# Challenges in Network Dynamics:

## Collective Nonlinear Dynamics for Autonomous Systems

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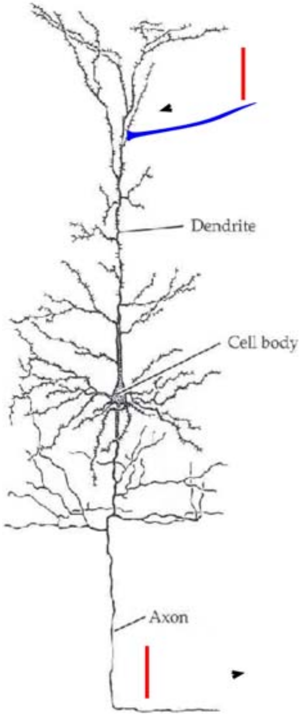
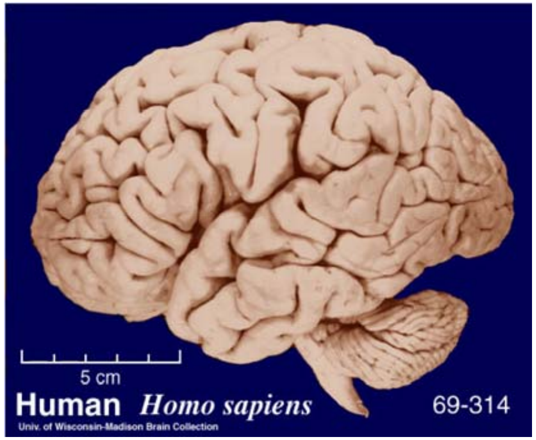
# Spatio-Temporal Coordination in Networks of Biology and Physics





## Biological Networks

$(10^{-3} - 10^{10} s;\ 10^{-5} - 10^{-1} m)$

- Neurons (sensory-/motor processing, memory formation…)
- „Tree“ of life
- Epidemic spreading …

## Networks of physical & artificial units

$(10^{-2} - 10^{10} s;\ \ 10^{-9} - 10^{6} m)$

- Complex disordered media in physics
- Electric power grids (mind the renewables!)
- Autonomously behaving robots

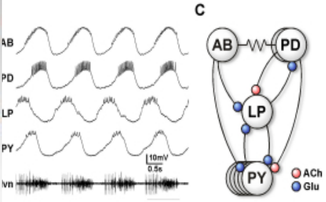
# Towards neuro-inspired autonomous systems

- Biomechanics

- Reflexes (local motor response to a local sensation)

- **Distributed neural (motor) control**

Central Pattern Generator (CPG)



**→ requires understanding**
**of collective nonlinear dynamics & self-organization**

# Adaptation and Learning

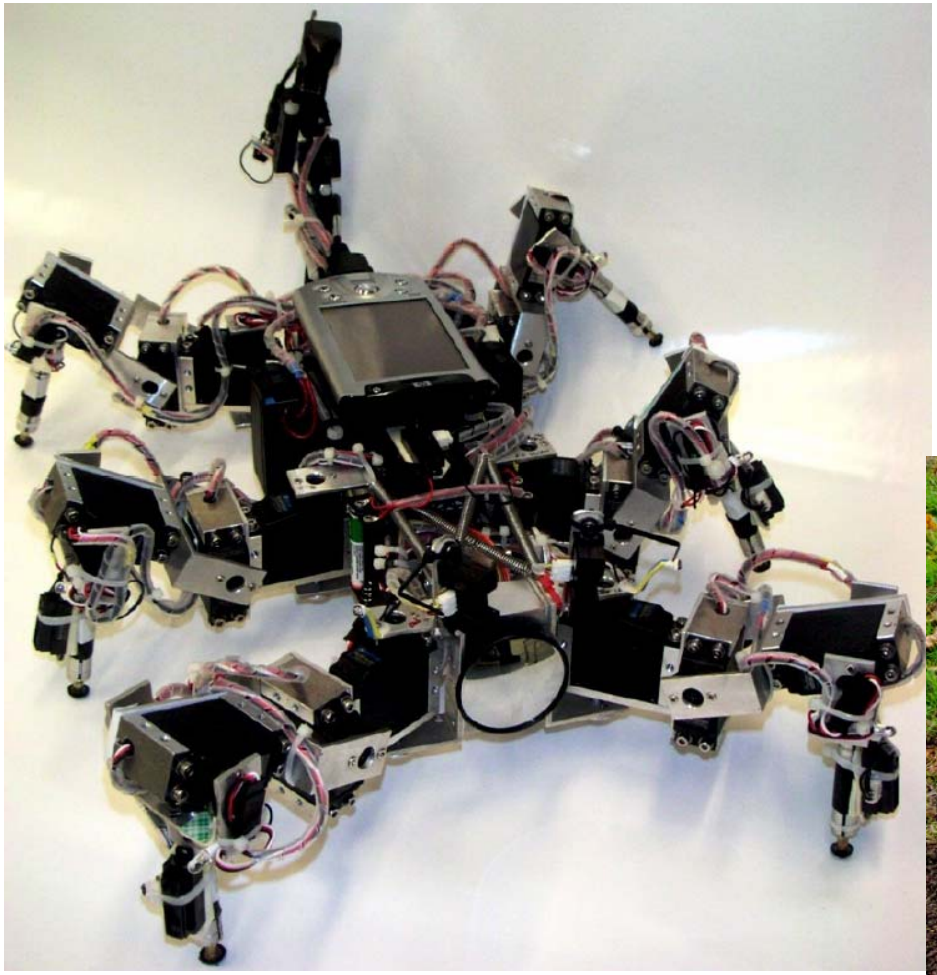
The two core processes supporting autonomy

1) **Adaptivity** (short-term and reversible)

2) **Learning** (long-term, sustained changes)

- are **nonlinear**
- induce **self-organized, emerging** collective states
- may be realized in a **neuro-analogous** way
  (bio-inspired development & possible explanation of biol. phenomena)

# Biomechanics of a versatile robot



**The walking machine AMOS-WD06**

Manoonpong et al RAS 2008

# Neural Control: standard approach vs. **adaptive chaos control**

Standard approach:
Neural implem. with several central pattern generators (CPGs)
**one periodic output for one specific gait** (periodic walking pattern)

- CPG1 → gait 1 (e.g. slow wave gait)
- CPG2 → gait 2 (e.g. fast wave gait)
- …
- CPGn → gait n (e.g. tetrapod gait)

**Problem:**
**Coordination & learning hard → number of different gaits restricted**

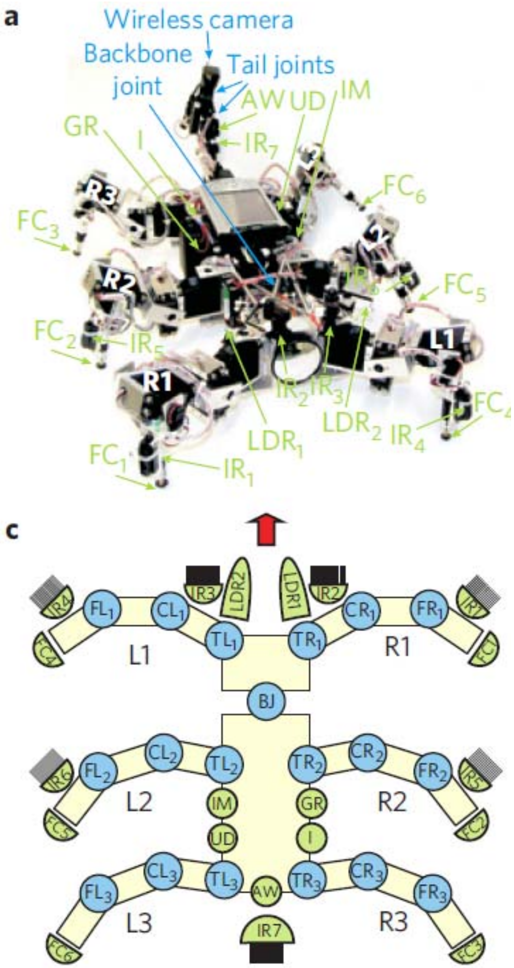
Nonlinear Dynamics Solution:
Adaptive neural chaos control:
**One chaotic CPG that is controlled to any selected period**

- single CPG → all desired gaits

**Coordination & learning simple, many gaits, contructive use of chaos**

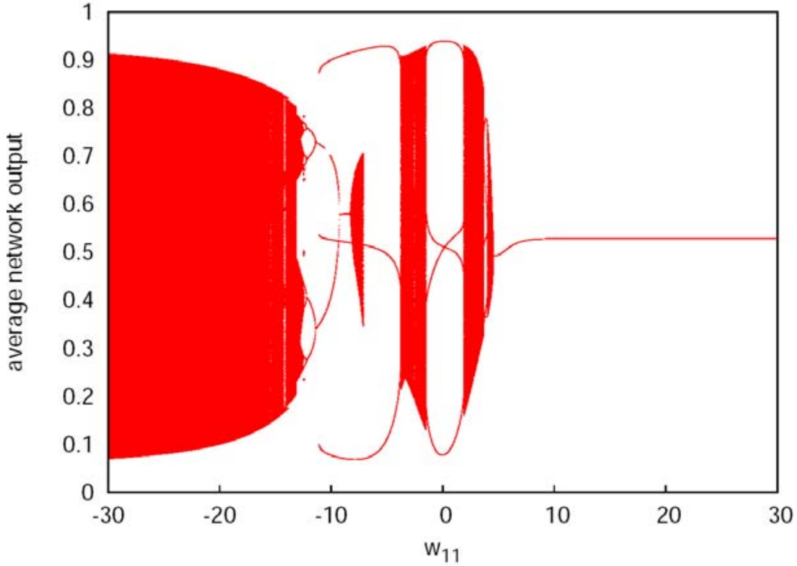
# From Dynamical Systems Theory to Versatile Autonomous Robots

How to coordinate **many** sensors with **many** motors in an **autonomous** way?

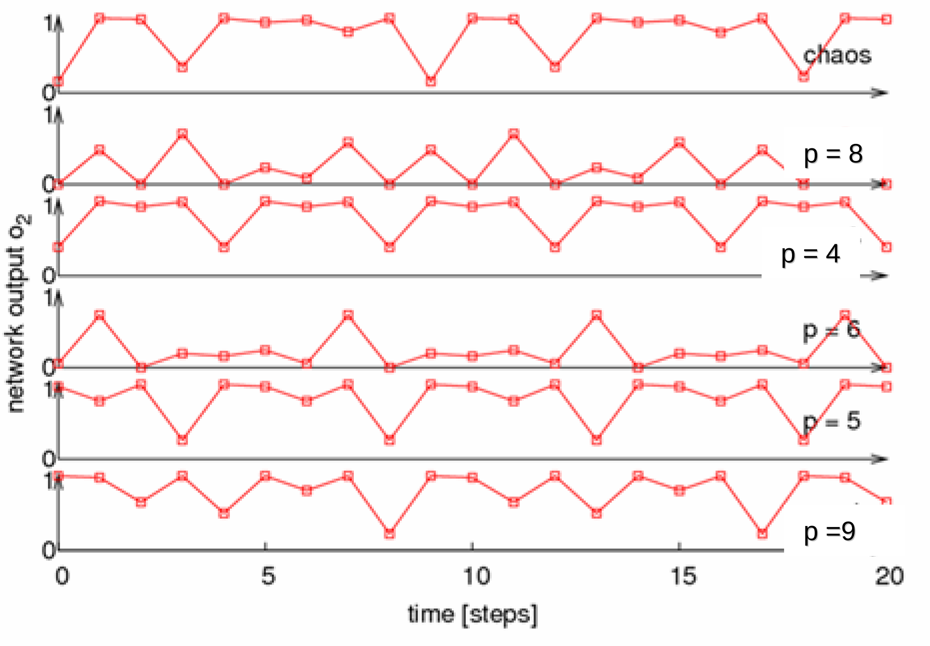


# Chaos embeds periodicity

**Robust Chaos**
**(wide of circuit parameters)**

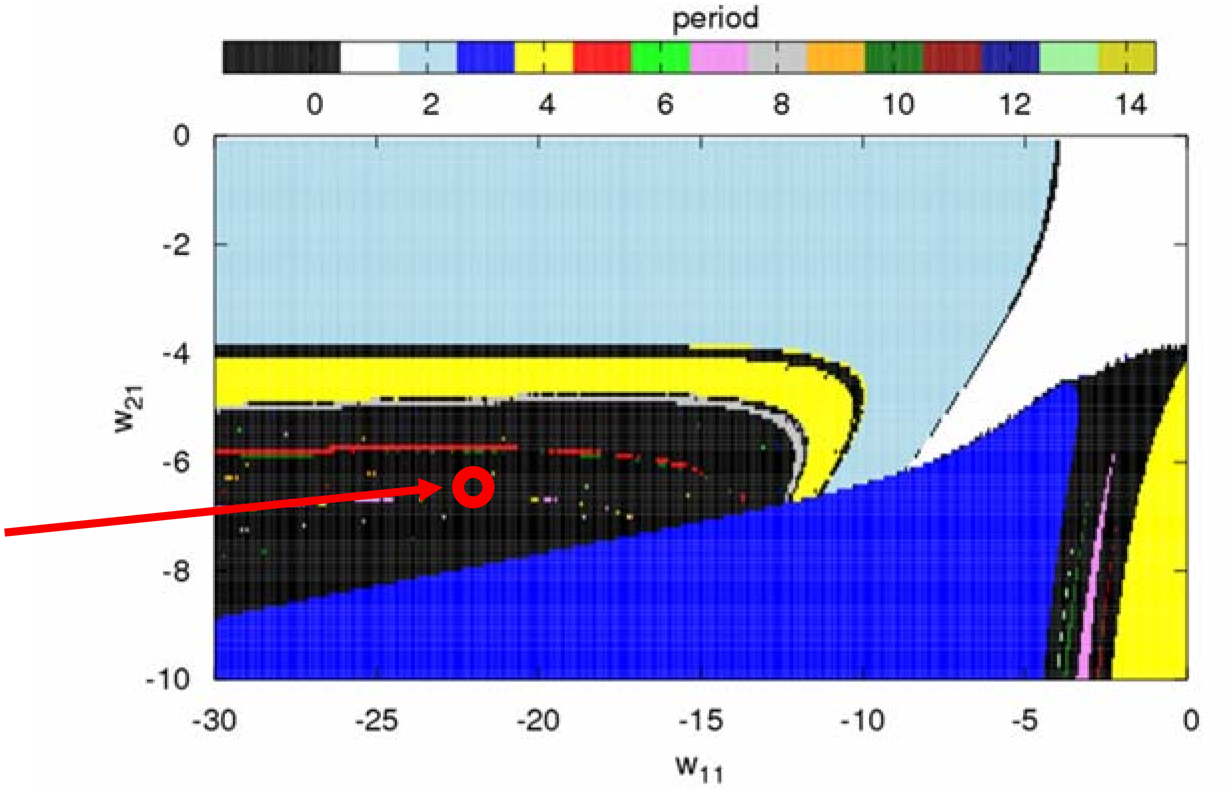


***Goal here: Sensor driven period selection***
**(at fixed parameters)**



Chaos embeds infinitely many unstable periodic orbits (UPOs)

# Chaos is robust w.r.t. parameter changes



**Robust Chaos**
**(wide range of all circuit parameters)**

# Advanced Nonlinear Dynamics→ Progress for Autonomous Systems

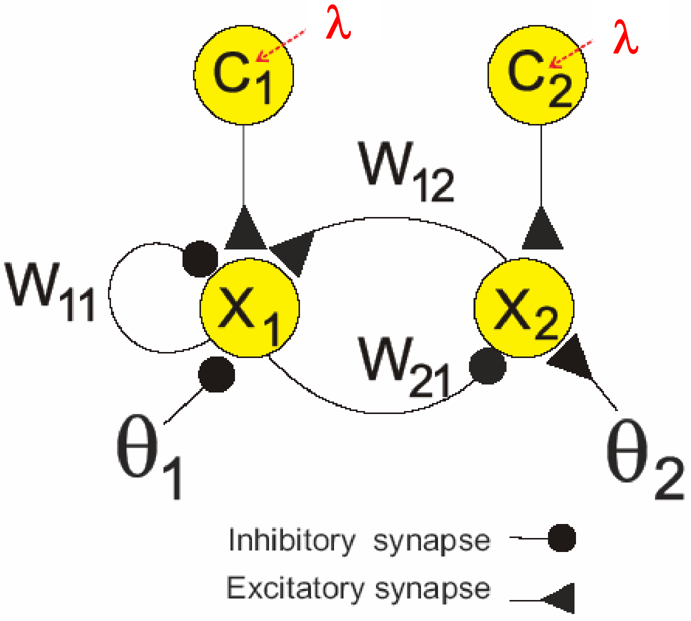
$$x_i(t+1) = \sigma\left(\theta_i + \sum_{j=1}^{2} w_{ij}x_j(t) + c_i^{(p)}(t)\right) \text{ for } i \in \{1,2\}$$

$$\sigma(x) = (1+\exp(-x))^{-1}$$

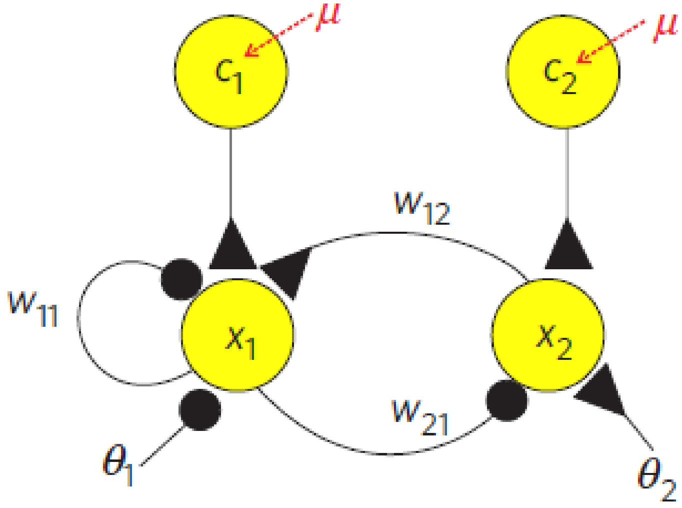
$$w_{11} = -22.0,\ w_{12} = 5.9,$$

$$w_{21} = -6.6,\ w_{22} = 0,$$

$$\theta_1 = -3.4,\ \theta_2 = 3.8,$$



# Adaptive, Neuronal Chaos Control



**Chaotic** dynamics controlled to be periodic

$$x_i(t+1) = \sigma\left(\theta_i + \sum_{j=1}^{2} w_{ij} x_j(t) + c_i^{(p)}(t)\right)$$

Standard time-delayed feedback

$$\Delta_j(t) = x_j(t) - x_j(t-p)$$

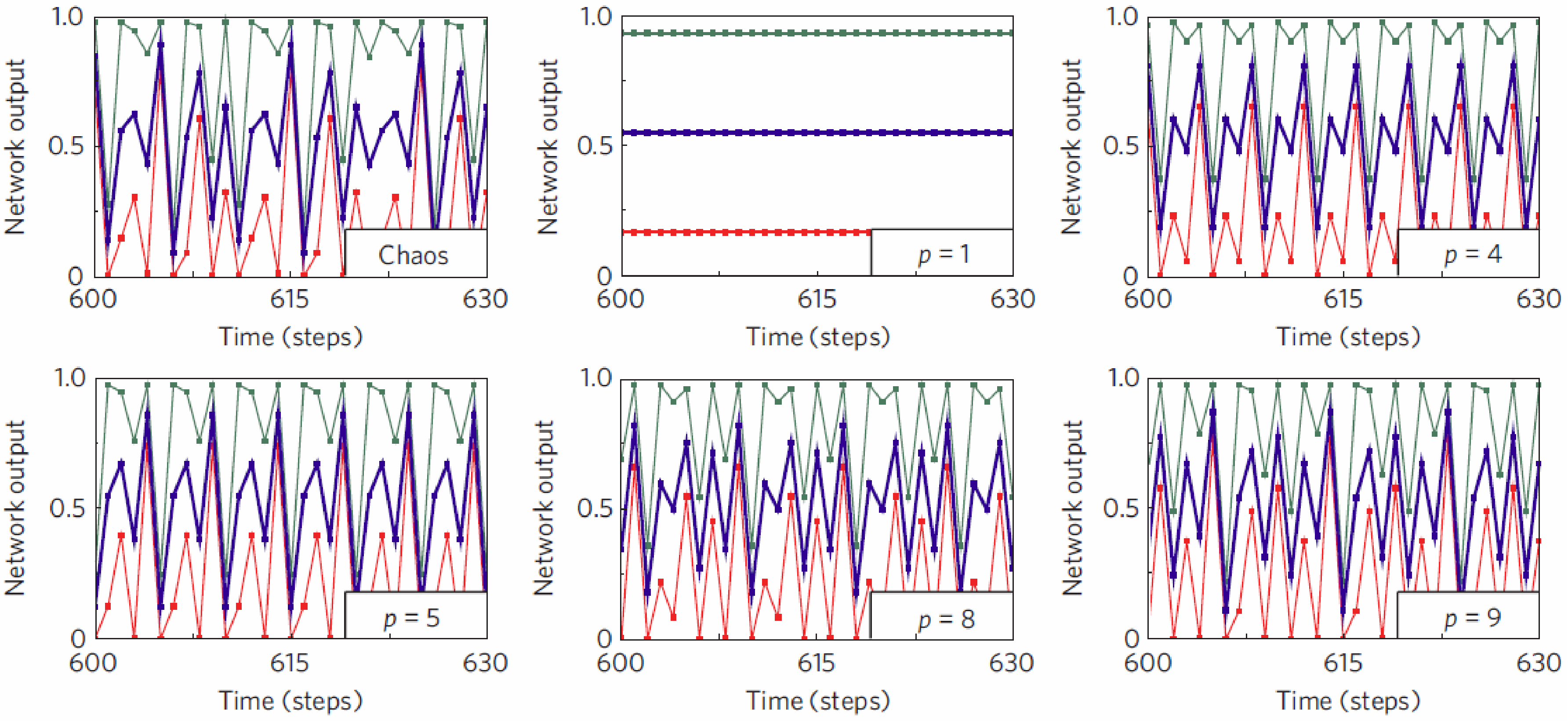
Control signal

$$c_i^{(p)}(t) = \mu^{(p)}(t) \sum_{j=1}^{2} w_{ij} \Delta_j(t)$$

**Adaptive** control strength

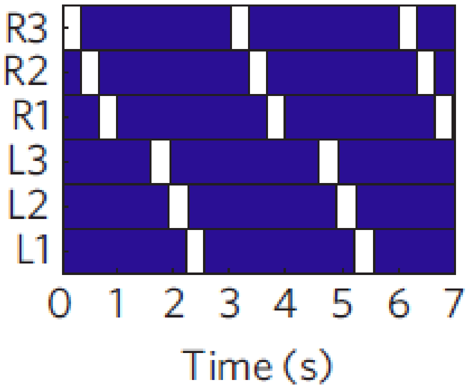
$$\mu^{(p)}(t+1) = \mu^{(p)}(t) + \lambda \frac{\Delta_1^2(t) + \Delta_2^2(t)}{p}$$

# Adaptive, Neuronal Chaos Control ...

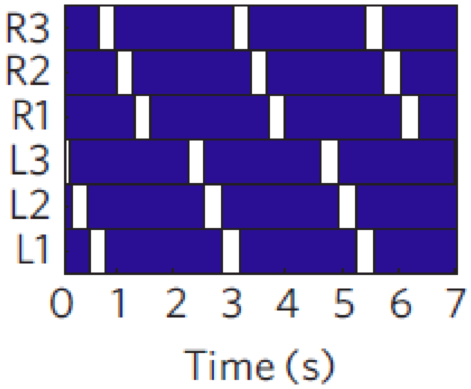


Multitude of periods (> 20) may be stabilized
(not normally possible by non-adapative chaos control)

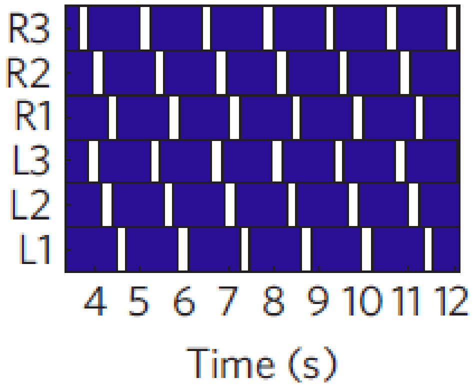
# ... Solves High-dim. Sensory-motor Coordination Problem ...



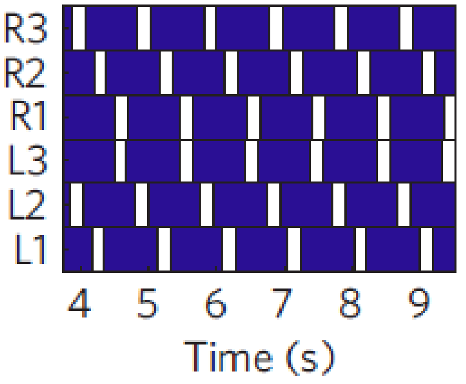
2. $p = 9$
Slow wave gait



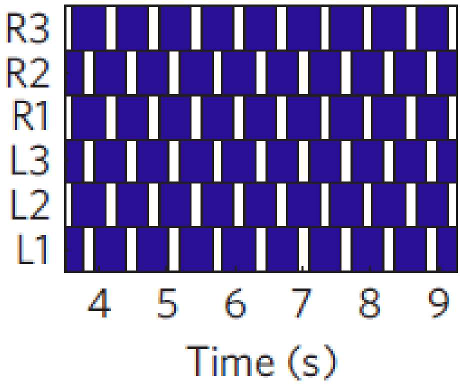
3. $p = 8$
Fast wave gait



4. $p = 6$
Transition gait



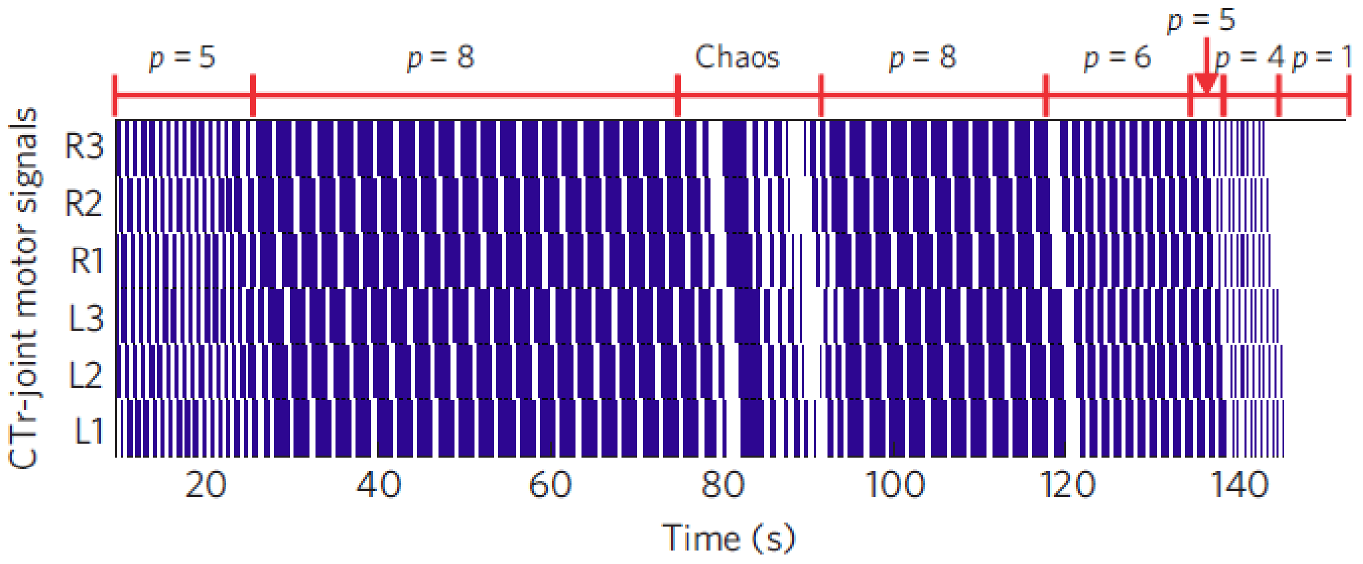
5. $p = 5$
Tetrapod gait

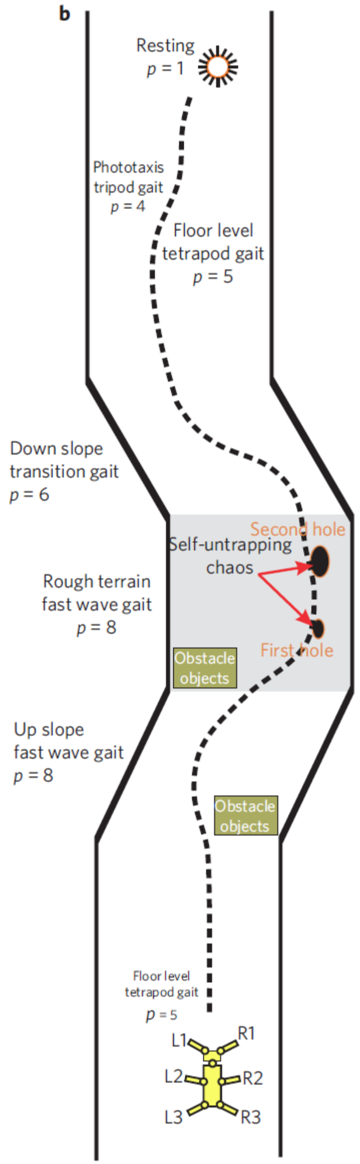


6. $p = 4$
Tripod gait

**many different gaits…**

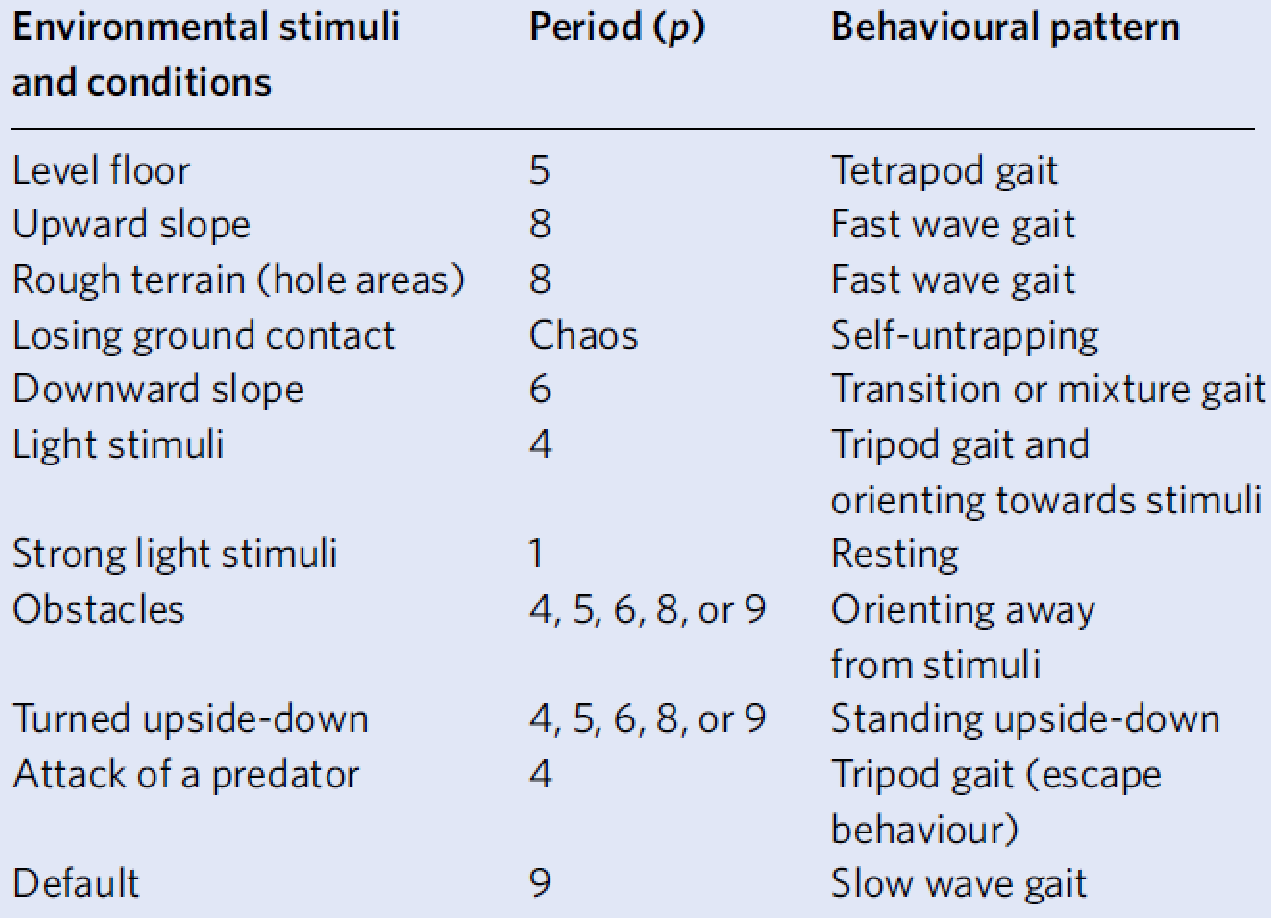
# ... and makes autonomous robot versatile





Large behavioral repertoire… autonomously coordinated

# Broad Behavioral Repertoire



| Environmental stimuli and conditions | Period ($p$) | Behavioural pattern |
|---|---|---|
| Level floor | 5 | Tetrapod gait |
| Upward slope | 8 | Fast wave gait |
| Rough terrain (hole areas) | 8 | Fast wave gait |
| Losing ground contact | Chaos | Self-untrapping |
| Downward slope | 6 | Transition or mixture gait |
| Light stimuli | 4 | Tripod gait and orienting towards stimuli |
| Strong light stimuli | 1 | Resting |
| Obstacles | 4, 5, 6, 8, or 9 | Orienting away from stimuli |
| Turned upside-down | 4, 5, 6, 8, or 9 | Standing upside-down |
| Attack of a predator | 4 | Tripod gait (escape behaviour) |
| Default | 9 | Slow wave gait |

**Complex set of predefined behavioral association**

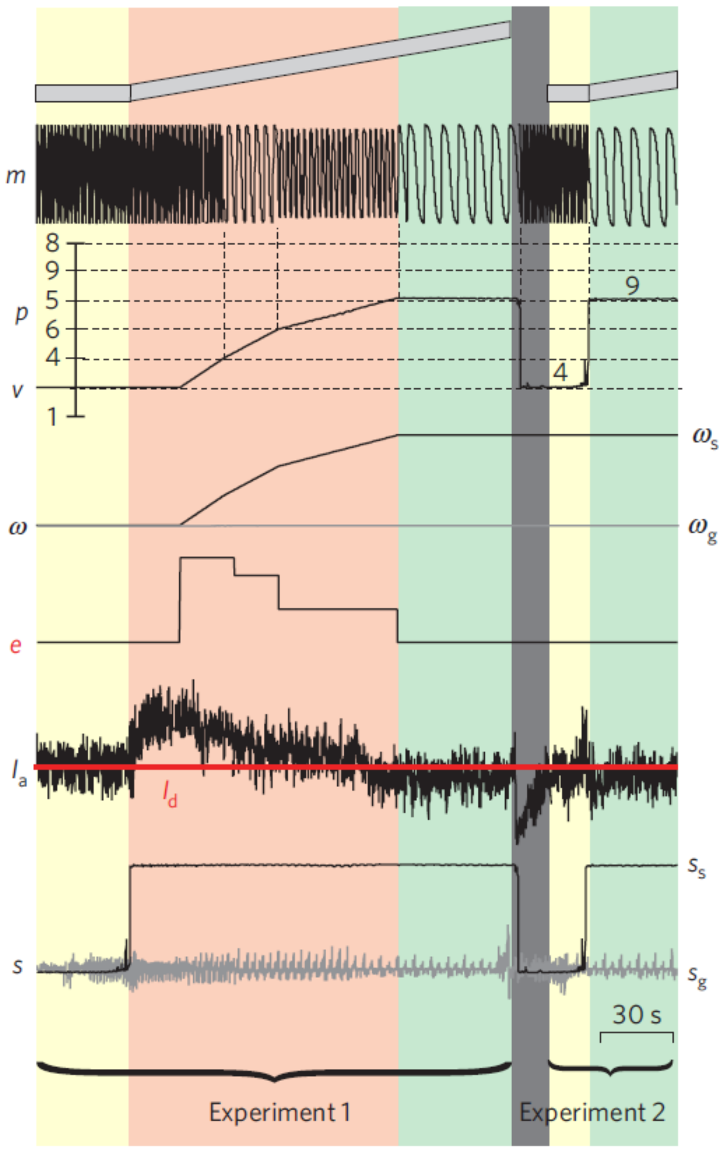
# Constructive Use of Chaos

Robot with leg in hole

- looses foot contact for longer time interval
- **switches control off → chaotic CPG → chaotic „gait“**
- successfully self-untraps

➔ Example for constructive use of chaos

# Learning Suitable Gait to Save Energy



**Learning to associate**

Robot on a slope (video!)

- **tries different gaits**
- selects the one with low power consumption
- **learns while trying**

➔Next time on slope energy-saving gait is chosen right away

# Advanced Nonlinear Dynamics→ Progress for Autonomous Systems

Advantages of single CPG approach
(instead of many separate CPGs, one for each gait)

- higher degree of **versatility**
  (16+2+2 sensors, 18 motors, 11 distinct **autonomous** behavioral patterns)

- **easily learnable** (standard learning at **one** CPG)

- **flexible** control (adding new types behaviors)

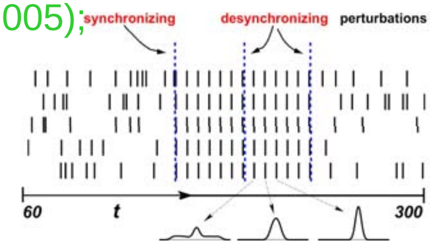
- **transferable** (2/4/8-legged robots, cars, vehicles, ortheses, …)

- **constructive use of chaos** (self-untrapping)
- …

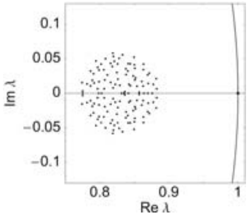
*Nature Phys.* 6:224 (2010);

# Challenges in Network Dynamics:
## New Mathematics joins Neuroscience, Engineering & Physics

- **Unstable Attractors:** New mathematics from neural models
  *Phys. Rev. Lett.* 89:154105 (2002a); *Chaos* 13:377 (2003); *Nonlinearity* 18:20 (2005); *Nature* 436:36 (2005); *Phys. Rev. E* 78:065201(R) (2008).



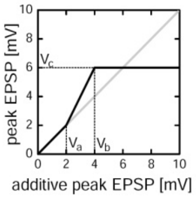
- **Synchronization** in Networks: Multi-operator problems
  *Phys. Rev. Lett.* 89:258701 (2002c); *Phys. Rev. Lett.* 92:074103 (2004a)
  *Phys. Rev. Lett.* 93 (2004c); *Nonlinearity* 21:1579 (2008);

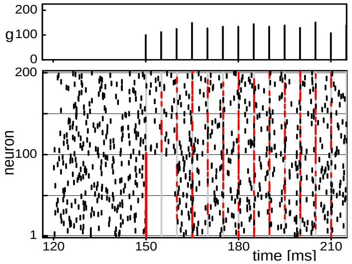


- **Speed Limits:** Explained by Random Matrix Theory
  *Phys. Rev. Lett.* 92:074101 (2004b); *Chaos* 16:015108 (2006);
- **Designing** networks exhibiting predefined patterns: 1st Inverse problem
  *Phys. Rev. Lett.* 97:188101 (2006); *Physica D* 224:182 (2006);
- **Reconstructing** complex network connectivity: 2nd Inverse problem
  *Europhys. Lett.* 76:367 (2006); *Phys. Rev. Lett.* 98:224101 (2007);
  *Frontiers Comp. Neurosci.*, under review (2010)
- **Data Analysis Methods** to detect spatio-temporal relations: spikes/LFPs
  *Neurocomputing* 70:2096 (2007); *Neurosci. Res.* 61:S280 (2008).

# Challenges in Network Dynamics:

## New Mathematics joins Neuroscience, Engineering & Physics





- Theory of **spatio-temporal spike patterns**
  *Frontiers in Neurosci.* 3:2 (2009);
  *Discr. Cont. Dyn, Syst.*, in press (2010);
  Handbook on Biological Networks (Chapter on 'Spike Patterns') (2010).
- **Novel routes to desynchronization:** Sequential bifurcations,…
  *Phys. Rev. Lett.* 102:068101 (2009); *Nonlinearity*, under review (2010);
  *Europhys. Lett.*, 90:48002 (2010); *SIAM J. Appl. Math.* 70:2119 (2010)
- **Cortical 'ground state':** Chaos does NOT generate irregularity!
  *Phys. Rev. Lett.* 100:048102 (2008); *Frontiers in Comput. Neurosci*. 3:13 (2009);

- Nonlinear dynamics for **computation** and **autonomous systems**
  *Nature Phys.*, 6:224 (2010); *J. Phys. A: Math. Theor.* 42:345103 (2009)
- **Complex disordered systems & counting problems** on graphs
  *Phys. Rev. Lett.* 88**:**245501 (2002); *Cornell Rep.* 1813:1352 (2007); *New J Phys.* 11:023001 (2009);
  *Nature Phys.*, under review (2010); *J. Phys. A: Math. Theor.*, 43:175002 (2010)

# Thanks to ...

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| | |
|---|---|
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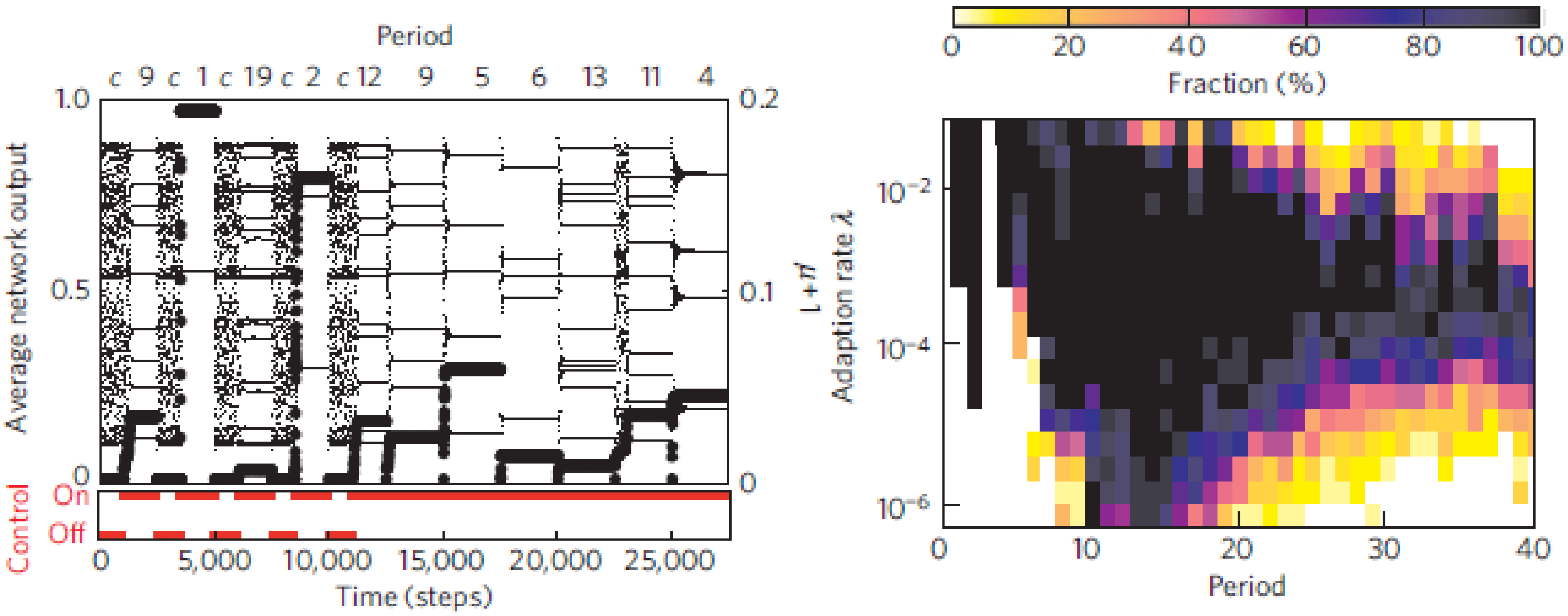
**YOU all for your attention !**

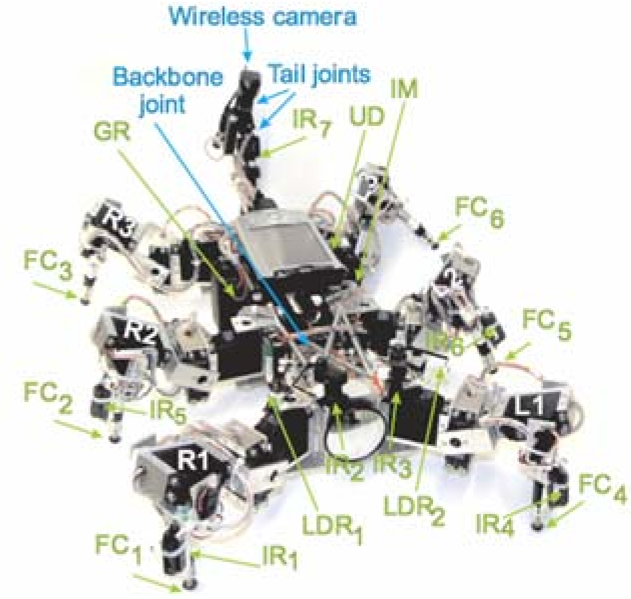
Questions & Comments Welcome!

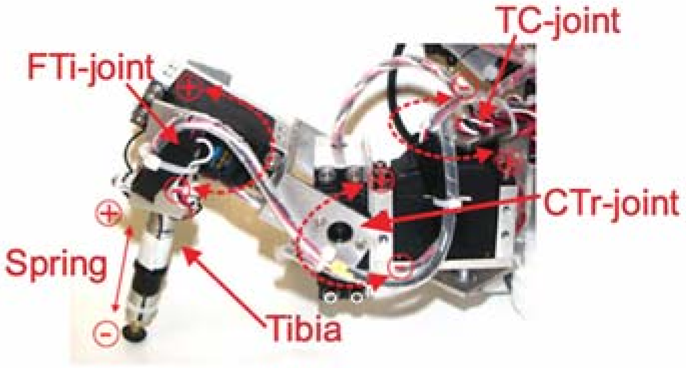
# Robust and Rapid Period Stabilization



Multitude of periods may be stabilized
(not normally possible by non-adapative control)

# Towards Versatile Autonomous Systems





TC-joint = Thoraco-coxal joint

CTr-joint = Coxa-trochanteral joint

FTi-joint = Femoral tibial joint