Organic Fault-tolerant Robot Control Architecture

E. Maehle,
J. Hartmann

W. Brockmann,
N. Rosemann

K.-E. Großpietsch

ITI

University of Lübeck
Institute of Computer Engineering

UNIVERSITÄT OSNABRÜCK

Institute of Computer Science
Computer Engineering Group

AIS
Institut Autonome Intelligente Systeme

Fraunhofer Institut AIS
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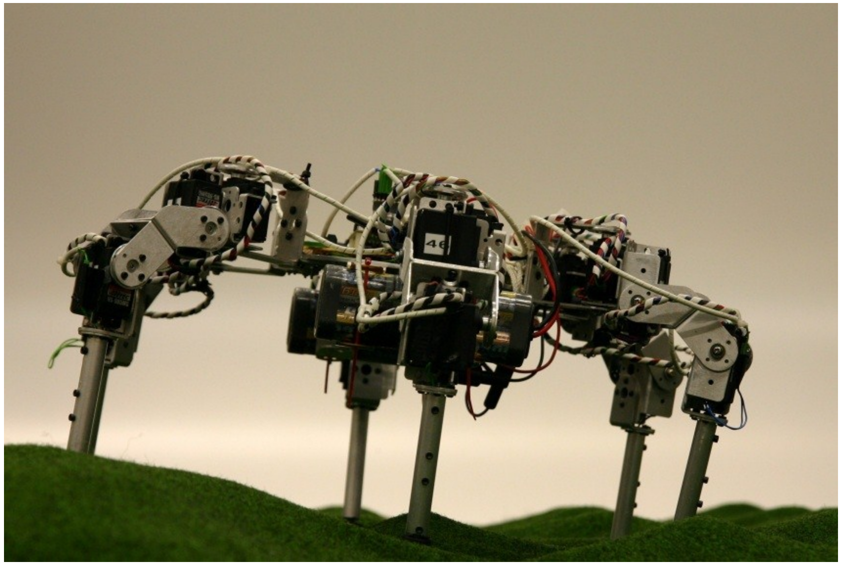
Motivation

Autonomous mobile robots in human environments

unstructured, dynamically changing environment

no explicit model of the environment

➢ fault-tolerance, safety

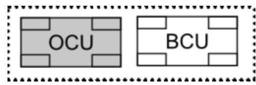


no explicit fault model

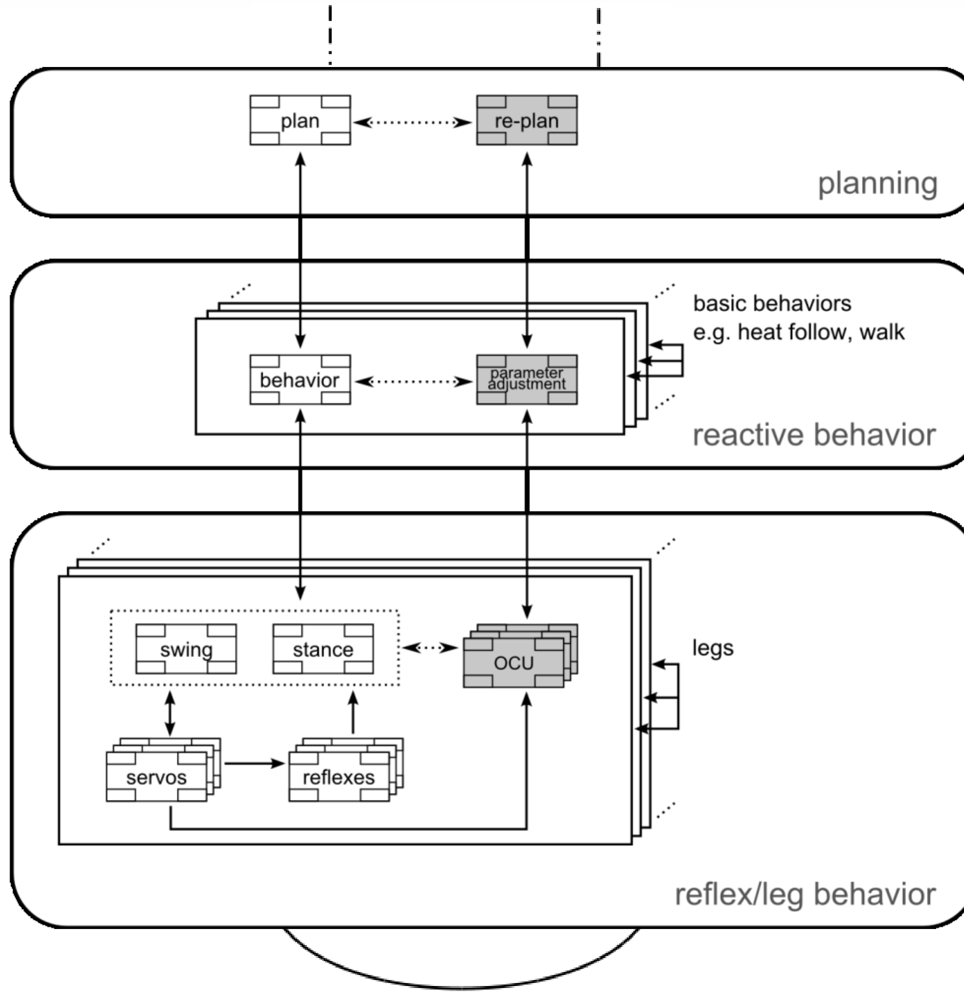
complex closed-loop dynamics

➢ engineering bottleneck

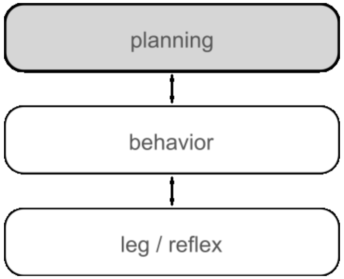
ORCA –
Organic Robot Control Architecture



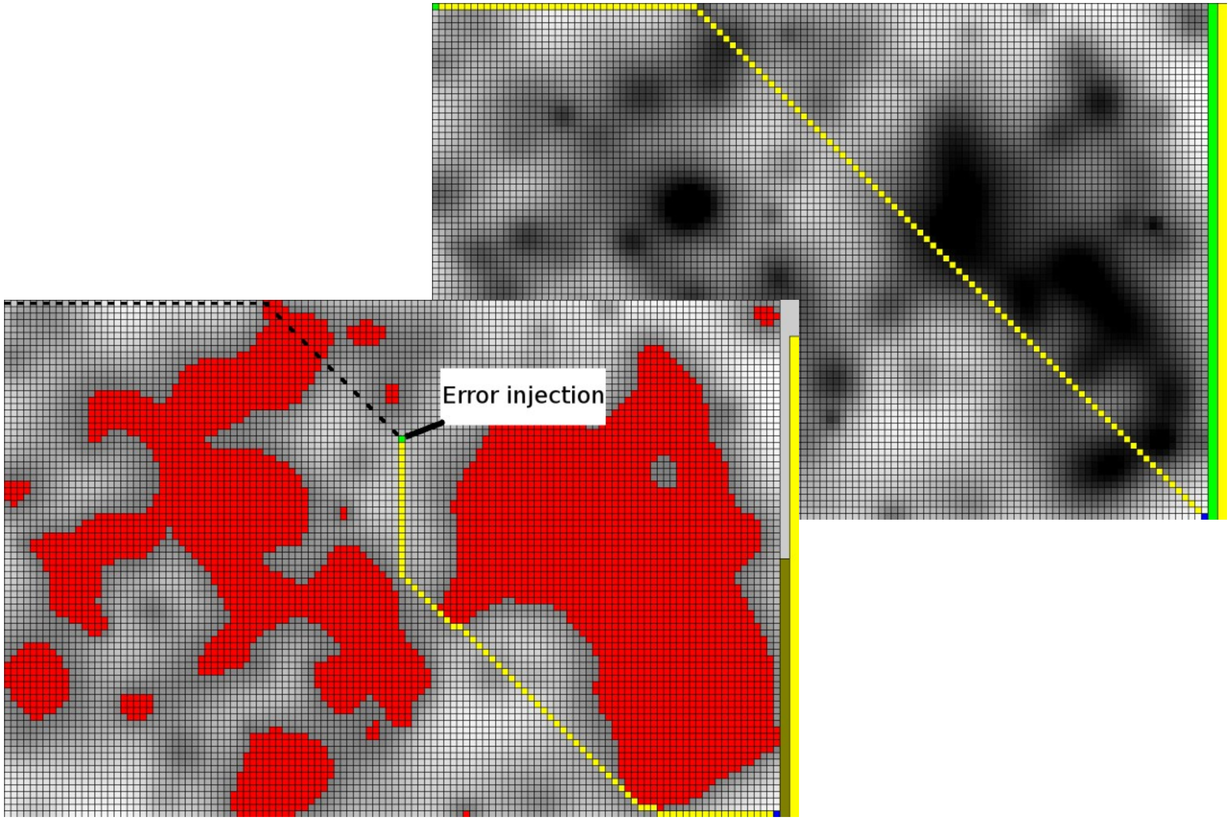
- Modular and hierarchic architecture [IWSOS2006]
- Observer / controller
- Main modules:
  - Basic Control Unit (BCU)
  - Organic Control Unit (OCU)
- Health signals to model health state of modules



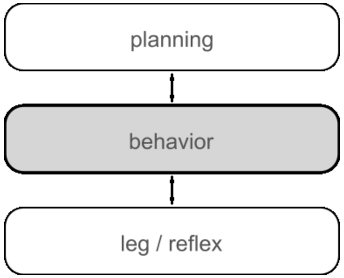
Planning Level



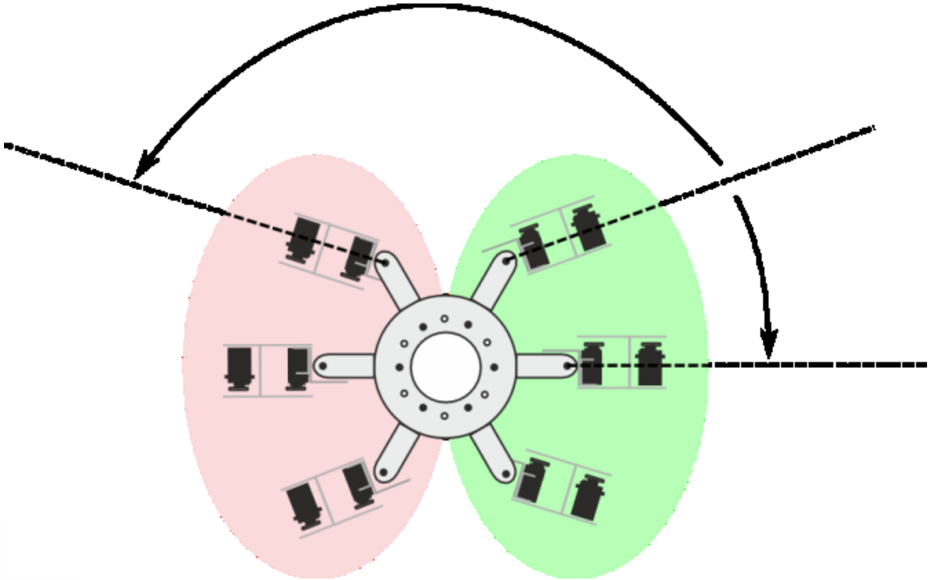
- Re-planning based on health status [ARCS2010]



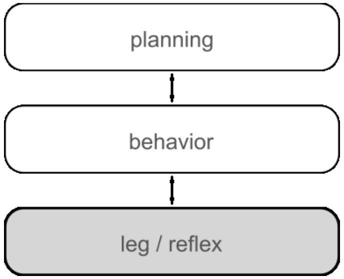
Behavior Level



- Leg amputation [SAB2006,CLAWAR2010]
  - In case of severe servo faults
  - In case of stuck legs
- Swarm Intelligence for Robot Reconfiguration (SIRR) [CWR2010]
  - Two groups of legs
  - Can handle amputation



Leg Behavior/Reflex Level

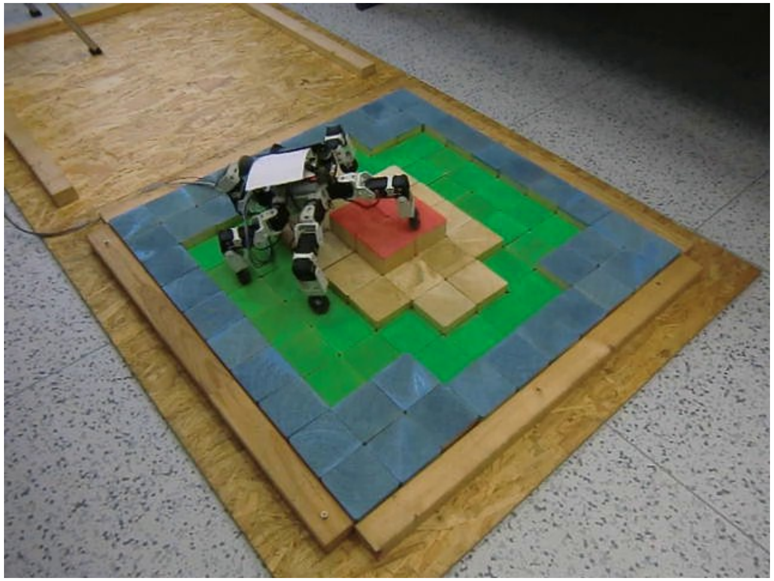


- Gait pattern generation [AMS2007,ARCS2010]
  - Swing phase: lift and move leg forward
  - Stance phase: move leg backward to move the robot
- Reflexes [Robotica2009]
  - Elevator reflex
  - Search reflex
  - Ground Contact reflex
- Fault detection
  - Based on correlation / mutual information [IARP2007]
  - Based on linear filters [IDIMT2010]

Recent Development

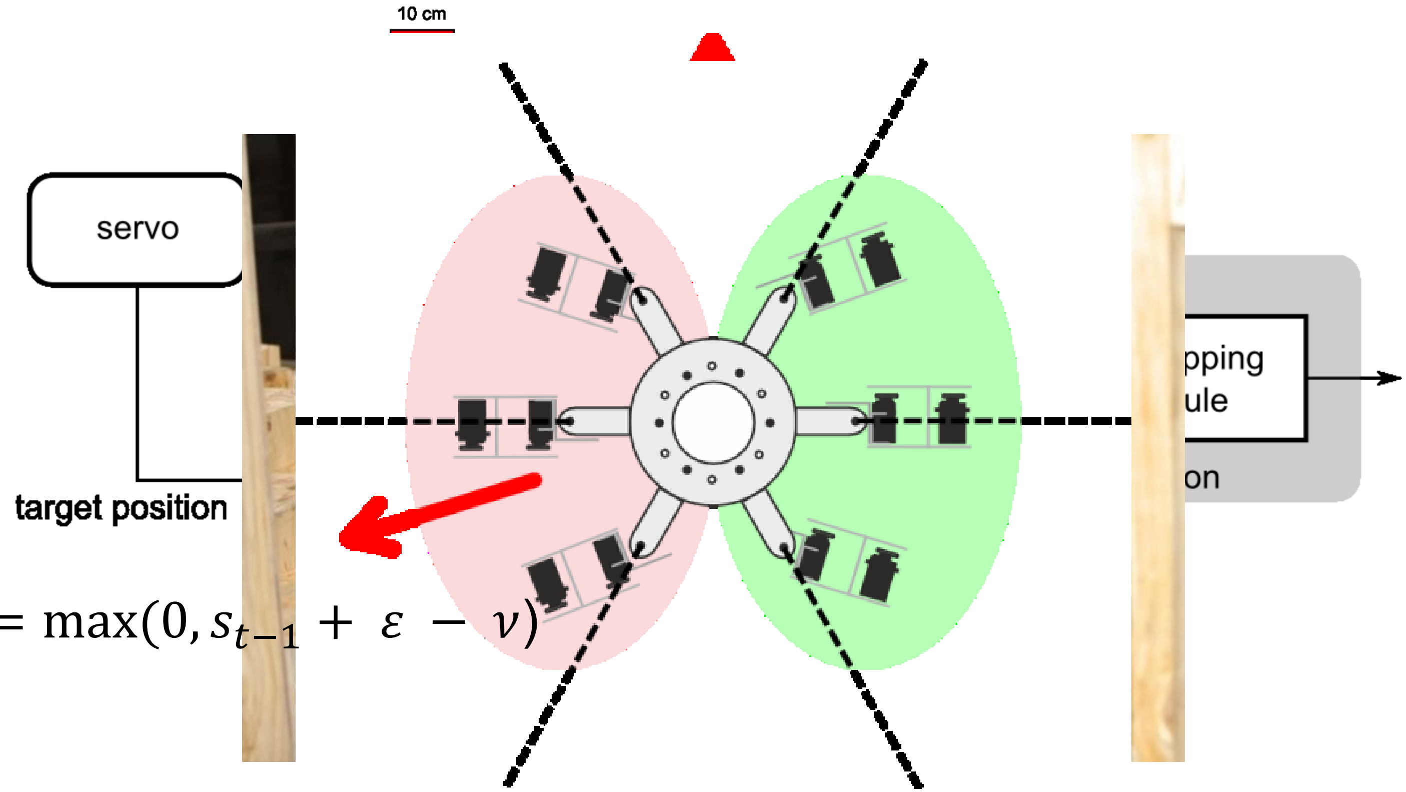
Demonstrator

- Joint implementation of
  - Planning
  - Reconfiguration
  - Gait generation
  - Reflexes
  - Fault detection
- Implemented on the Bioloid Robot Kit



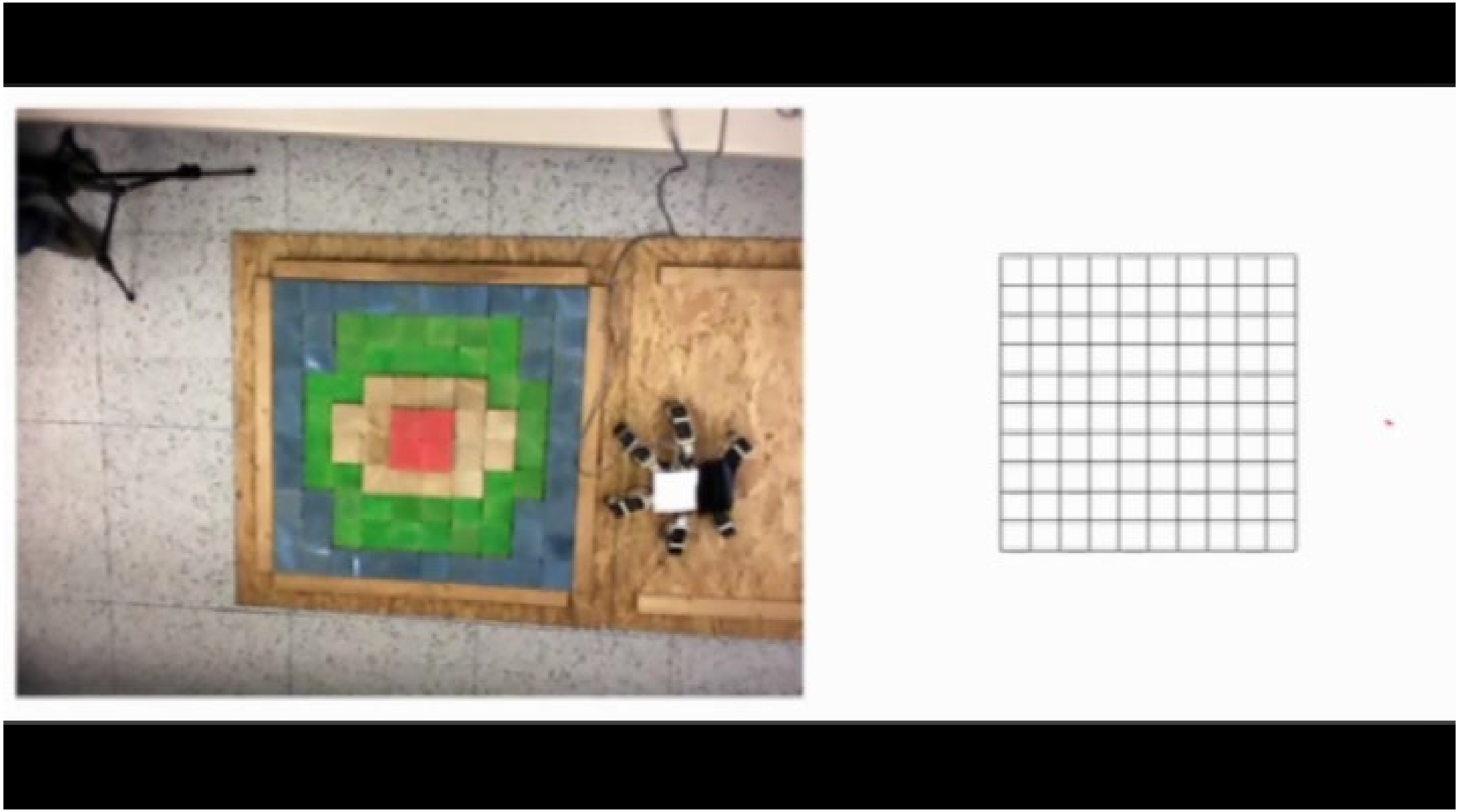
New Developments

- Test scenario RoboCup Rescue
- Omni-directional navigation
- Change detection for fault detection



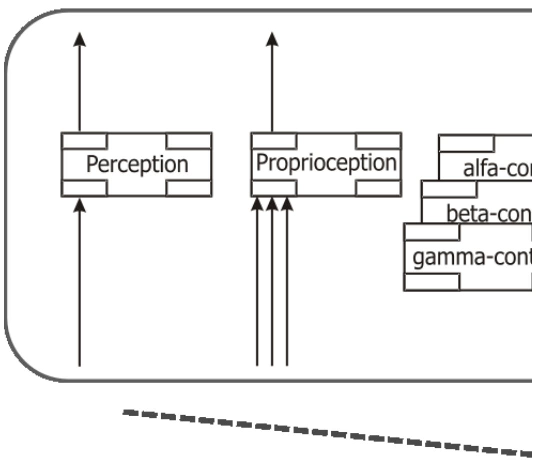
  - $s_t = \max(0, s_{t-1} + \varepsilon - \nu)$

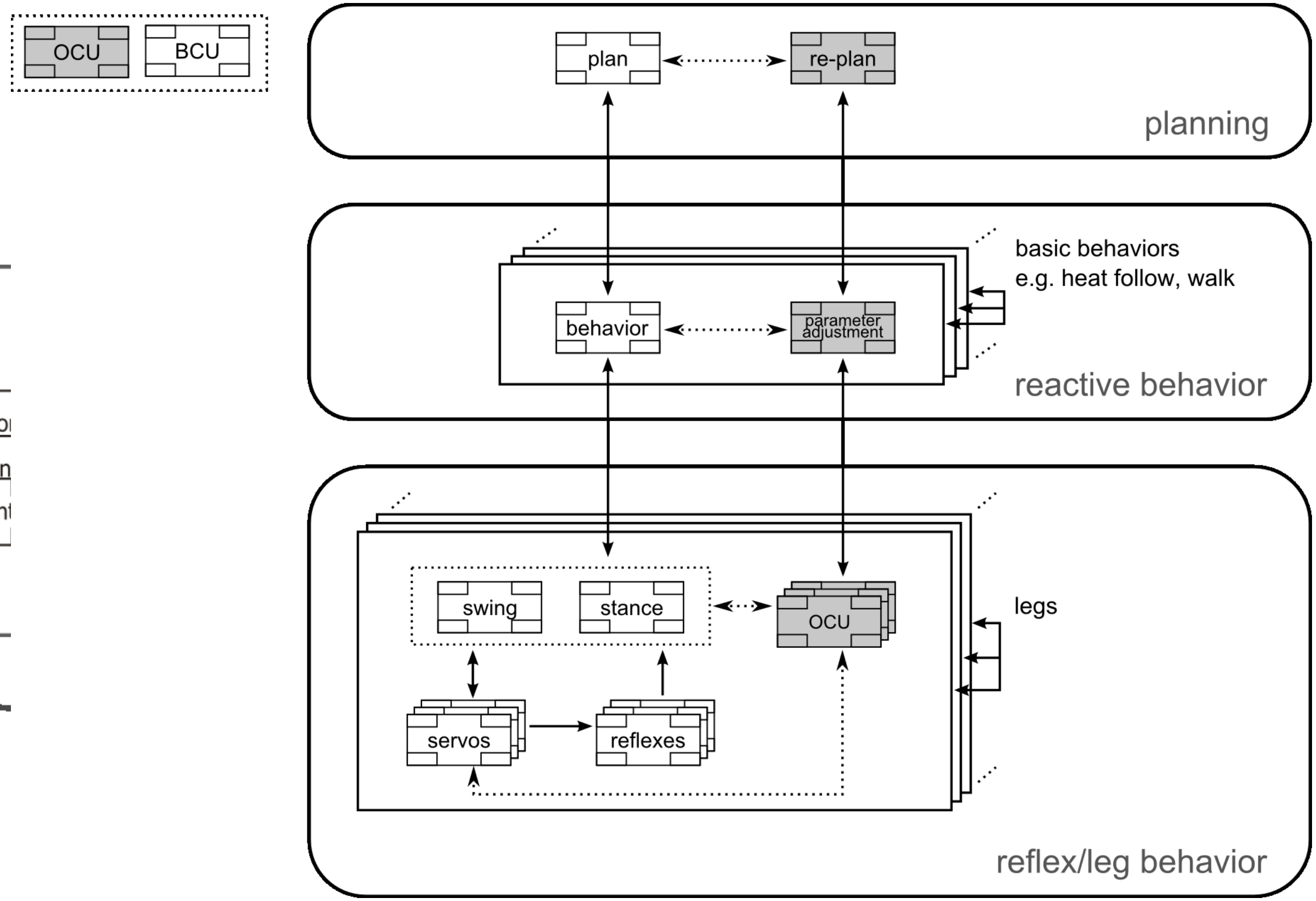
Test Scenario



Methodological Work Package

Examplary multi-level ORCA architecture

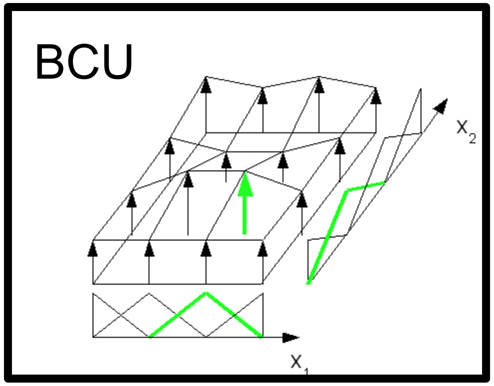




Methodological Work Package

- BCU/OCU tasks at lower level of architecture:
  - Closed-loop operation even in case of anomalies
  - Interplay with higher levels
  - → Self-optimizing, self-healing interface for higher levels
- Ease engineering:
  - Enable BCUs to self-tune at start of operation
  - Enable BCUs to self-optimize behavioral knowledge
  - Enable BCUs to self-adapt to changes

  } self-x @ anomalies



Self-*x* @ Anomalies

- Dynamic changes of system/environment/BCU behavioral knowledge

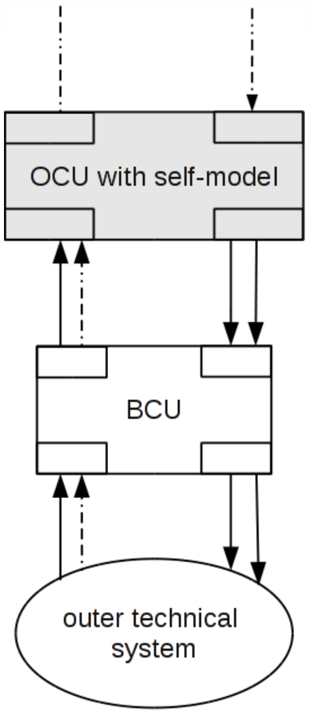
  → learn normality at run-time

- General approach: learn system dynamics at run-time, e.g.

  $$\boldsymbol{x}(t+1) = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t), \ldots) + \boldsymbol{x}(t)$$

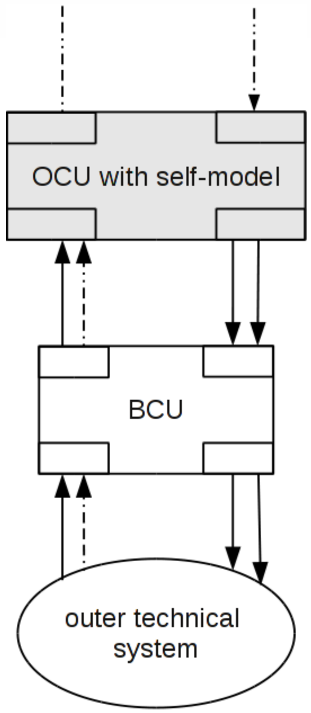
- Anomalies are deviations between prediction of self-model and measured data

  → map deviations to health signals

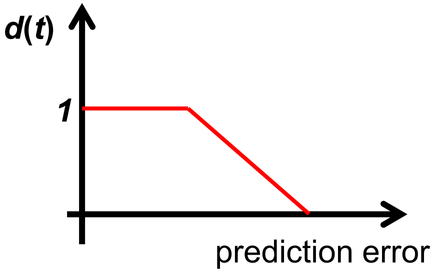


Anomaly Detection by Self-models

- Challenge: limited amount of data and only in parts of input space
  - Self-model has to distinguish *anomalous* from *unlearned* (anomaly-novelty discrimination dilemma)



- Specific approach within ORCA: enhance function approximator by degree-of-certainty estimator ***c*(*t*)** [SSCI2011]
  - Map difference between prediction and measurement to ***d*(*t*)**
  - Health signal: ***h*(*t*) = 1.0 - *c*(*t*) (1.0 - *d*(*t*))**



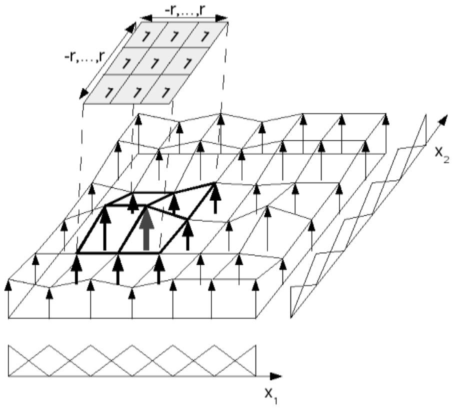
Reaction to Anomalies

- Protect behavioral BCU knowledge:
  - Reduce learning rate proportional to ***h*(*t*)**
  - Use ***h*(*t*)** as additional input variable
  - Increase adjustment rate of **SILKE approach**
  - Change OCU law of adaptation [KI2009]
  - Decay learning rate after switching between alternate BCUs [CI2008]
  - Blend between a safe fallback BCU and a self-optimizing BCU based on HS [SSCI2011]

Video

→ Recent developments

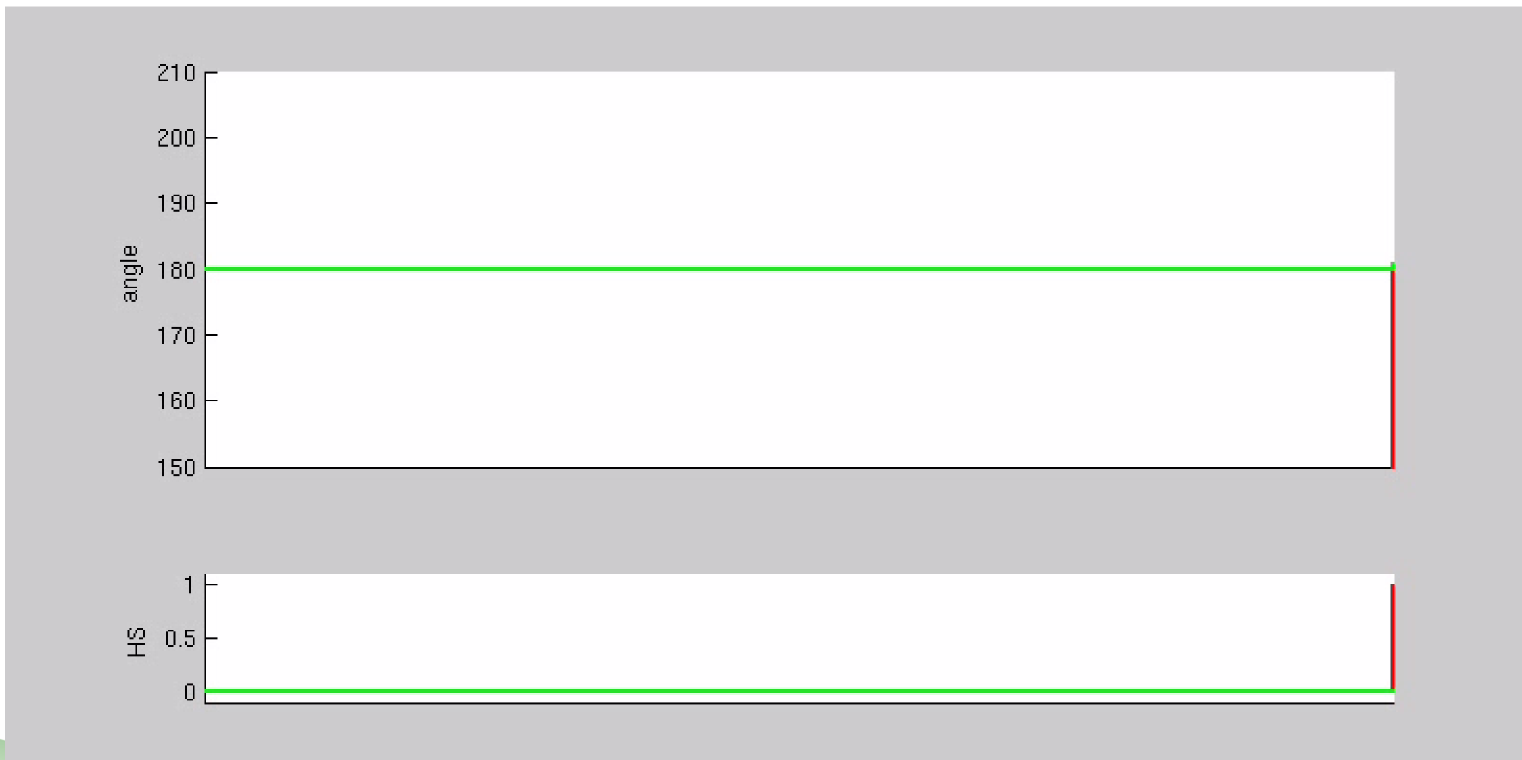
- Prevent windup of learning
- Allow careful adaption for recurring anomalies
- Guide learning to avoid negative impact on system dynamics



Example: self-opt. BCU of robot leg

goal angle

actual angle



goal angle

actual angle

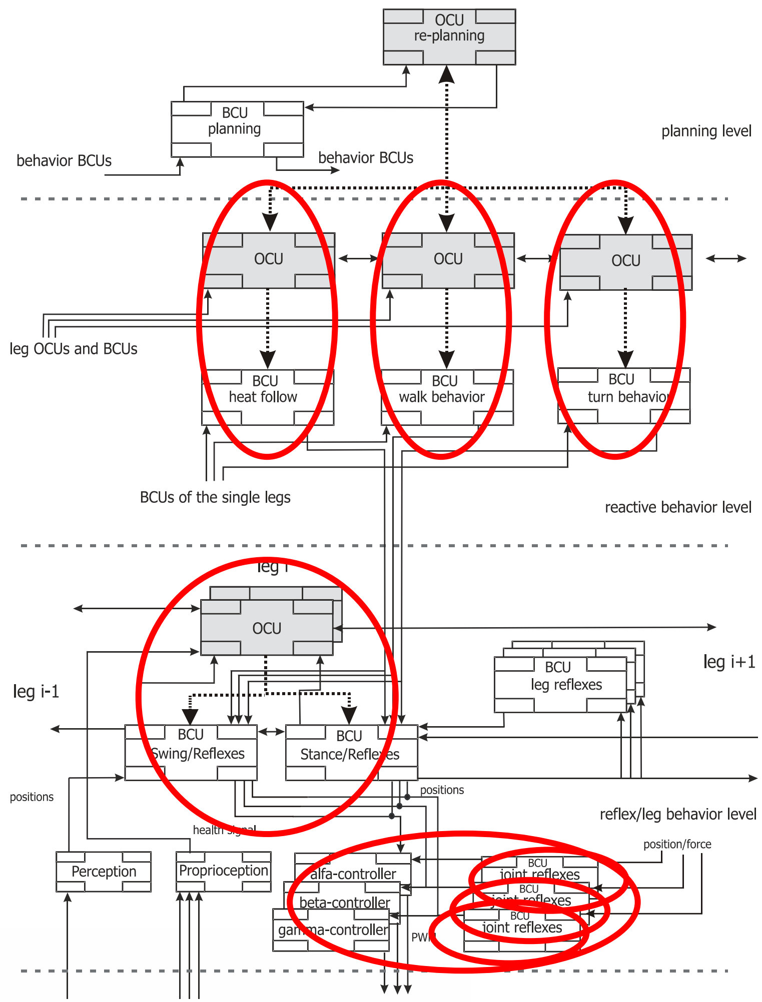
self-model

health signal

model certainty

Interacting Self-optimizing Systems

- General case: multiple, interacting self-optimizing BCU/OCUs



planning level

behavior level

reflex/leg behavior level

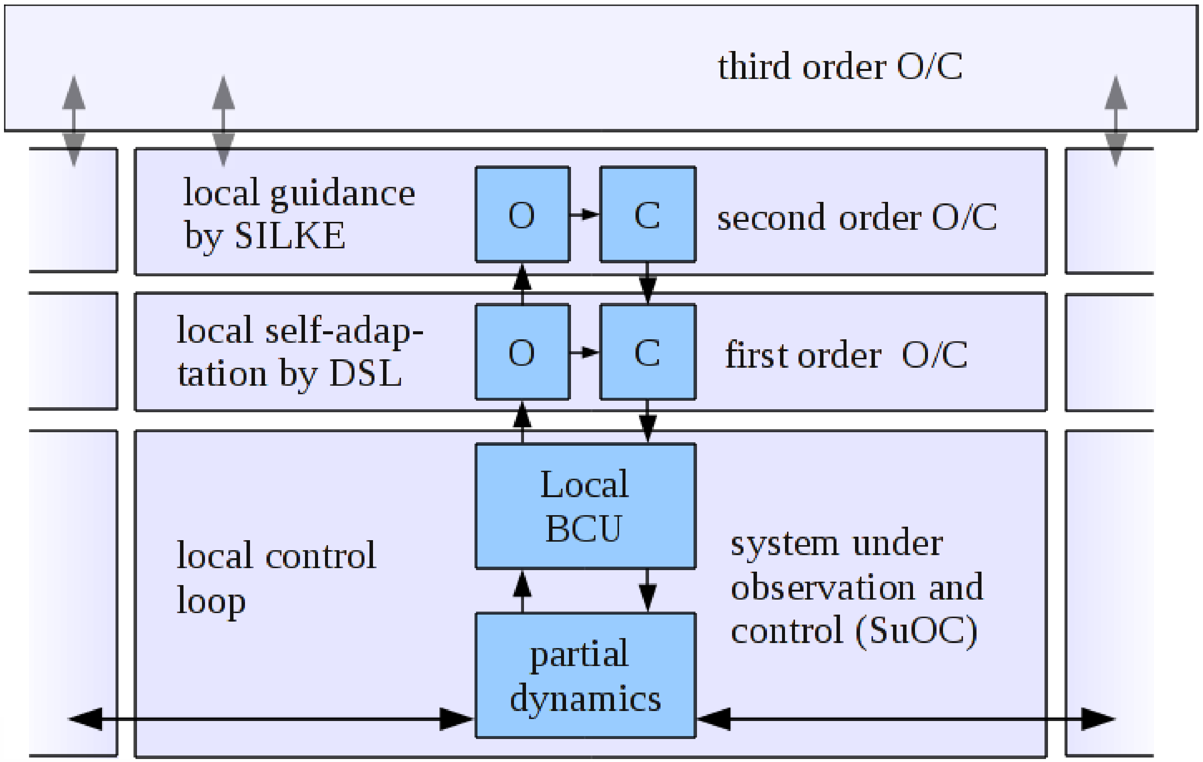
Interacting Self-optimizing Systems

- General case: multiple, interacting self-optimizing BCU/OCUs
- Theory: global view of system needed for each BCU → intractable
- Instead:
  - Only local point of view (appropriately reduced set of input variables)
  - Continuous and rapid self-adaptation of BCU knowledge
- But:
  - Indirect interactions of learning dynamics via physical coupling

    → Unintended interactions can become systematic

Interacting Self-optimizing Systems

- Approach:
  - Local/decentral guidance of self-optimization by SILKE approach [SASO2011]
  - Controlled self-optimization



Controlled Self-opt.: Formalization

Motivation: design guidelines and guarantees

Approach: formalization of the SILKE approach as matrix operation on lattice-based function approximators
[CI2007,Informatik2008,IFSA-EUSFLAT2008,WCCI2010]

Formal statements on contraction properties

- Convergence analysis for TS0 and TS1 systems
- Eigenvector and –value analysis
- Construction rules for SILKE templates

Formal criteria for compatibility of multiple, regional SILKE templates

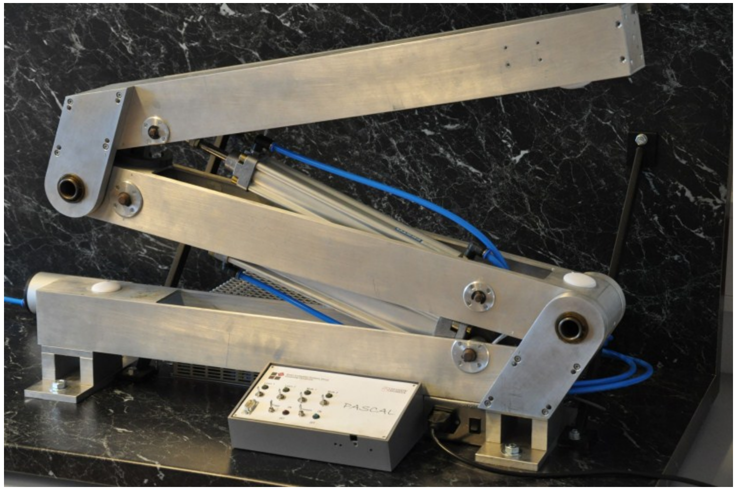
- Expression of locally different meta-level properties

Stability analysis

- Laplace transformation
- Lyapunov theory (ongoing)
- Prediction of fixed points

General Applicability

- Industry-like application:
  pneumatically actuated robotic arm
  - Non-linearity, time-variance
    - → Formal model very hard to obtain
    - → Online learning necessary
  - Complex closed-loop dynamics
    - → Interacting self-optimizing systems
    - → Controlled self-optimization
  - Safety critical
    - → No trial and error learning
    - → Controlled self-optimization
  - Hard real time (1 ms)
    - → Methods have to be very fast
    - → Methods need deterministic run-time



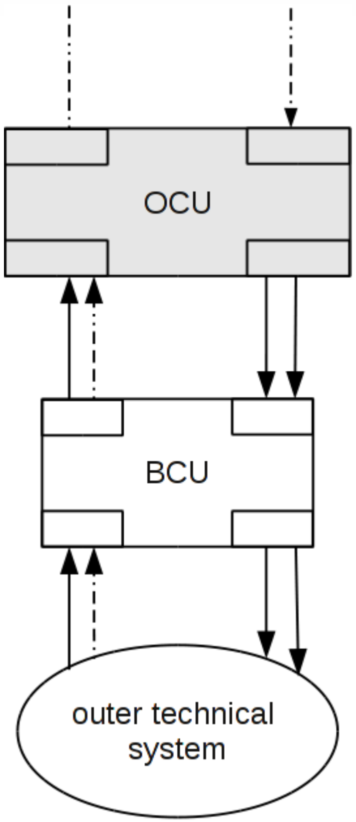
→ Generalizable self-*x* methods

Conclusion

→ Methods to tackle general OC challenges:

– Anomalies, safety and trustworthiness of self-*x*

– Systematic interactions between multiple self-*x* systems



→ ORCA architecture and controlled self-optimization

- For unstructured environments
- Without explicit models (of system and/or faults)
- For closed- and open-loop operation in complex dynamic systems (e.g. OSCAR)

→ Self-*x* properties transferable to more general applications

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Certainty Estimation

Legend:

new trust estimation θ_{new}, old trust estimation θ_{old}, learning rate λ, adaptation of current rule $|\Delta p|$, sensitivities δ_t, δ_s, rule activation $\mu(\vec{x})$

1. Certainty estimation for each rule involved into last learning step:

$$\theta_{\text{est}} = \begin{cases} 1 & \text{for } |\Delta p| < \delta_t \\ \frac{\delta_t + \delta_s - |\Delta p|}{\delta_s} & \text{for } \delta_t < |\Delta p| < \delta_t + \delta_s \\ 0 & \text{else} \end{cases}$$

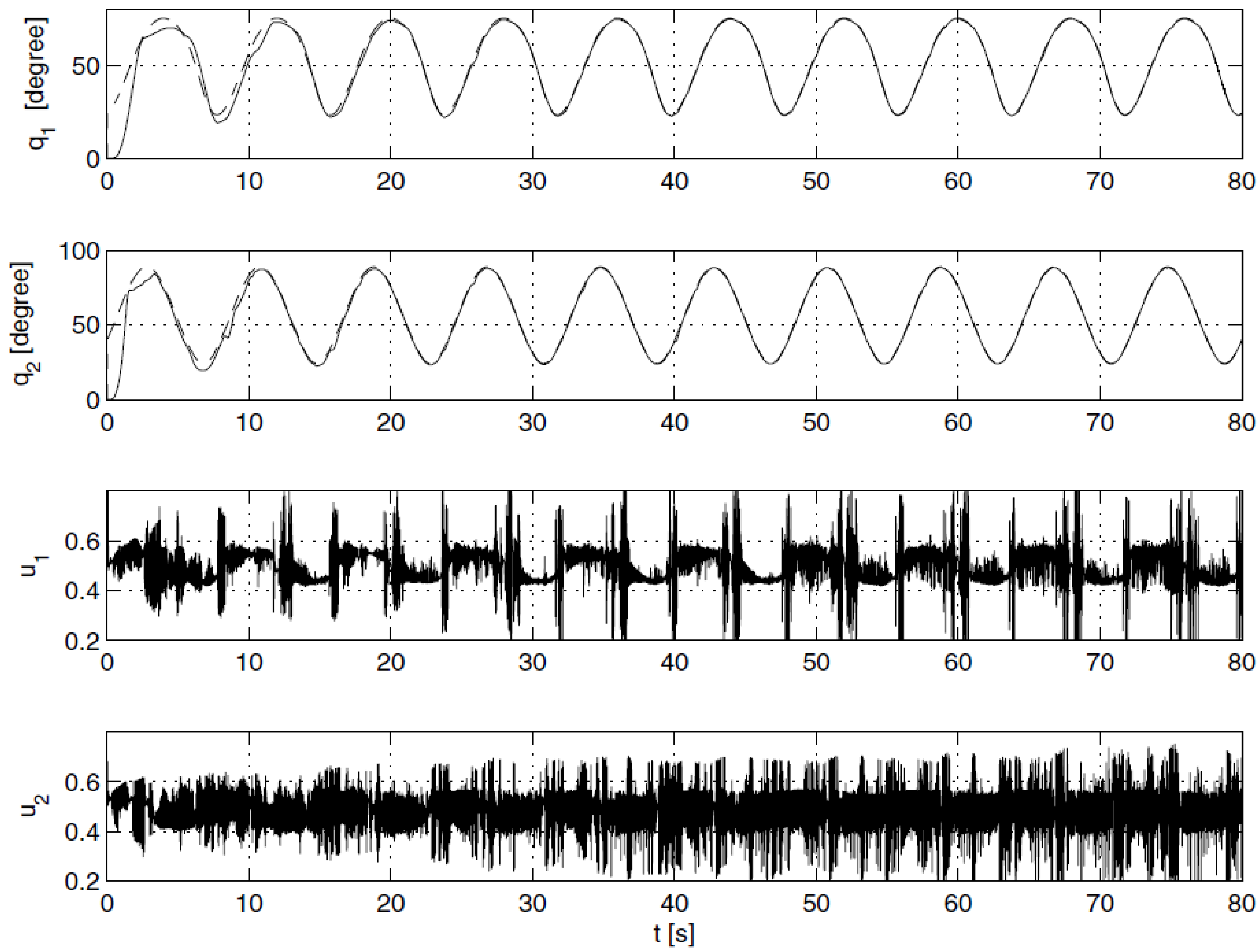
2. Consideration of rule activation

$$\theta_{\text{act}} = \theta_{\text{est}} \cdot (\mu(\vec{x}) + (1 - \mu(\vec{x})) \cdot \theta_{\text{old}})$$

3. Consideration of learning rate

$$\theta_{\text{new}} = \lambda \cdot \theta_{\text{act}} + (1 - \lambda) \cdot \theta_{\text{old}}$$

Results of Pneumatic Robotic Arm



Results of Pneumatic Robotic Arm