Embodied AI: How complex motion arises from single-neuron controllers

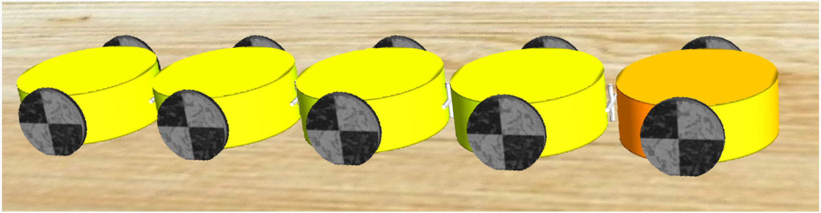
Frederike Kubandt

June 2018

Institute for Theoretical Physics
Goethe University Frankfurt

For simulation videos, go to
https://github.com/fkubandt/wheeled_snake_robots

Idea

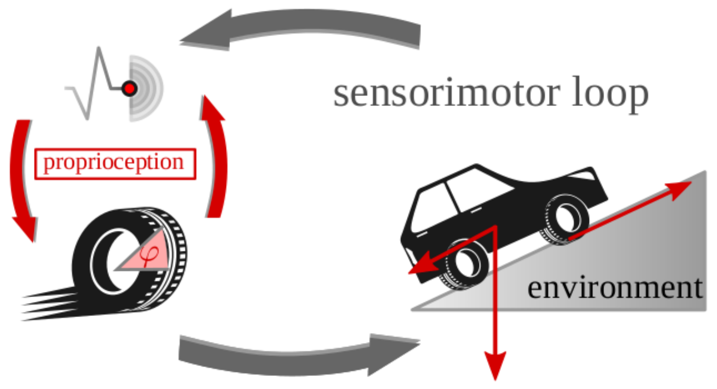


Designing a Robot Controller **without** relying on

- central computing
- environmental sensors
- learning algorithm
- information about body composition
- internal communication

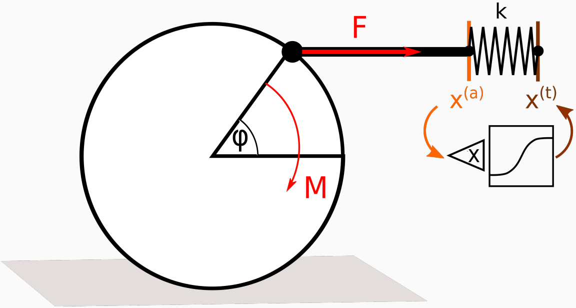
But then, what do we have?

Design of the Controller



B. Sàndor

Design of the Controller



$$x^{(a)} = \cos(\varphi)$$

$$F = k \cdot (x^{(t)} - x^{(a)})$$

$$M = r \cdot F \sin(\varphi)$$

$$\begin{aligned} \tau\dot{x} &= x^{(a)} - x \\ x^{(t)} &= \tanh(x) \end{aligned}$$

System Equations

Adding friction factor $-rf\omega$ leads to

$$
\begin{aligned}
\tau\dot{x} &= \cos(\varphi) - x \\
\dot{\varphi} &= \omega \\
I\dot{\omega} &= M_{\text{eff}} = r\Big(k\Big(\tanh(x) - \cos(\varphi)\Big)\sin(\varphi) - f\omega\Big)
\end{aligned}
$$

System Equations

Adding friction factor $-rf\omega$ leads to

$$\begin{aligned} \tau\dot{x} &= \cos(\varphi) - x \\ \dot{\varphi} &= \omega \\ I\dot{\omega} &= M_{\text{eff}} = r\left(k\left(\tanh(x) - \cos(\varphi)\right)\sin(\varphi) - f\omega\right) \end{aligned}$$

---

set of relevant (stable) fixpoints:

$$\begin{aligned} x^* &= \cos(\varphi_0^*), \\ \omega^* &= 0, \\ \varphi_0^* &= n\pi \end{aligned}$$

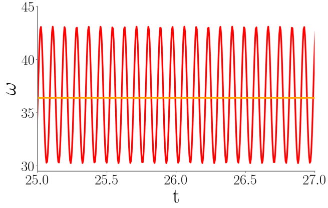
System Equations

Adding friction factor $-rf\omega$ leads to

$$\begin{aligned} \tau\dot{x} &= \cos(\varphi) - x \\ \dot{\varphi} &= \omega \\ I\dot{\omega} = M_{\text{eff}} &= r\Bigg(k\Big(\tanh(x) - \cos(\varphi)\Big)\sin(\varphi) - f\omega\Bigg) \end{aligned}$$

---

two symmetric limit cycles → forward and backward rotation



mean velocity depends on k

limit cycles dominate for $k > k_c \approx 0.54$

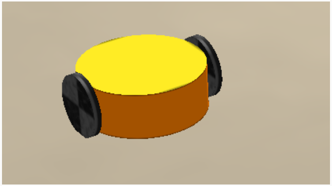
Two-wheeled Robot

Implement this controller in simple robot:

cylindric body with two wheels

wheels are controlled **indepedently** by **identical** controllers

no communication or coupling except mechanical link to body

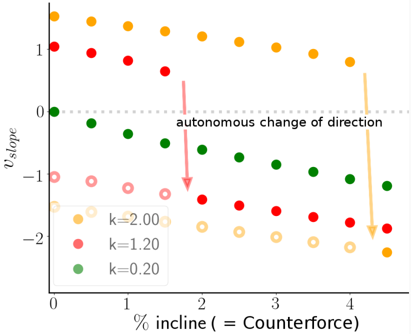


→ forward and backward driving, rotation, rest

Autonomous Change of Direction

- wall destroys the limit cycle of forward motion
- the system converges to other limit cycle or fixpoint
- time delay between impacts introduces curves

Autonomous Change of Direction



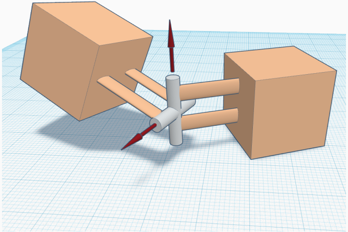
- slope introduces a counterforce → similar effect
- on slopes, no (stable) fixpoints exist
- no arbitrarily low upward velocity

Chain of Robots

add complexity by creating a chain of robots:

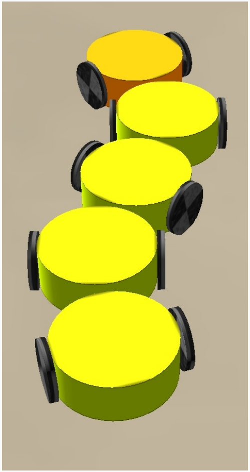
5 identical two-wheeled robots

allow (damped) motion along pitch and yaw axis



→ 10 independent controllers, mechanically coupled

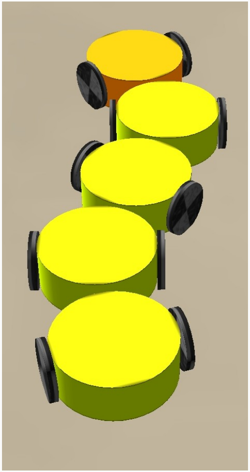
≡ 10 "neurons"



Chain of Robots

different locomotion patterns emerge, depending on all parameters, e.g.

- motorstrength k
- damping of the joints D
- friction parameter f



Emerging Locomotion Patterns

$D = 0.005$

$k = 2$

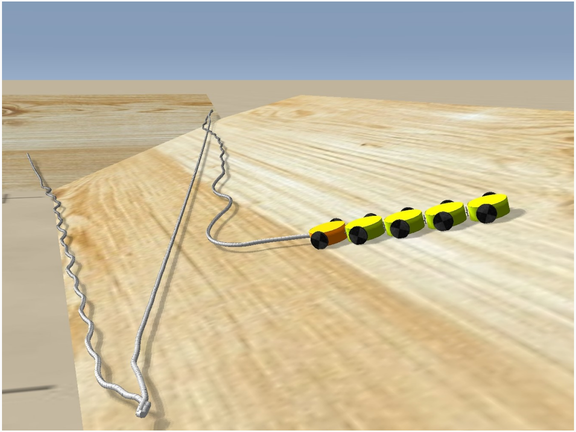
Emerging Locomotion Patterns

D = 0.005

k = 2.9

Interaction with Environments

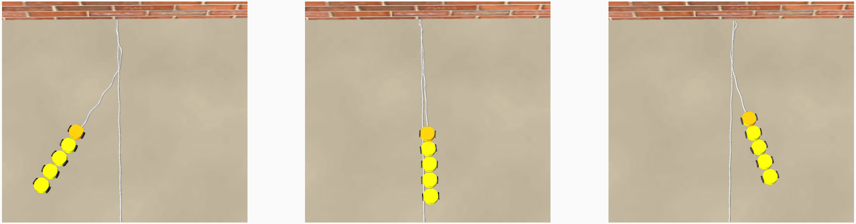
In a structured environment, autonomous changes between locomotion patterns occur.



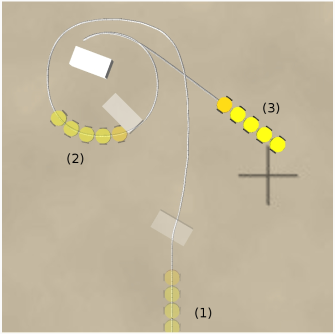
Interaction with Environments

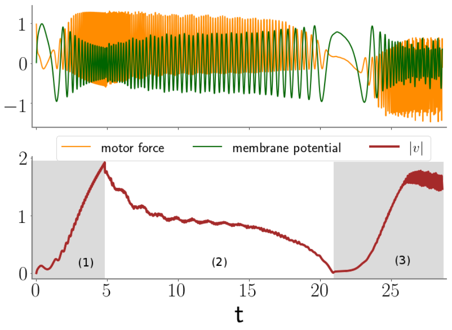
high variability of modules' relative positions
→ collision can introduce change between gaits and high variance in resulting direction.

Exploratory behaviour



Interaction with Environments





Interaction with Environments

Conclusions

- complex behaviour emerges from very simple controllers that are coupled mechanically
- proprioception in a dynamical system allows autonomous changes between locomotion patterns as a response to structured environment
- coordinated and uncoordinated behaviour can be realized

Further work on this topic

- it could be shown, that the emergent behaviour is very robust toward mismatches of motor strength and even motor failure
- it seems to be sensitive to mechanical deviations and small-scale environmental structures

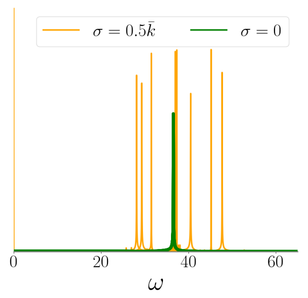
F. Kubandt *Robustness and Synchronization in a Chain of Two-Wheeled Robots*, Thesis, Institute for Theoretical Physics,

Goethe University Frankfurt

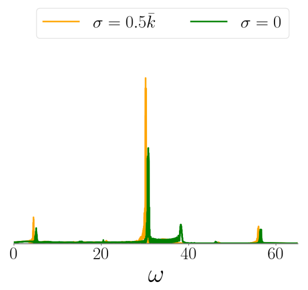
- with adaptation (second neuron), the controller was succesfully transferred to a physical two-wheeled robot EV3 (for the chain this remains to be tested)
- for the 2-neuron controller, kick-control for top-down transition between attractors could be successfully implemented in simulation and EV3

B. Sàndor, M. Nowak, T. Koglin, L. Martin, and C. Gros. *Kick control: using the attracting states arising within the sensorimotor loop of self-organized robots as motor primitives.* Frontiers in Neurorobotics preprint.

Variation of Motor Strength

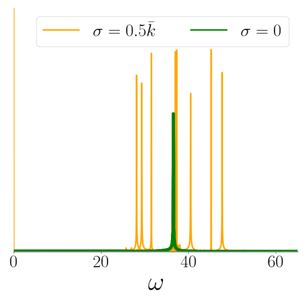


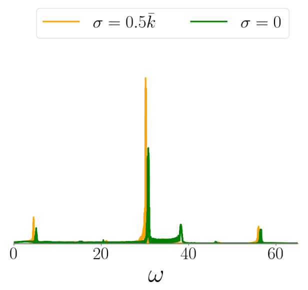
uncoupled (air)



coupled (ground)

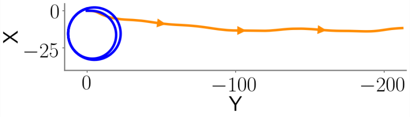
Variation of Motor Strength





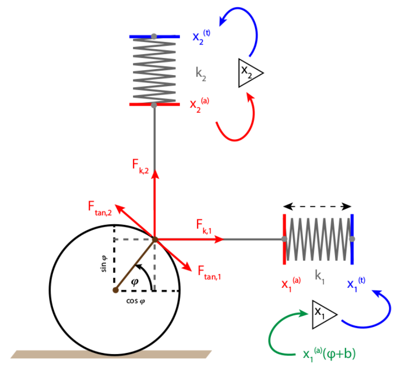
uncoupled (air)

coupled (ground)



Real-World Implementation

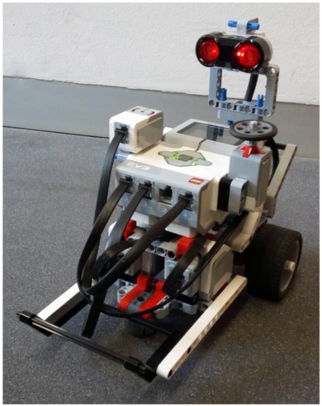
For realization in a physical system, the controller was adapted:
→ two neurons to avoid zero-crossing



work by M. Nowak

Real-World Implementation

The controller was implemented in Lego EV3



---

work by M. Nowak

Real-World Implementation

Real-World Implementation