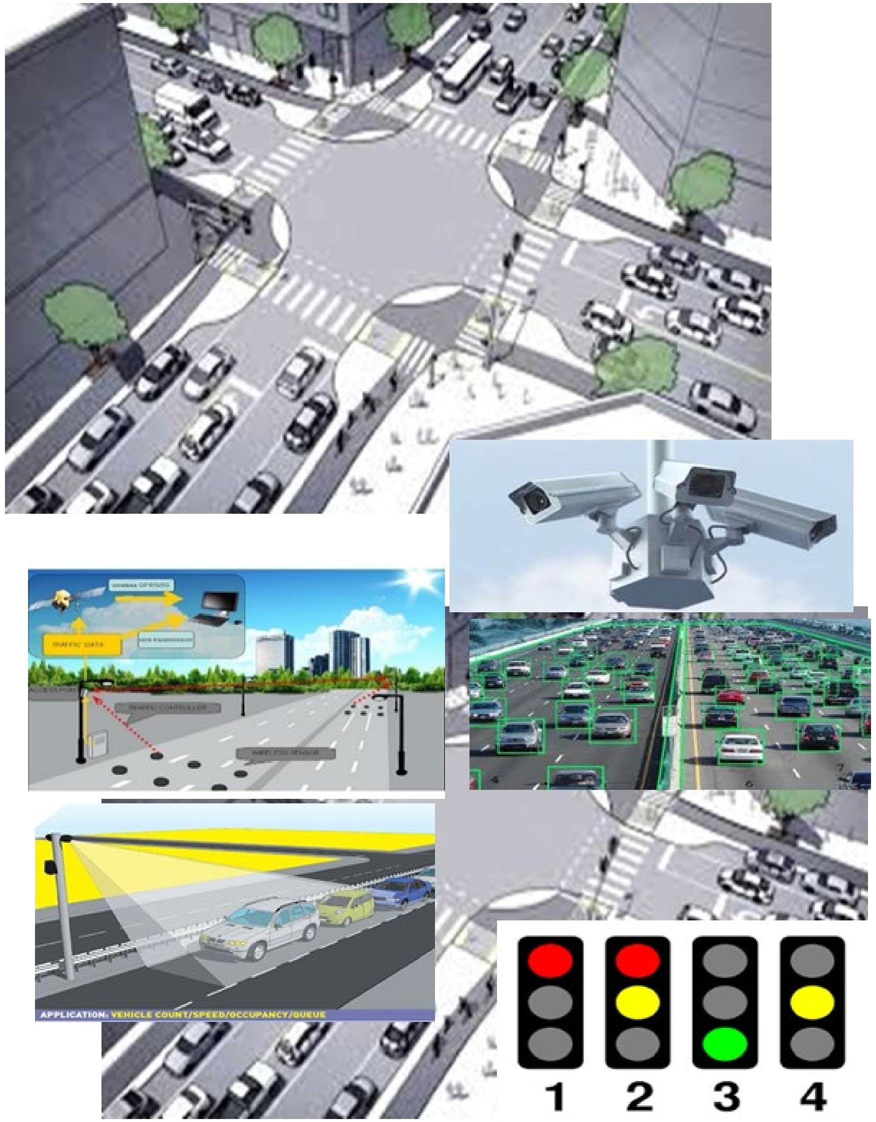
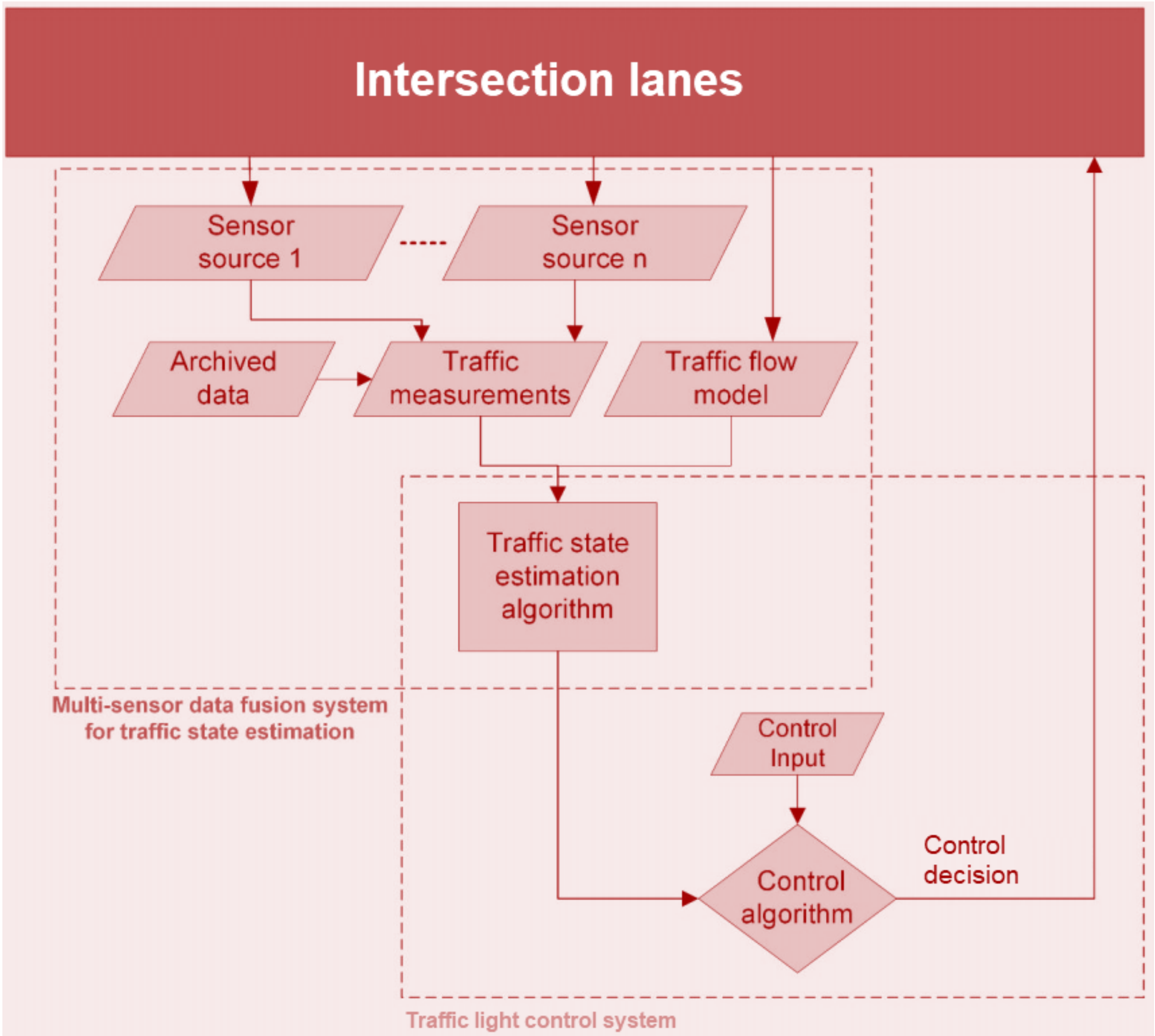
Neural Control Systems

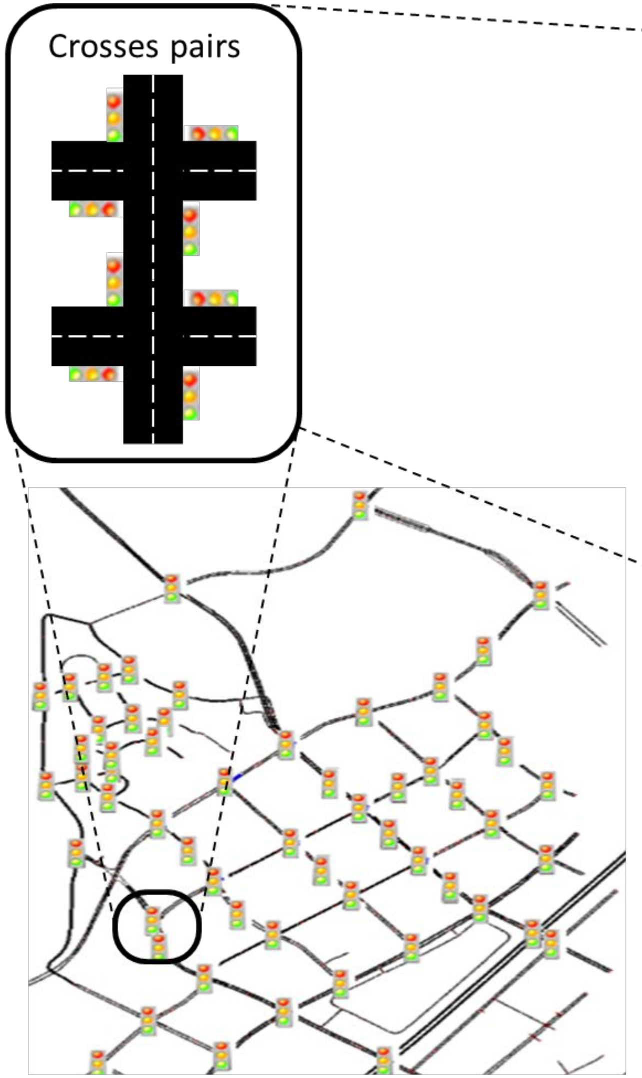
Road traffic control

Carver, Mead. *Analog VLSI and neural systems*. Addison-Wesley, 1989.

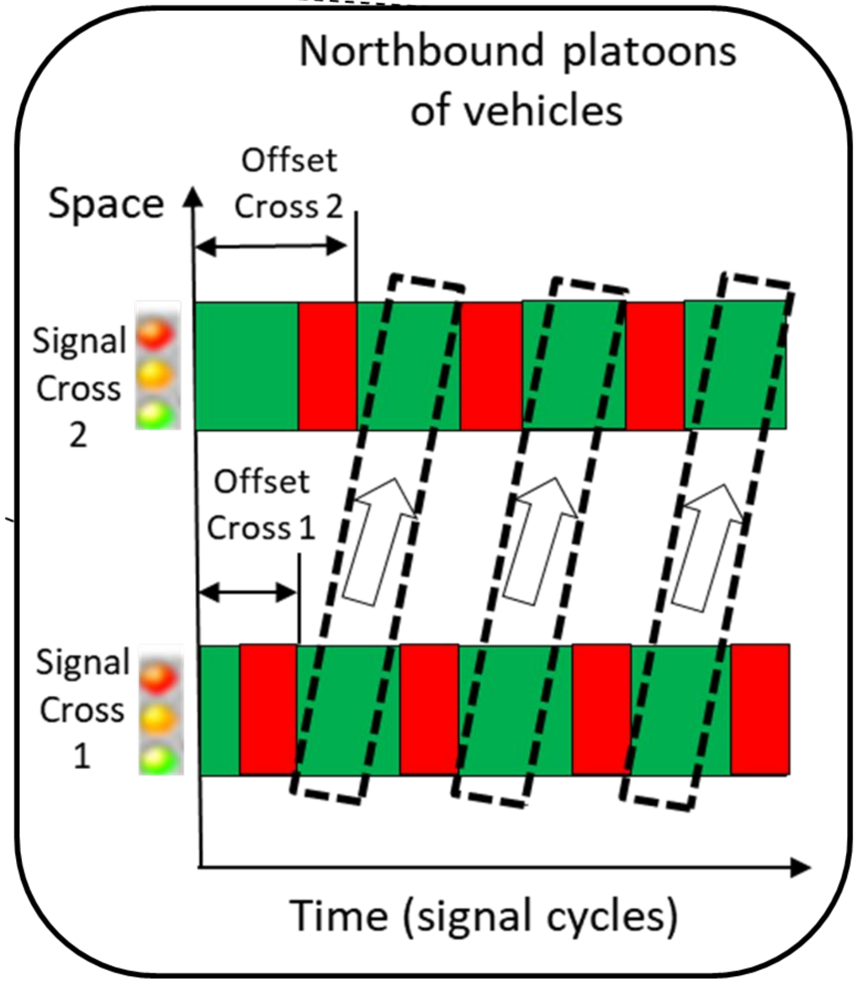



APPLICATION: VEHICLE COUNT/SPEED/OCCUPANCY/QUEUE
1
2
3
4

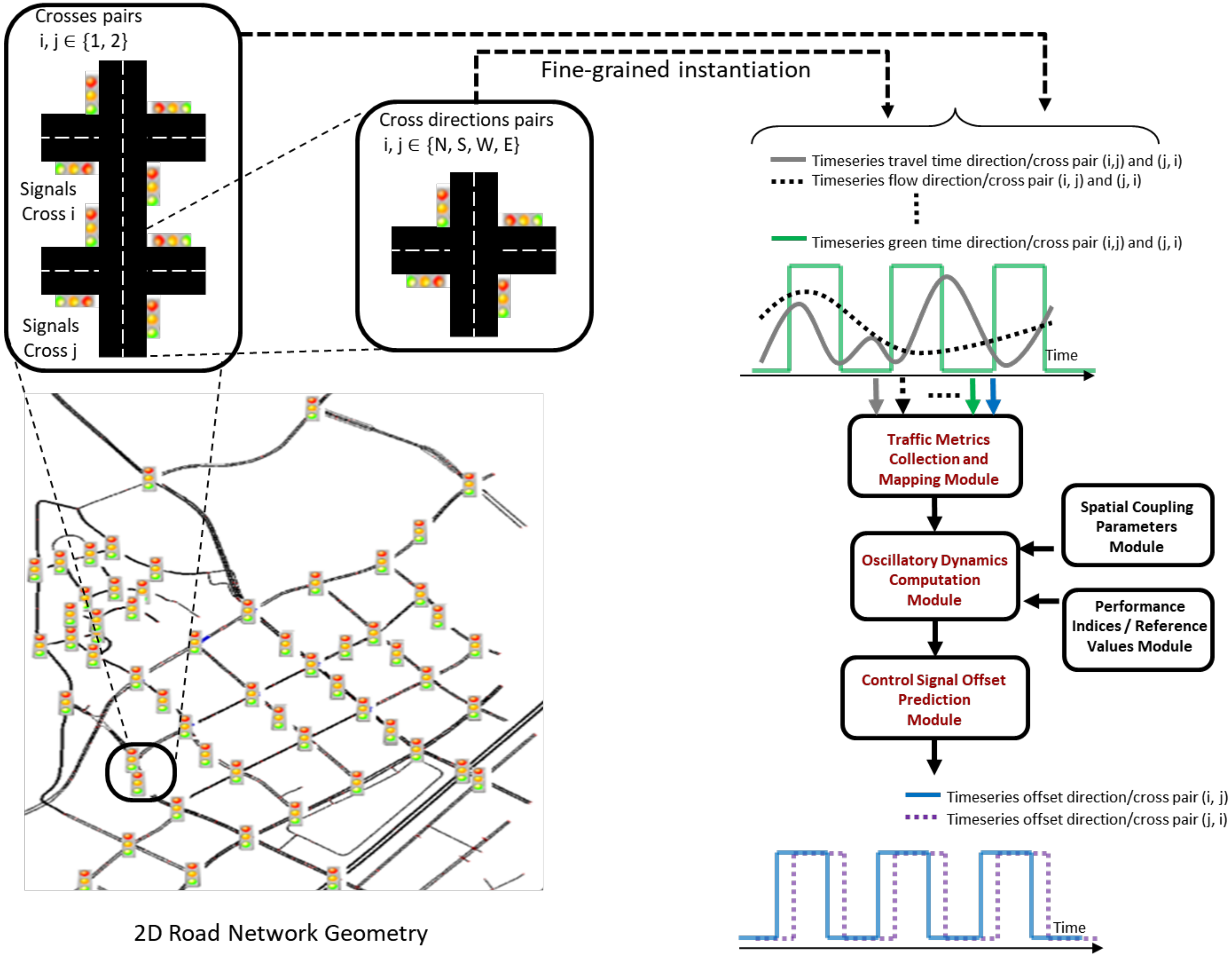

Intersection lanes
Sensor source 1
Sensor source n
Archived data
Traffic measurements
Traffic flow model
Traffic state estimation algorithm
Multi-sensor data fusion system for traffic state estimation
Control Input
Control algorithm
Control decision
Traffic light control system



2D Road Network Geometry



An idealized time-distance diagram showing signal coordination with a fixed time plan and the corresponding offset calculation


Crosses pairs
i, j ∈ {1, 2}
Signals
Cross i
Signals
Cross j
Fine-grained instantiation
Cross directions pairs
i, j ∈ {N, S, W, E}
Timeseries travel time direction/cross pair (i,j) and (j, i)
Timeseries flow direction/cross pair (i, j) and (j, i)
Timeseries green time direction/cross pair (i,j) and (j, i)
Time
Traffic Metrics Collection and Mapping Module
Spatial Coupling Parameters Module
Oscillatory Dynamics Computation Module
Performance Indices / Reference Values Module
Control Signal Offset Prediction Module
Timeseries offset direction/cross pair (i, j)
Timeseries offset direction/cross pair (j, i)
Time
2D Road Network Geometry

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Angular speed | Coupling strength | Variability

$$\frac{d\theta_i(t)}{dt} = \omega_i(t) + k_i(t)\sum_{j=1}^{N} A_{ij}sin(\theta_j(t) - \theta_i(t)) + F_i sin(\theta^*(t) - \theta_i(t))$$

where:
θ_i - the amount of green time of traffic light i
ω_i - the frequency of traffic light i oscillator
k_i - the flow of cars passing through the direction controlled by traffic light i oscillator
A_{ij} - the static spatial adjacency coupling between oscillator i and oscillator j
F_i - the coupling of external perturbations (e.g. maximum cycle time per phase imposed by law)
θ^* - the external perturbation (e.g. the upper limit of green time)

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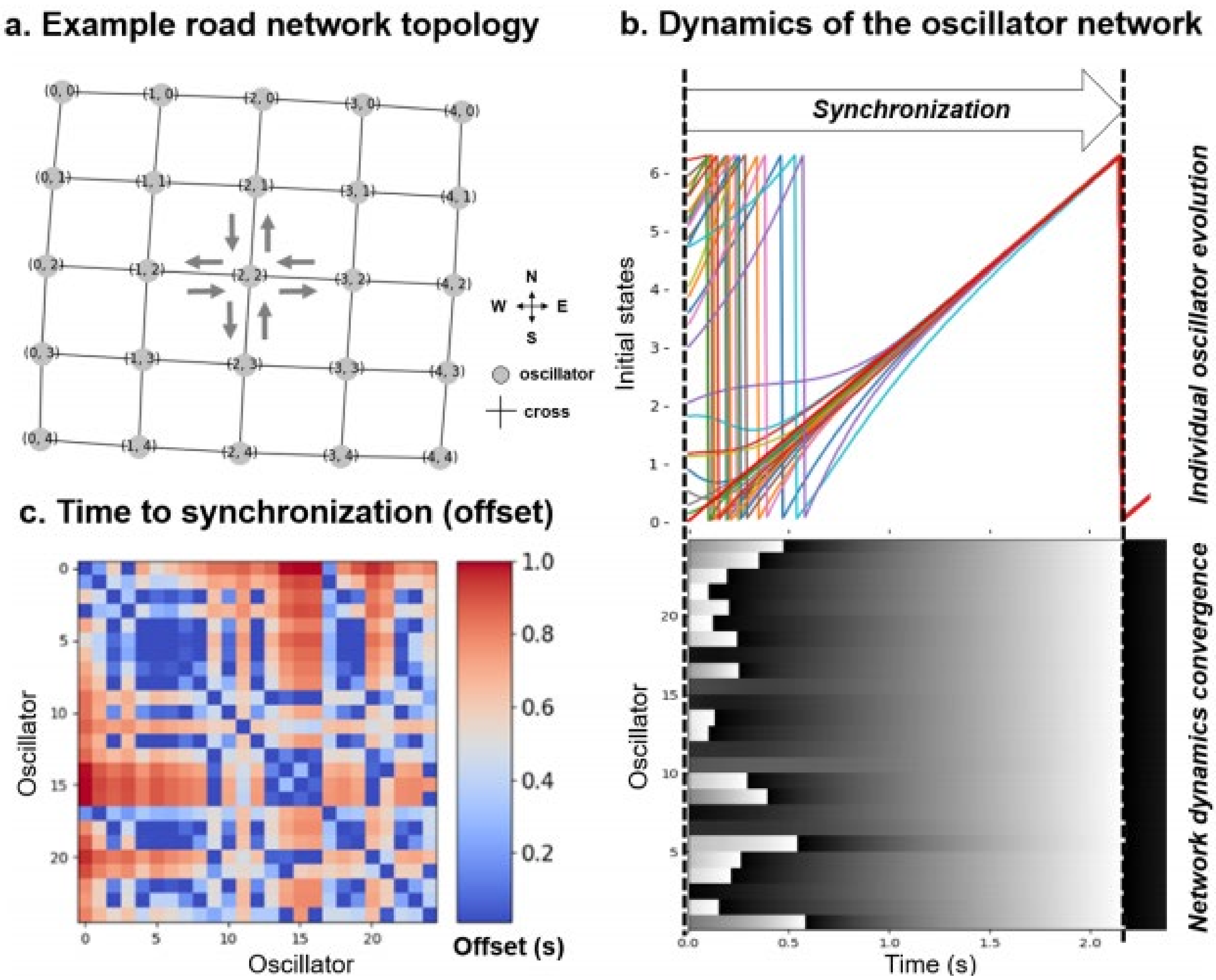


Oscillator dynamics

Regularizing control law

$$\frac{d\theta_i(t)}{dt} = \omega_i(t) + k_i(t)\sum_{j=1}^{N} A_{ij} sin(\theta_j(t) - \theta_i(t)) + F_i sin(\theta^*(t) - \theta_i(t)) + u_i(t)$$

with

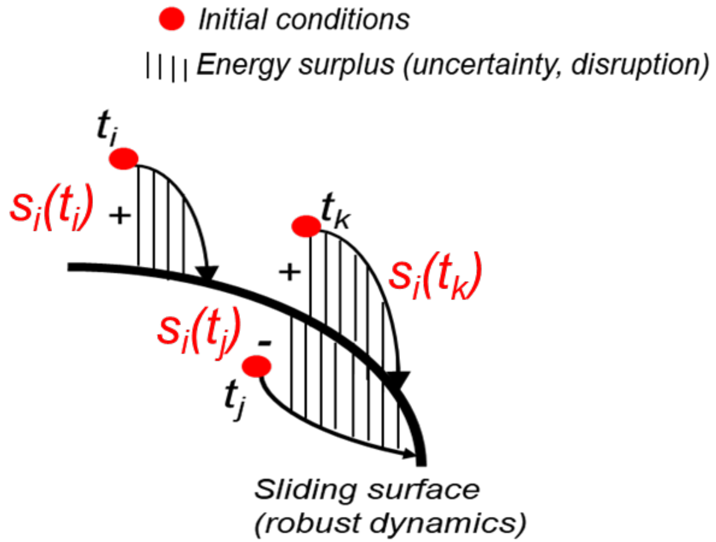
Sliding Mode Control

$$u_i(t) = \epsilon_1 \int_0^t \hat{s}_i(\tau)d\tau$$

$$\frac{\hat{s}_i(t)}{dt} = \epsilon_2\left(\sum_{i,j}(\hat{s}_j(t) - \hat{s}_i(t)) + s_i(t)\right)$$

$$\frac{s_i(t)}{dt} = \epsilon_3\sum_{j}\left(s_j(t) - \frac{\hat{s}_i(t)}{dt}\right) - sign(\hat{s}_i(t))\frac{d^2\theta_i(t)}{dt^2}$$

$$0 < \epsilon_1 < \epsilon_2 < \epsilon_3 < 1$$



where:

$s_i(t)$ - the surplus energy of traffic light i oscillator

$\hat{s}_i(t)$ - the estimated surplus energy of traffic light i oscillator

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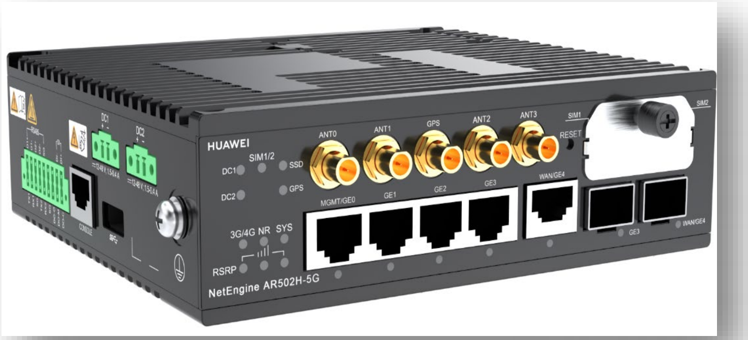
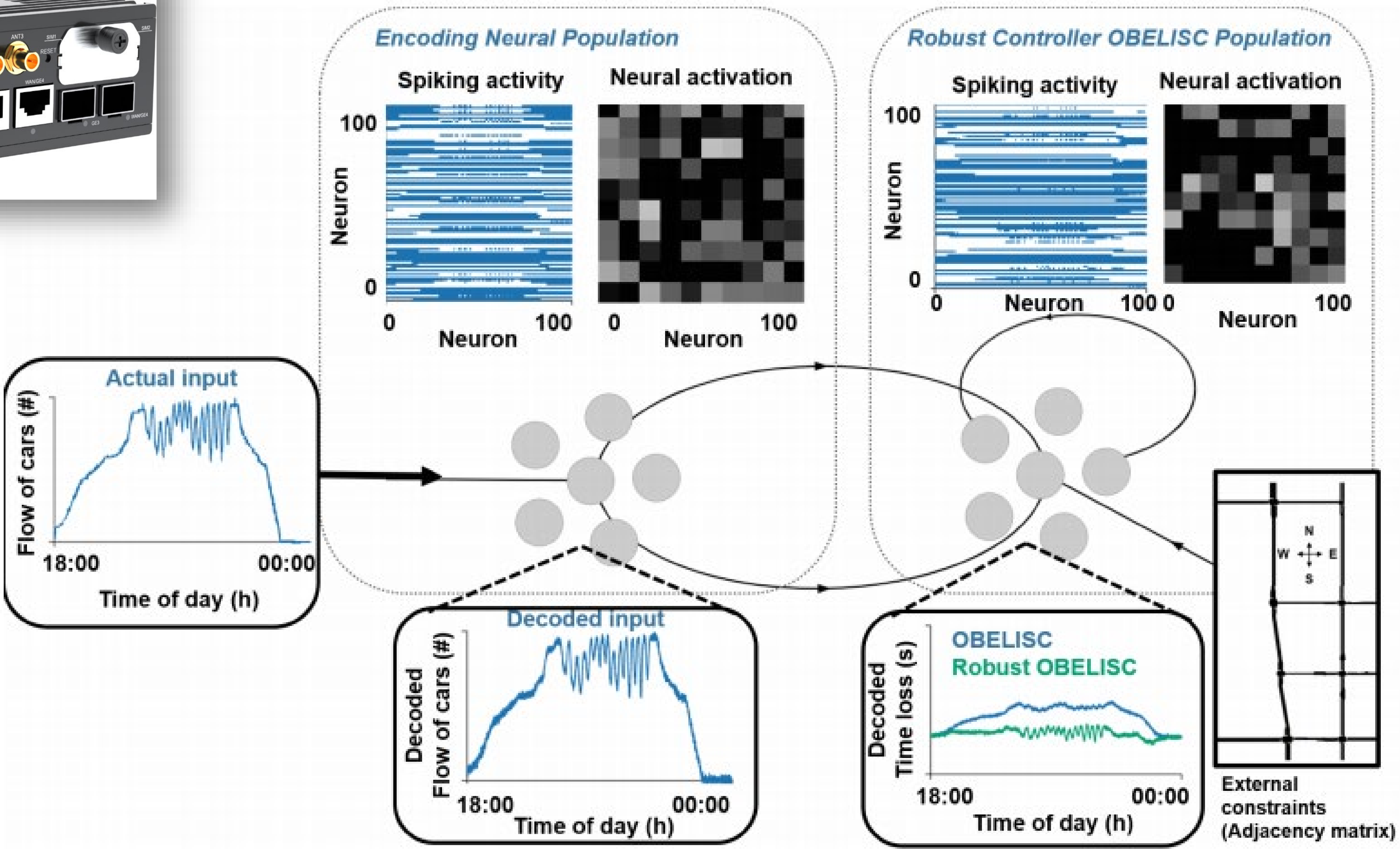
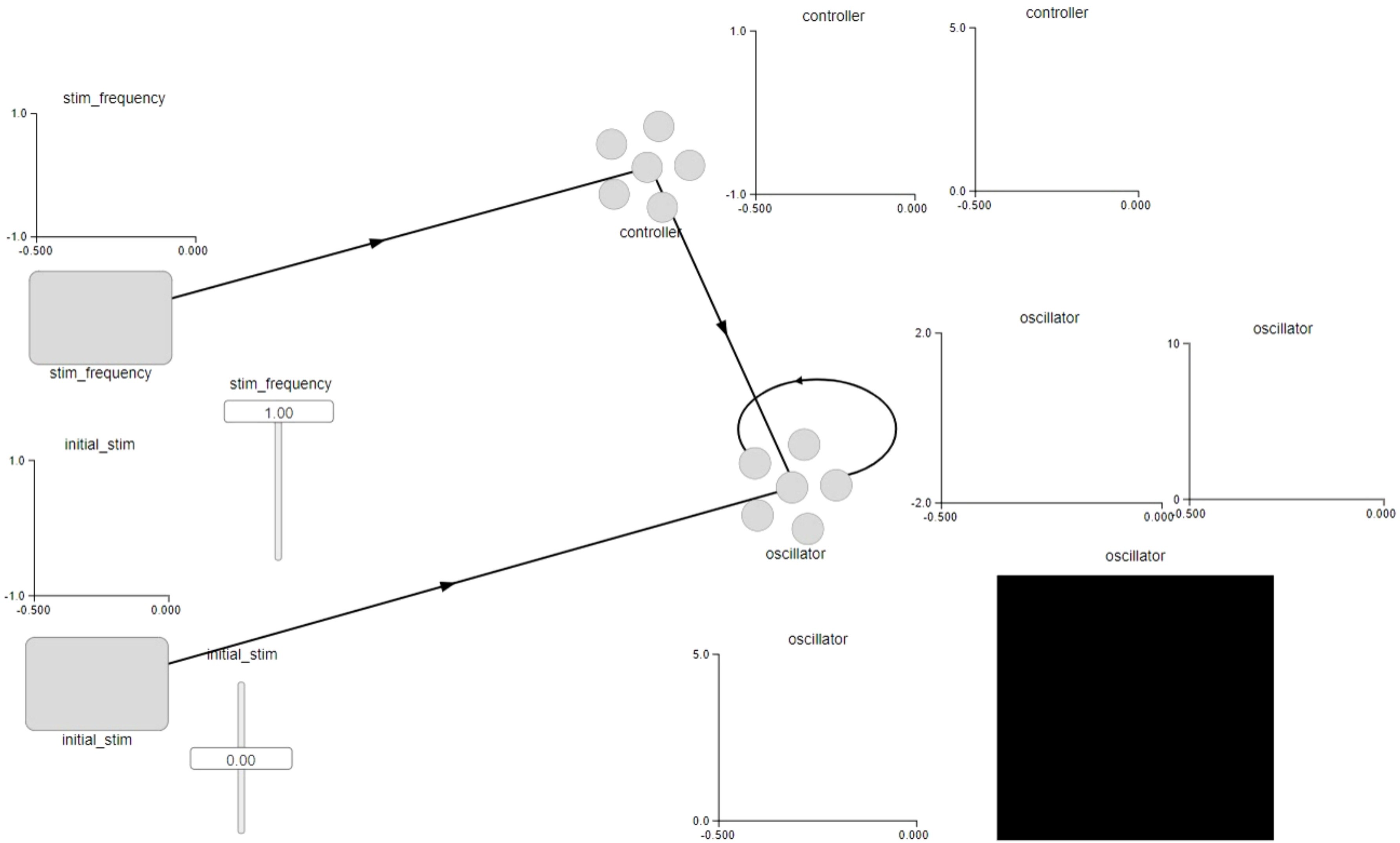
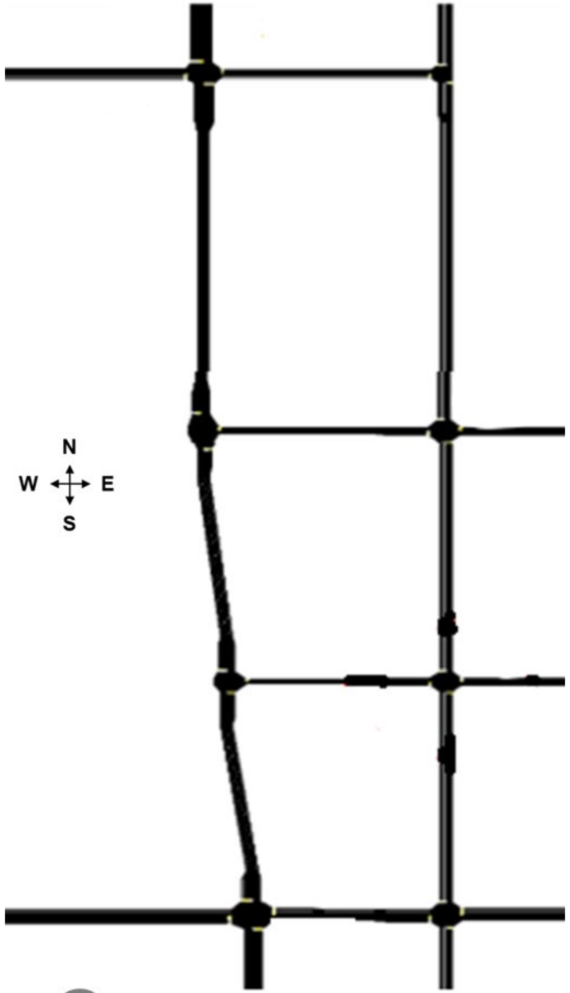


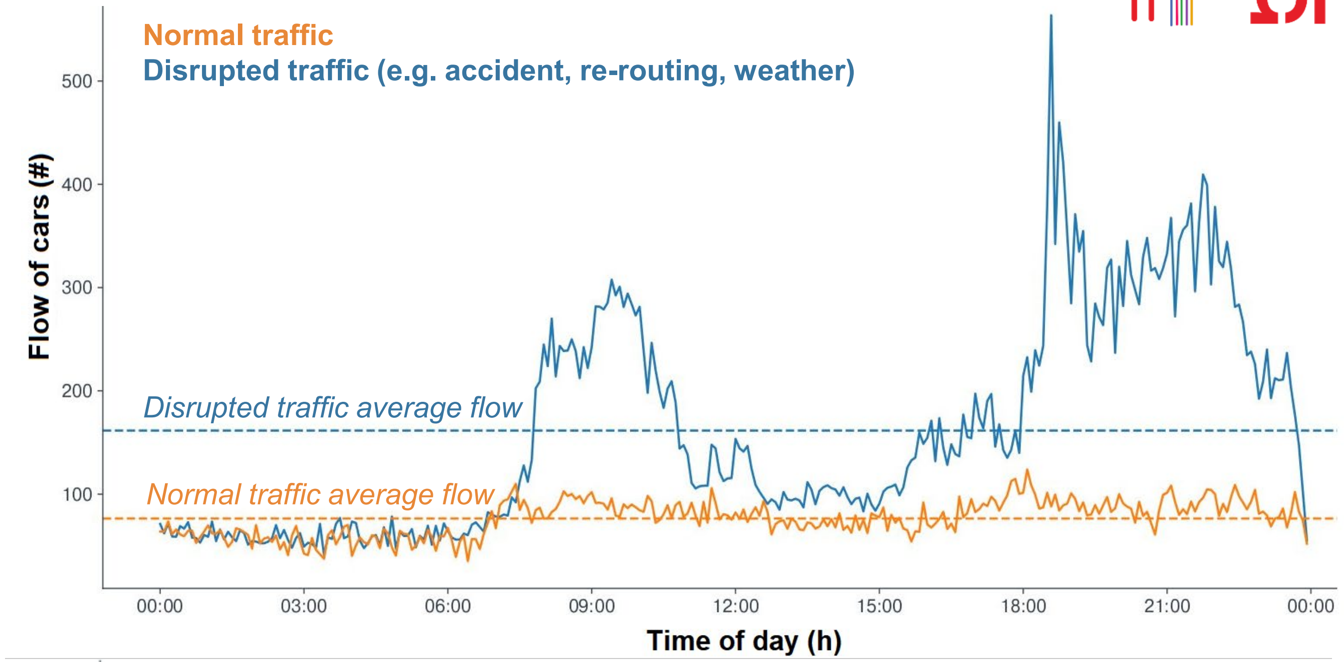


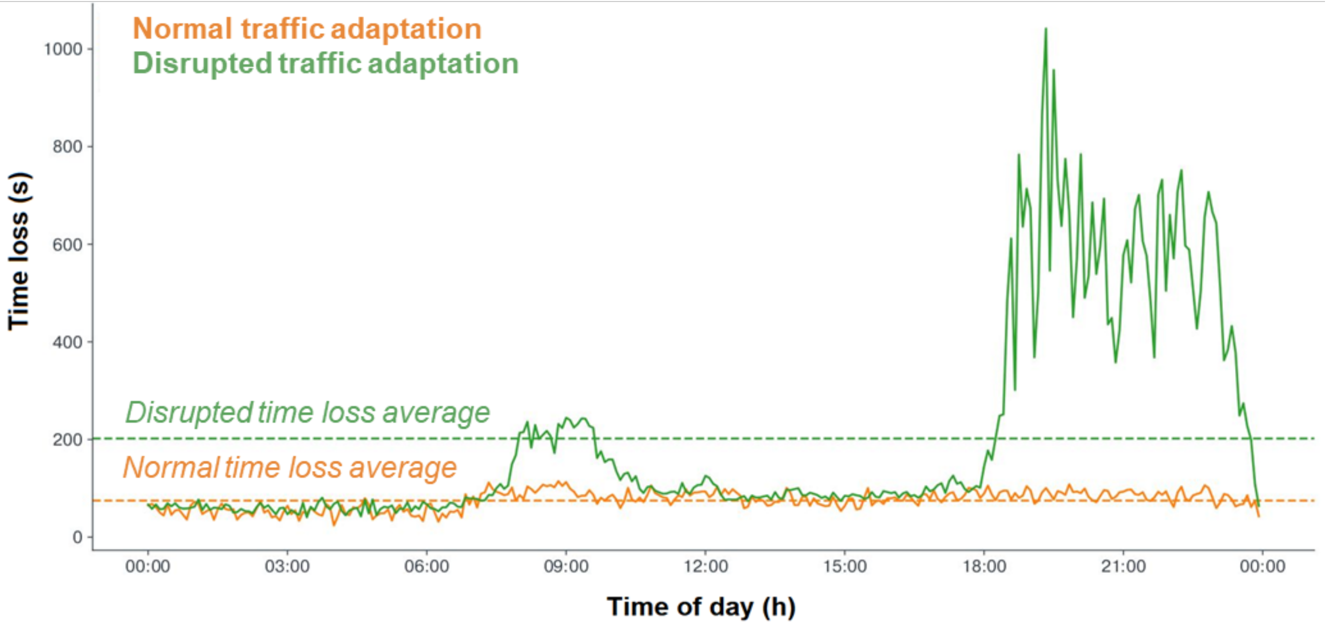


stim_frequency
1.0
-1.0
-0.500
0.000
stim_frequency
stim_frequency
1.00
initial_stim
1.0
-1.0
-0.500
0.000
initial_stim
initial_stim
0.00
controller
controller
1.0
-1.0
-0.500
0.000
controller
5.0
0.0
-0.500
0.000
oscillator
oscillator
2.0
-2.0
-0.500
0.000
oscillator
10
0
-0.500
0.000
oscillator
oscillator
5.0
0.0
-0.500
0.000

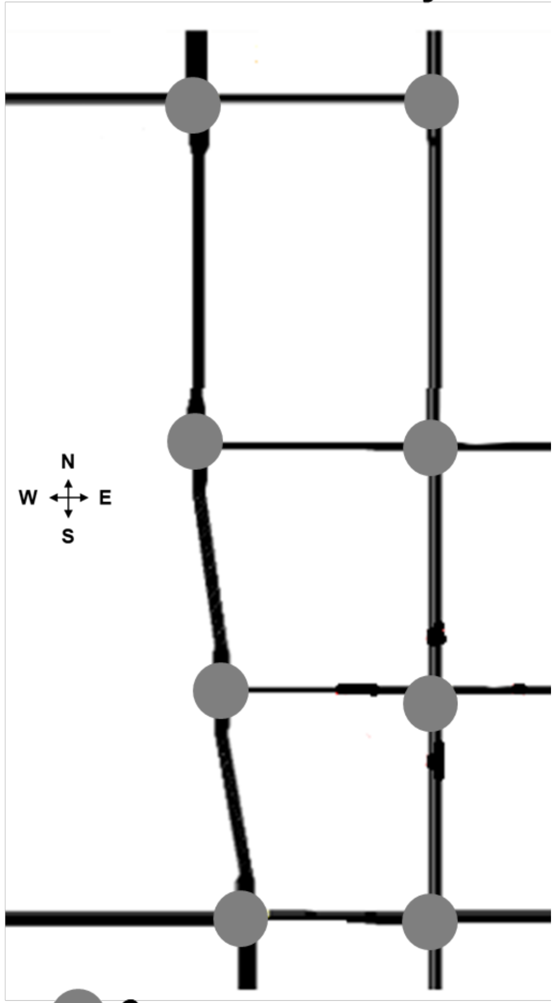


Crosses
1 oscillator per direction
5 crosses with 4 directions
3 crosses with 3 directions



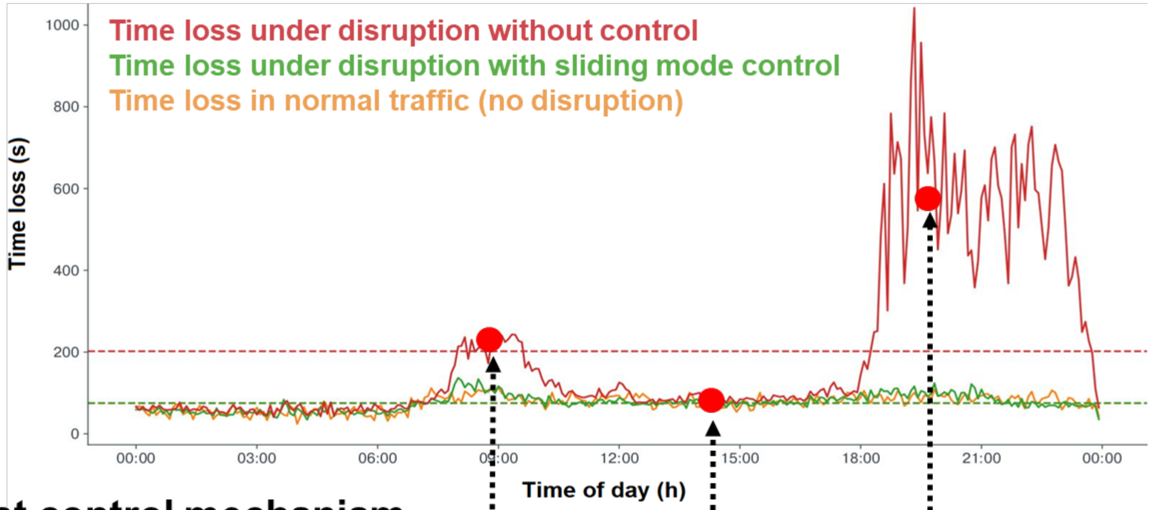


Real road network layout

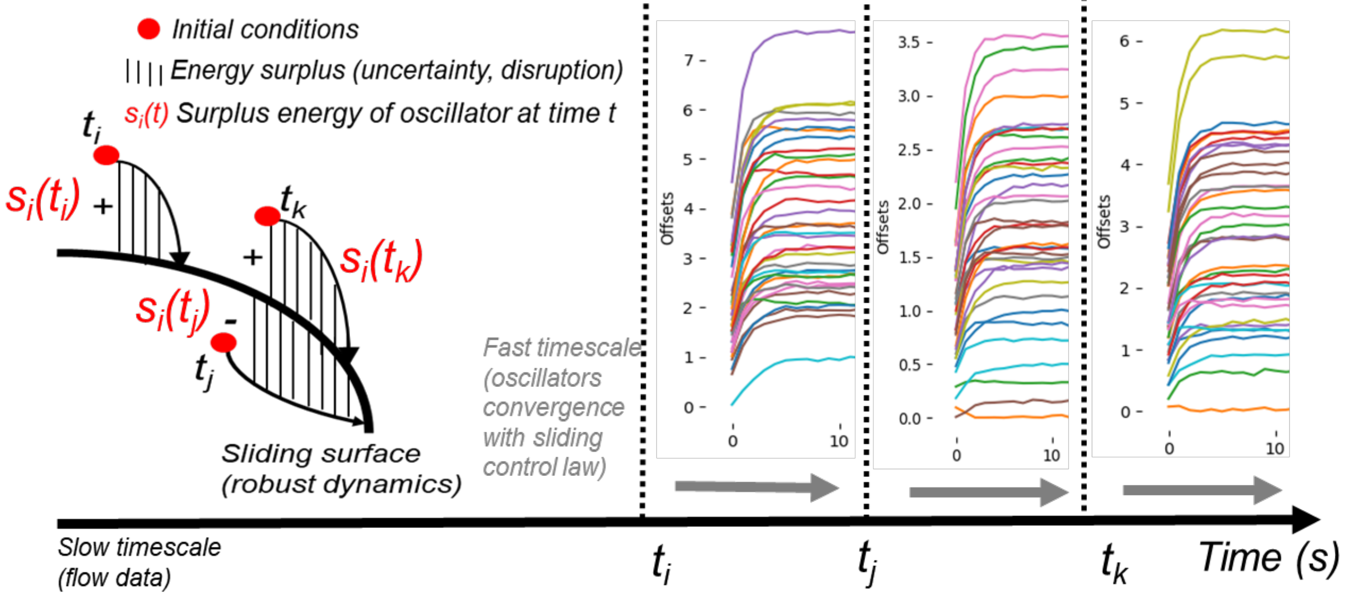


Crosses
1 oscillator per direction
5 crosses with 4 directions
3 crosses with 3 directions

Traffic profile in the road network



Robust control mechanism



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http://neuromorphics.bayern