Topics in Autonomous Robots
Locomotion control

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Topics

Topics:

- Wheeled locomotion
- Animal locomotion
- Different control approaches in legged robotics
- Examples of projects from the Biorob lab

Biorobotics Lab (A.J. Ijspeert)

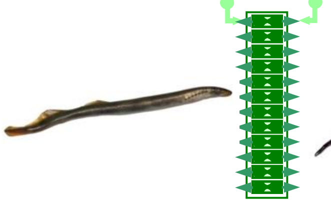
Goals:

- **To get a better understanding of animal sensorimotor control** using numerical simulation and robots as scientific tools.

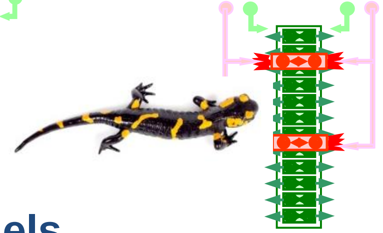
- **To design and control robots** that exhibit **motor skills with the same agility as animals**

- To contribute to **rehabilitation of locomotor skills** through exoskeletons

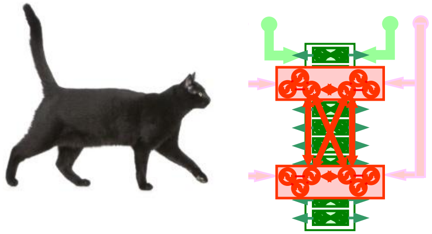
Lamprey



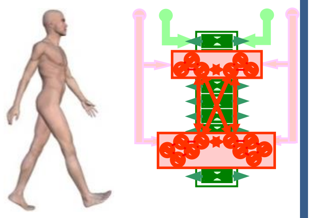
Salamander



Cat



Human



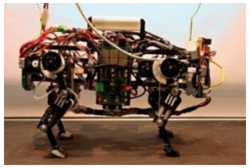
Biological models

Amphibot

Salamandra robotica

Pleurobot

Cheetah-Cub



Oncilla

iCub

CoMan

Biorobots

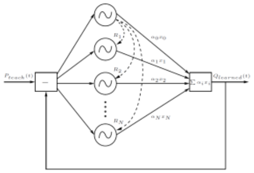
$$\tau \dot{z} = \alpha_z(\beta_z(g - y) - z) + f + C_t$$

$$\tau \dot{y} = z$$

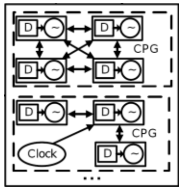
$$\tau \dot{x} = -\alpha_x x + C_c$$

$$f(x) = \frac{\sum_{i=1}^{N} \Psi_i(x) w_i}{\sum_{i=1}^{N} \Psi_i(x)} x(g - y_0)$$

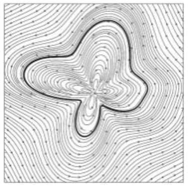
Dyn. movement primitives



Adaptive frequency oscillators



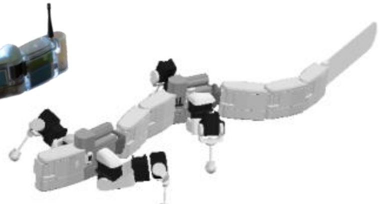
Discrete and rhythmic pattern generator



Morphed oscillators

Dynamical systems

Pollution detection
Envirobot



Search-and-rescue
NCCR

Roombots: assistive furniture

Control of Exoskeletons
Symbitron

Applications

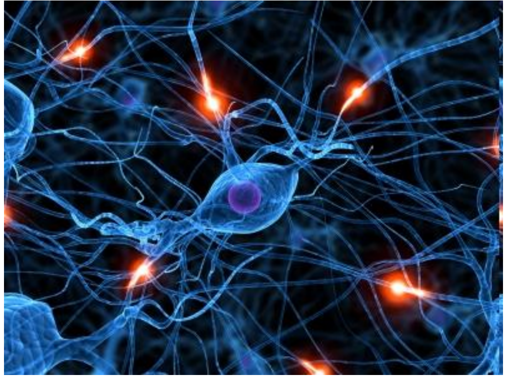
The beauty of animal movement control

The beauty of animal movement control

Why is locomotion important?

Engineering:

Having **robots that move better** in unstructured and unknown environments is absolutely **necessary for multiple applications**



Science:

Moving is fundamental to animals.

Society:

Having motor deficits is one of the **worst handicaps**

Why is locomotion control a difficult and unsolved problem?

Locomotion and movement are due to **complex interactions between the controller**, **the body, and the environment**

Requires **solving multiple complex computational challenges**: good coordination of multiple DOFs, dealing with uncertainties, keeping balance, adapting to terrain/environment, adapting to changing body properties, …

Still not properly solved in robotics

Still not properly understood in animals

But there is exciting progress in both fields!

Wheeled robots

Pioneer 3-AT

E-Puck (EPFL)

Uranus robot (CMU)

http://www.bluebotics.com/solutions/Shrimp/

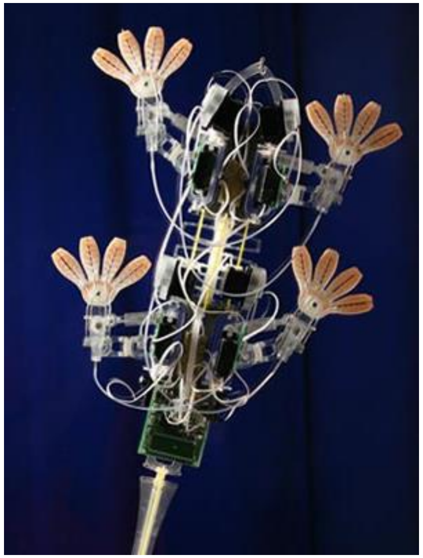
Roomba (iRobot)

Stanley (Stanford)

Legged robots

ANYmal
ETHZ, Switzerland

Aibo, SONY, Japan



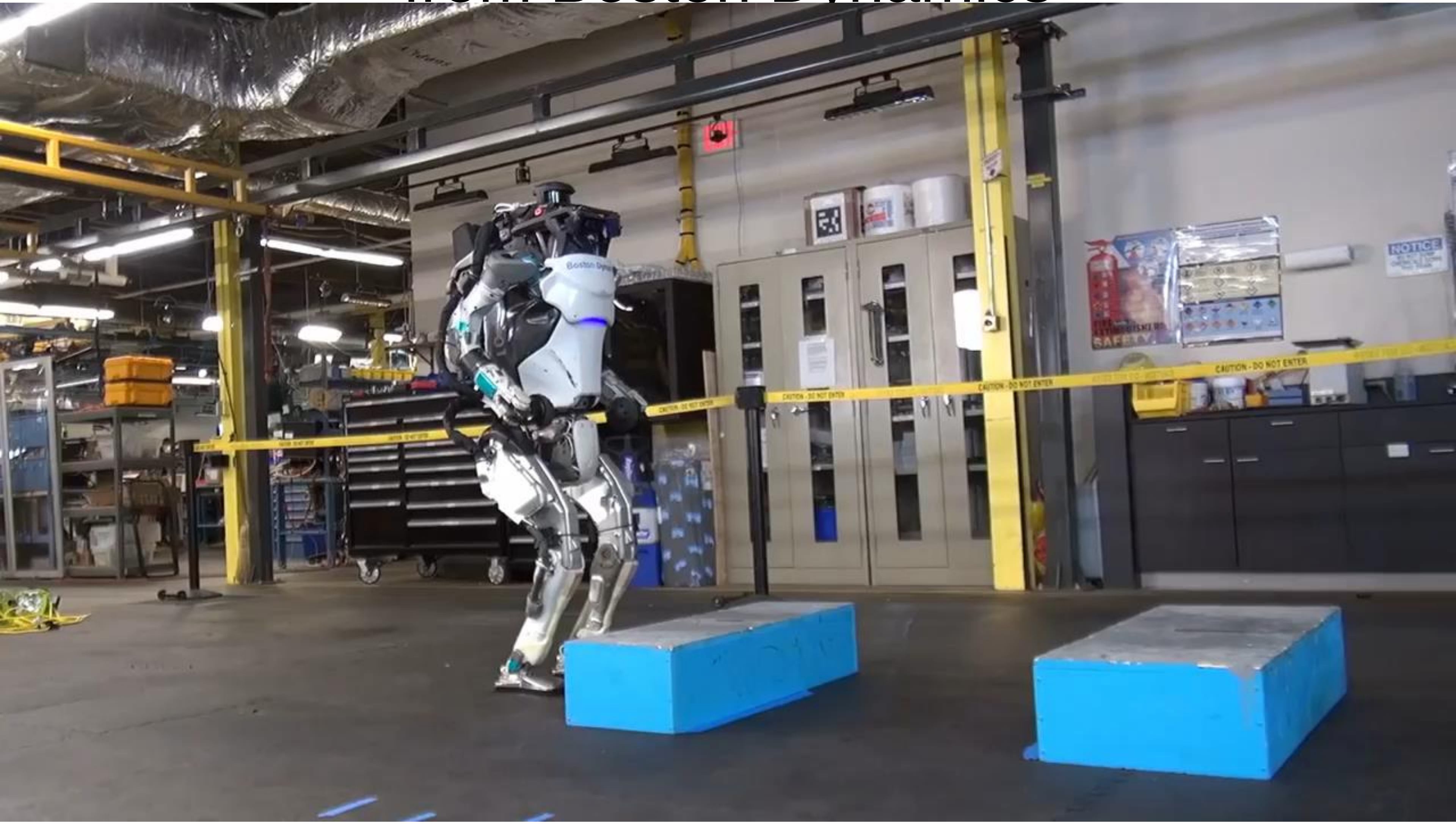
StickyBot, Stanford, USA

RHex robot, USA

Asimo, Honda, Japan

BigDog,
Boston Dynamics, USA

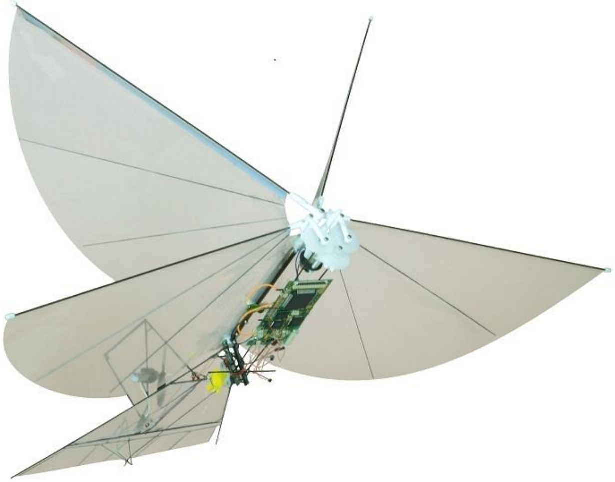
Impressive recent results from Boston Dynamics



Flying robots

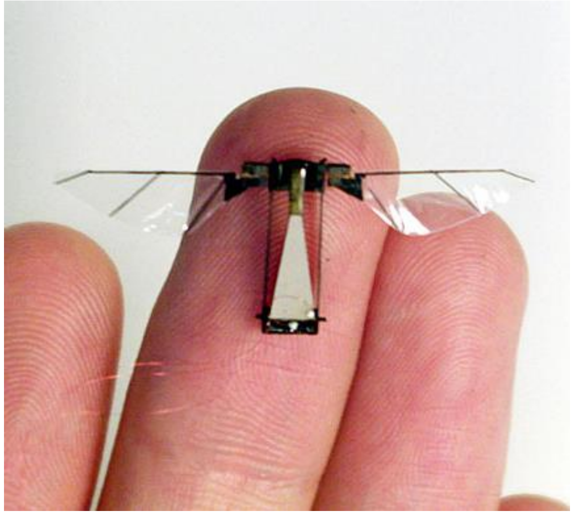
Feathered Drone, LIS, EPFL

Hummingbird,
AeroVironment, USA



Ornithopter robot, U. Berkeley, USA

SmartBird, Festo, Germany



Micro aerial vehicle, Harvard Univ., USA

Swimming and crawling robots

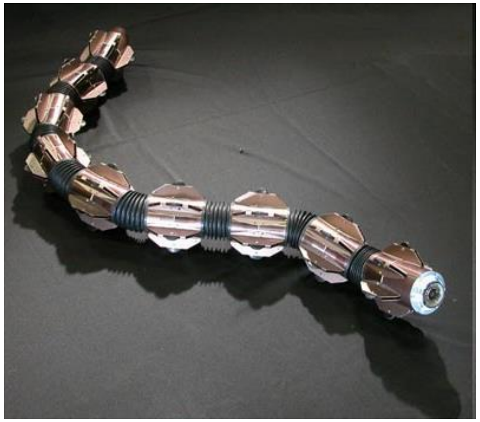
G6 Fish Robot,
University of Essex, UK

Manta Ray
EvoLogics, Germany

Lamprey robot, U. of Northeastern, USA

Lamprey robot, SSSA, Italy

Penguin robot, Festo,
Germany

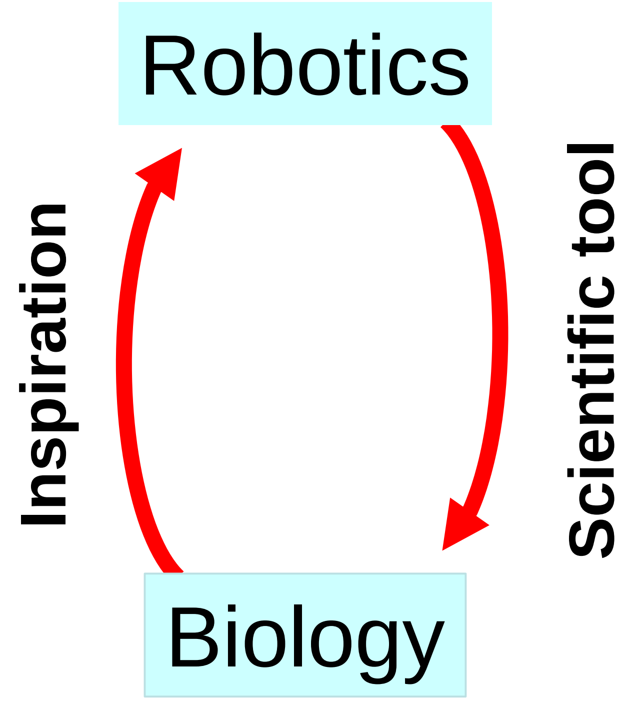


ACM robot, Tokyo Inst of
Tech Japan

Snake Robot, CMU, USA

Biorobotics

Field robotics
Search and rescue
Transport
Agriculture
Environmental monitoring



Robotics

Inspiration

Scientific tool

Biology

Neuroscience
Biomechanics
Hydrodynamics

Ijspeert 2014: Biorobotics: Using robots to emulate and investigate agile locomotion, ***Science*** **346, 196, 2014**

Wheeled mobile robots

Wheels are appropriate for a number of applications (at least on reasonably flat terrain)

Adapted from slides of J.-C. Zufferey (EPFL Mobile Robots Course) and from Siegwart & Nourbakhsh, 2004, ch. 2

General principles

- The design of a wheeled robot requires finding the right **tradeoff between stability, controllability, and maneuverability**
- *Stability*: not falling over
- *Controllability*: the ease of converting motor commands into desired rotational and translational velocities, good controllability is useful for accurate steering and for proper dead reckoning (i.e. estimation of one’s position based on previous positions)
- *Maneuverability*: ability to change direction. Highest maneuverability: omnidirectional, i.e. the ability to move at any time in any direction on the ground plane

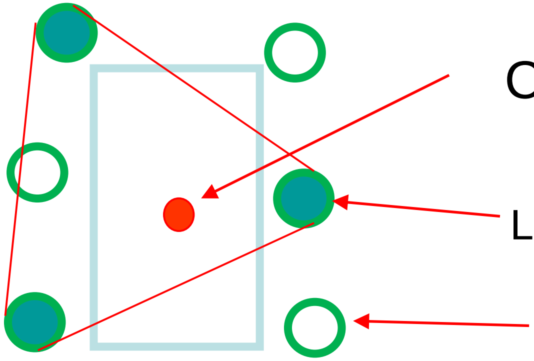
- **Static stability** of a vehicle is guaranteed with 3 wheels
  - center of gravity is within the triangle which is formed by the ground contact point of the wheels.
- With 4 or more wheels dynamic stability is improved
  - however, these arrangements are hyperstatic and require a flexible suspension system.

Stability

Stability

- ***statically stable*** ⇔ the center of gravity is above the support polygon spanned by the contact points (static stability means that no motion is required to maintain balance)
- ***dynamically stable*** ⇔ motion is required to remain upright

Statically stable tripod gait in a hexapod robot:

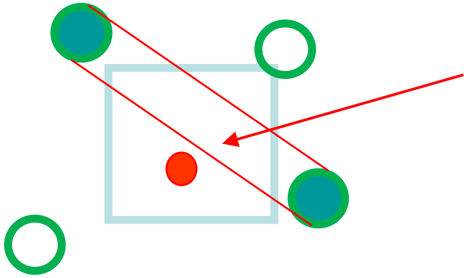


Center of mass

Leg on ground

Leg in the air

Dynamically stable trotting gait in a quadruped robot:



Center of mass

General principles

- There is often an inverse correlation between **controllability** and **maneuverability**. For instance:
  - cars have good controllability but poor maneuverability
  - omnidirectional robots using Swedish wheels have good maneuverability but poor controllability (due to uncertainty in steering and speed)

- In summary, there is **no ideal drive configuration** that simultaneously maximizes stability, maneuverability and controllability.

- Let’s have a look at the multiple options available.

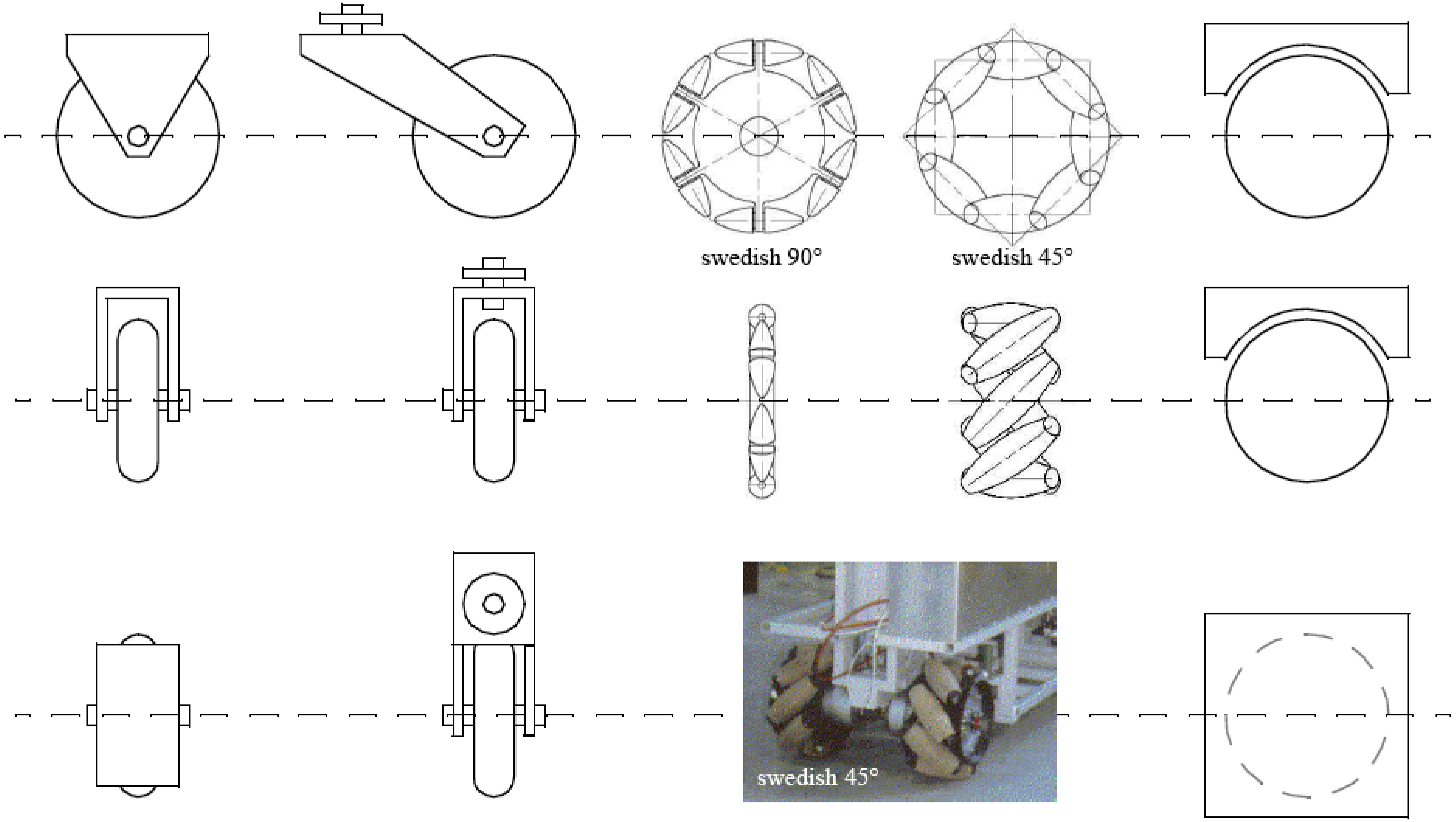
The four basic wheel types

a) **Standard wheel**: rotation around the (motorized) wheel axle and the contact point.

b) **Castor wheel**: rotation around the wheel axle, the contact point and the castor axle.

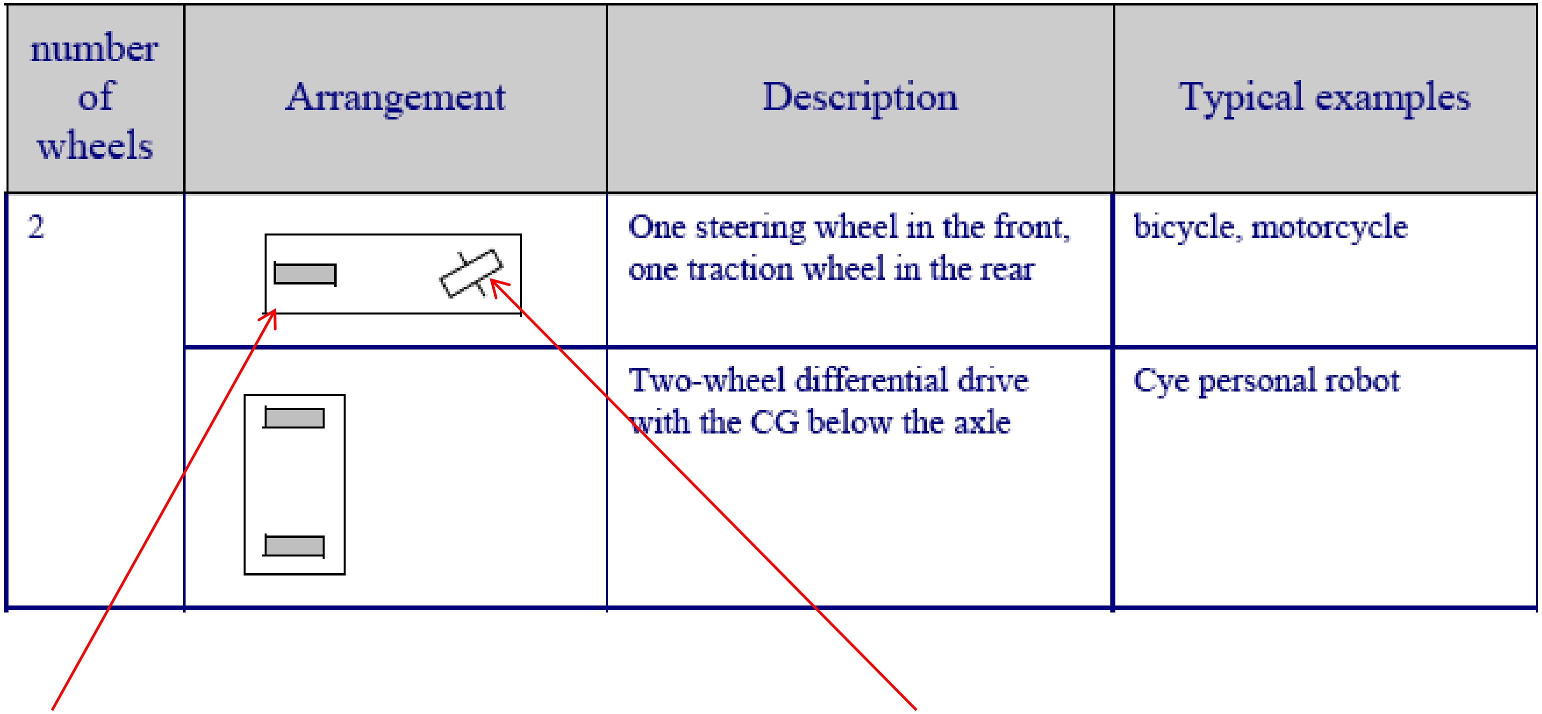
c) **Swedish (or mecanum) wheel**: rotation around the (motorized) wheel axle, around the rollers and around the contact point.

d) **Ball or spherical wheel.**



Various arrangements of wheels

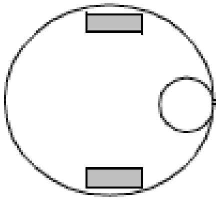
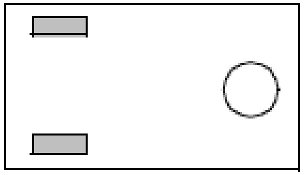
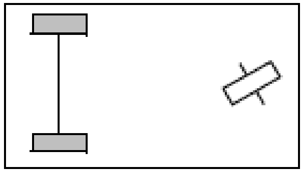
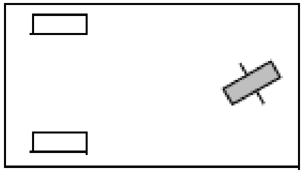
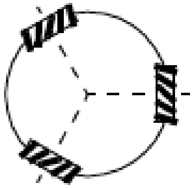
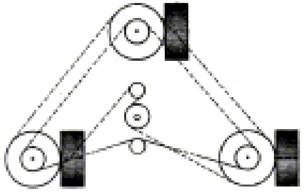
- Typical examples with 2, 3, 4, 6 wheels



number of wheels	Arrangement	Description	Typical examples
2		One steering wheel in the front, one traction wheel in the rear	bicycle, motorcycle
		Two-wheel differential drive with the CG below the axle	Cye personal robot

Gray: actuated wheel

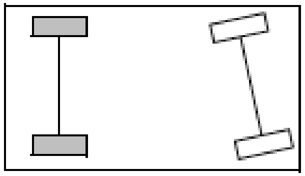
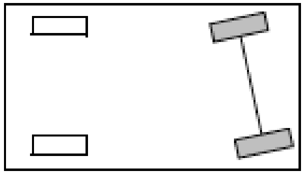
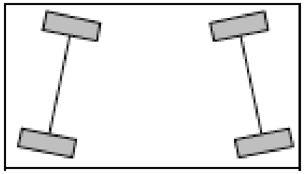
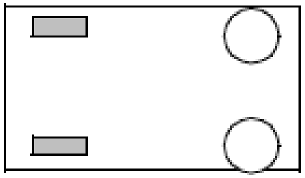
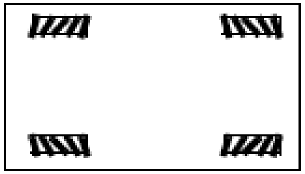
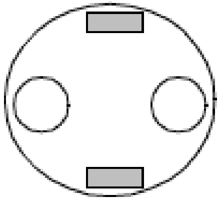
White: free wheel

3		Two-wheel centered differential drive with a third point of contact	Nomad Scout, smartRobII EPFL
		Two independently driven wheels in the rear/front, one unpowered omnidirectional wheel in the front/rear	many indoor robots, including the EPFL robots Pygmalion and Alice
		Two connected traction wheels (differential) in rear, one steered free wheel in front	Piaggio mini-trucks
		Two free wheels in rear, one steered traction wheel in front	Neptune (Carnegie-Mellon University
		3 motorized swedish or spheric wheels arranged in a triangle. Omnidirectional movement is possible.	Stanford-wheel Tribolo EPFL
		3 synchronously motorized and steered wheels. The orientation is not controllable.	'synchro drive' Denning MRV-2, Georgia Institute of Technology, I-Robot B24, Nomad 200

Differential drive

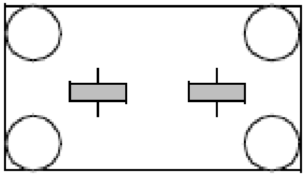
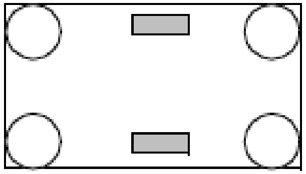
Omnidirectional drive

Synchro drive

4		2 motorized wheels in the rear, 2 steered wheels in the front; Steering has to be different for the two wheels to avoid slipping/ skidding.	car with rear wheel drive
		2 motorized and steered wheels in the front, 2 free wheels in the rear; Steering has to be different for the two wheels to avoid slipping/skidding.	car with front wheel drive
		4 steered and motorized wheels	four wheel drive, four wheel steering
		Two traction wheels (differential) in rear/front, two omnidirectional wheels in the front/rear	Charlie (DMT-EPFL)
		Four omnidirectional wheel	CMU Uranus
		Two wheel differential drive with two additional points of contact	EPFL Khepera, Hyperbot Chip

“Ackermann”

Differential drive

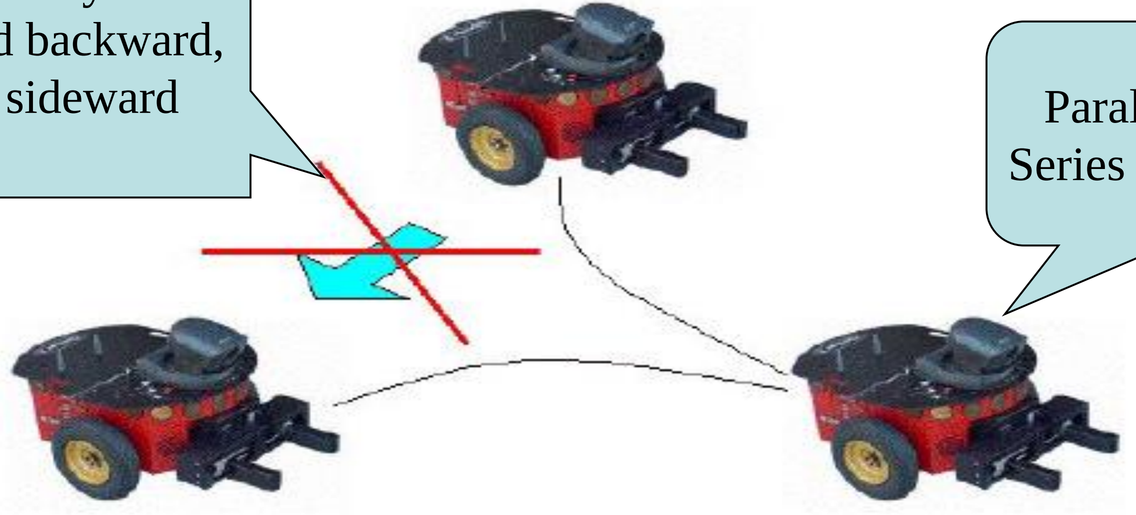
number of wheels	Arrangement	Description	Typical examples
6		Two motorized and steered wheels aligned in center, one omnidirectional wheel at each corner	First
		Two traction wheels (differential) in center, one omnidirectional wheel at each corner	Terregator (Carnegie Mellon University)

Holonomic/non-holonomic robots

- **Controllable DOF**: if a given robot has an actuator for every DOF of its task space, then all of the DOFs are controllable. Usually not all DOFs are controllable, which makes robot control harder.
- For instance, a standard car has 3 DOF: position (x,y) and orientation (θ). But only 2 DOF are controllable: *forward speed* through the gas pedal and the forward-reverse gear, and *steering* through the steering wheel. Since there are more DOFs than are controllable, there are motions that cannot be done, like moving sideways (that's why parallel parking is hard). **A car can get to any 2D position but it may have to follow a very complicated trajectory**.
- In robotics, **holonomicity** refers to the relationship between the controllable and total DOF of a given robot (or part thereof). If the **controllable DOF** is equal to the total degrees of freedom (in the task space) then the robot is said to be **holonomic**. If the controllable degrees of freedom is less than the total DOF it is **non-holonomic**. A robot is considered to be **redundant** if it has more controllable DOF than DOF in its task space. Example: a car is non-holonomic
- Caution: (in general) omnidirectional != holonomic

Non-holonomic constraint

- A non-holonomic constraint is a constraint on the feasible velocities of a body.
- E.g. a differential-drive robot can move in some directions (forward and backward), but not others (sideward).

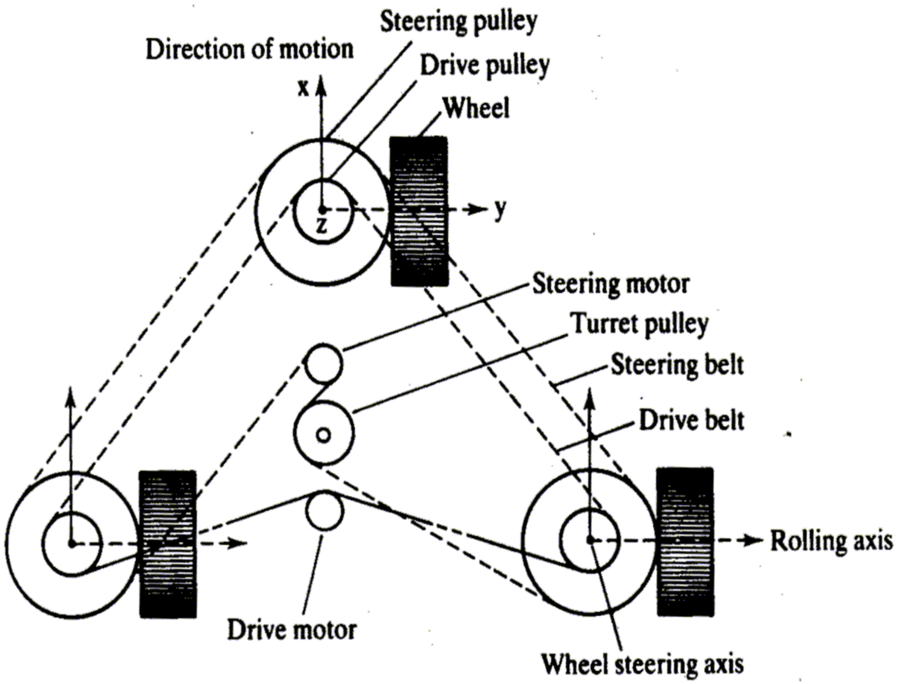


The robot can instantly move forward and backward, but can not move sideward

Parallel parking,
Series of maneuvers

Synchro drive

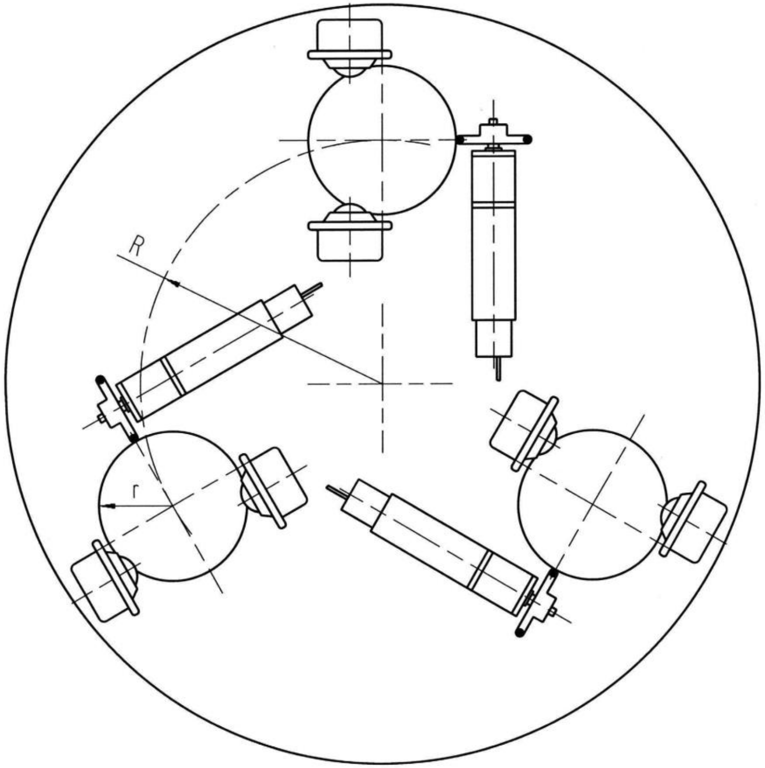
- All wheels are actuated synchronously by one motor
  - defines the speed of the vehicle
- All wheels steered synchronously by a second motor
  - sets the heading of the vehicle
- The orientation in space of the robot frame will always remain the same
  - It is therefore not possible to control the orientation of the robot frame.
  - Omnidirectional (can change x,y) but not holonomic (no control of θ)

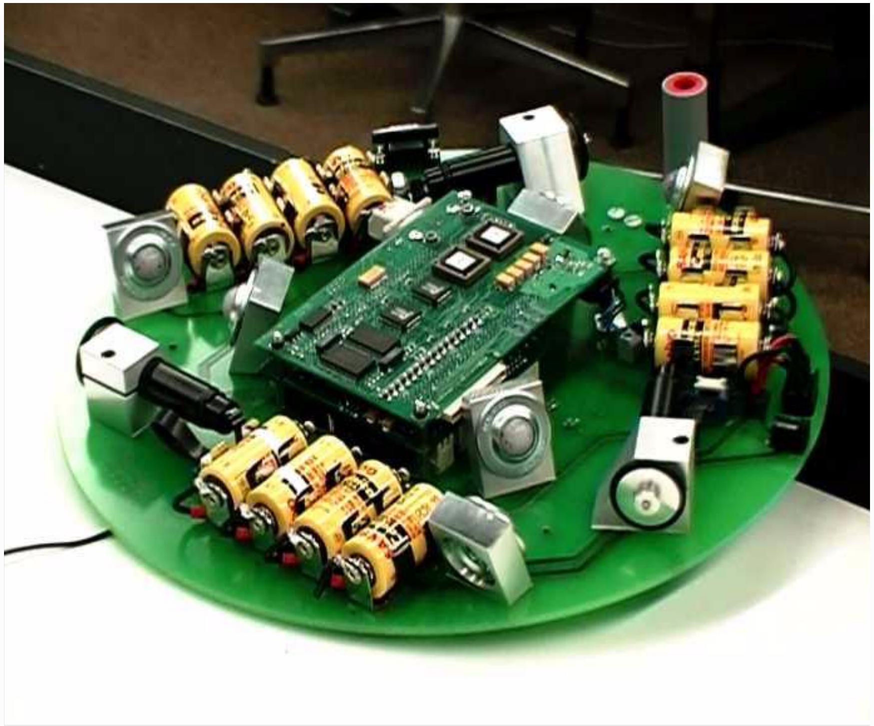


Example: Robot Mouche by N. Franceschini

Tribolo, an omnidirectional drive

- 3 spherical wheels
- Holonomic robot: it can move in any direction at any time, including rotations on one-self (control of x,y, and θ)





video

Ball-balancing Robot

- Not passively stable -> active sensing and stabilization
- Holonomic

Movie

Tohoku-Gakuin University, Japan
http://www.mech.tohoku-gakuin.ac.jp/rde/index_e.html

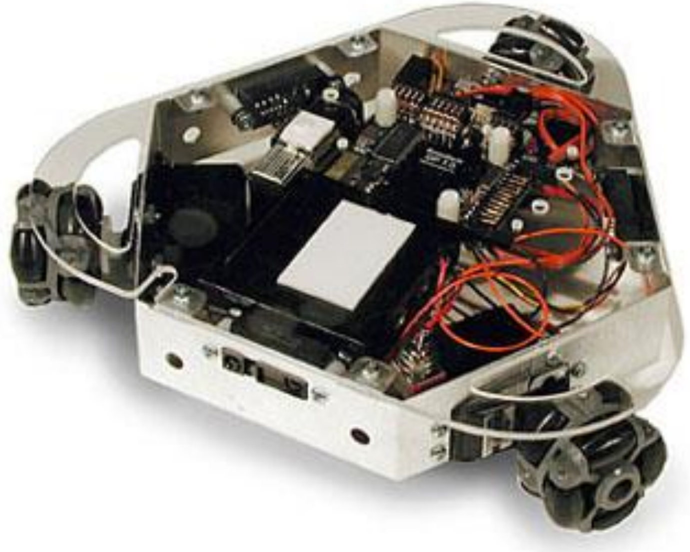
Swedish-wheel (Mecanum) omnidirectional drive

- Movement in the plane has 3 DOF
  - thus only three wheels can be independently controlled

$$v_y = (v_0 + v_1 + v_2 + v_3)/4$$

$$v_x = (v_0 - v_1 + v_2 - v_3)/4$$

$$v_\theta = (v_0 + v_1 - v_2 - v_3)/4$$



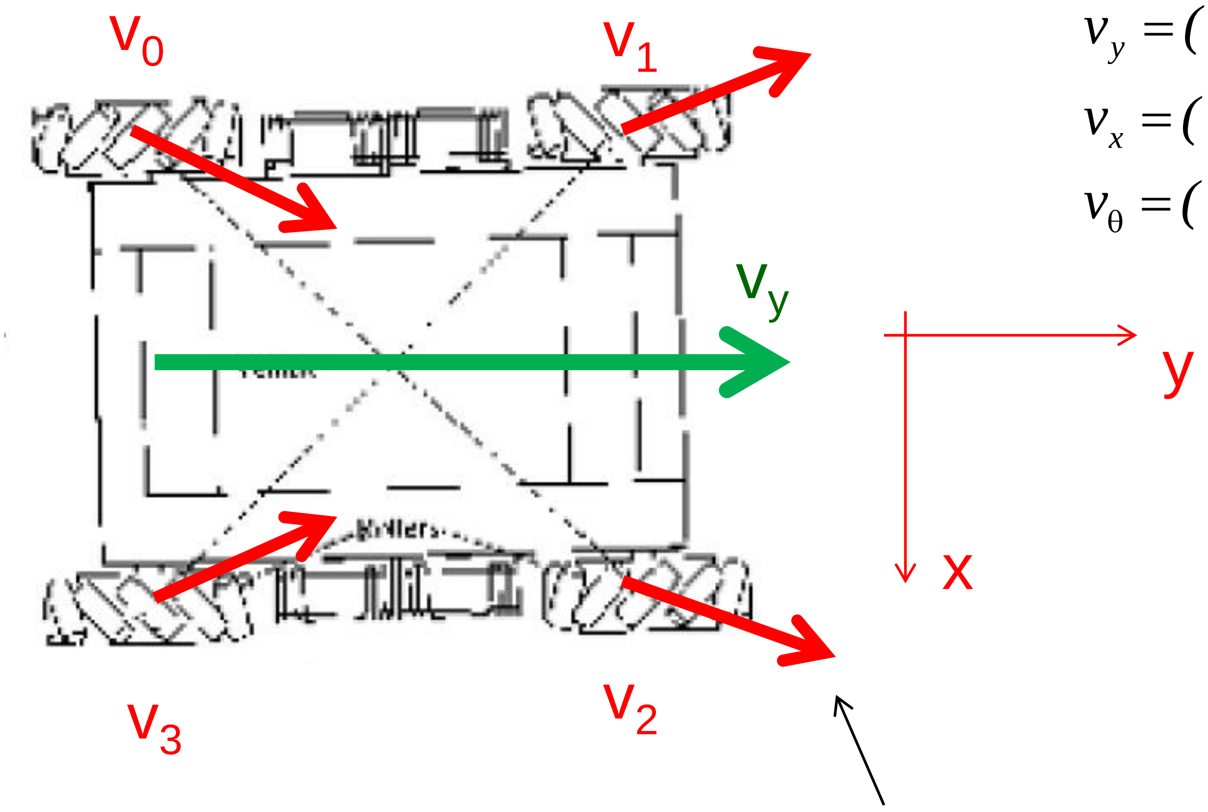
Poly Wheels (Acroname)

Uranus robot (CMU)

Airtrax
Omni-Directional Technology
Changing the way vehicles move

Video: http://www.airtrax.com/vehicles/sidewinder.html

Swedish-wheel omnidirectional drive



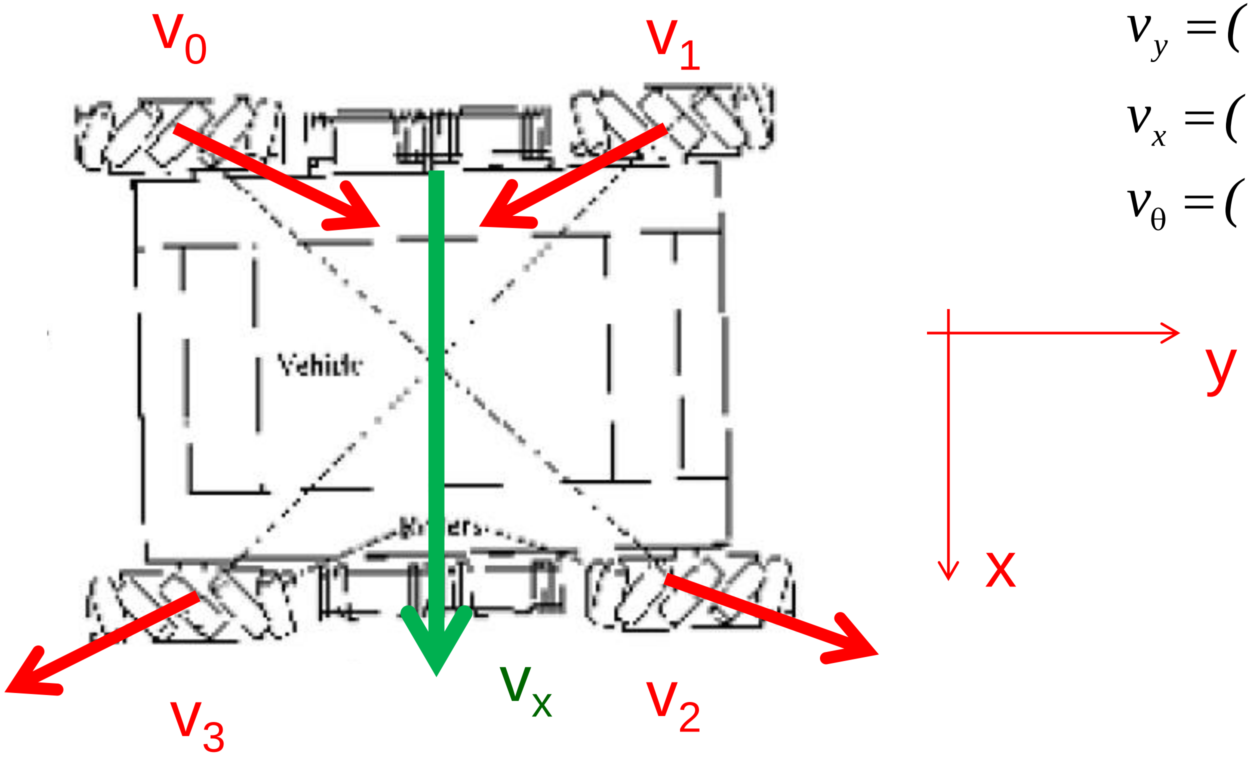
$$v_y = (v_0 + v_1 + v_2 + v_3)/4$$

$$v_x = (v_0 - v_1 + v_2 - v_3)/4$$

$$v_\theta = (v_0 + v_1 - v_2 - v_3)/4$$

Approximate force exerted when v_2 is positive

Swedish-wheel omnidirectional drive

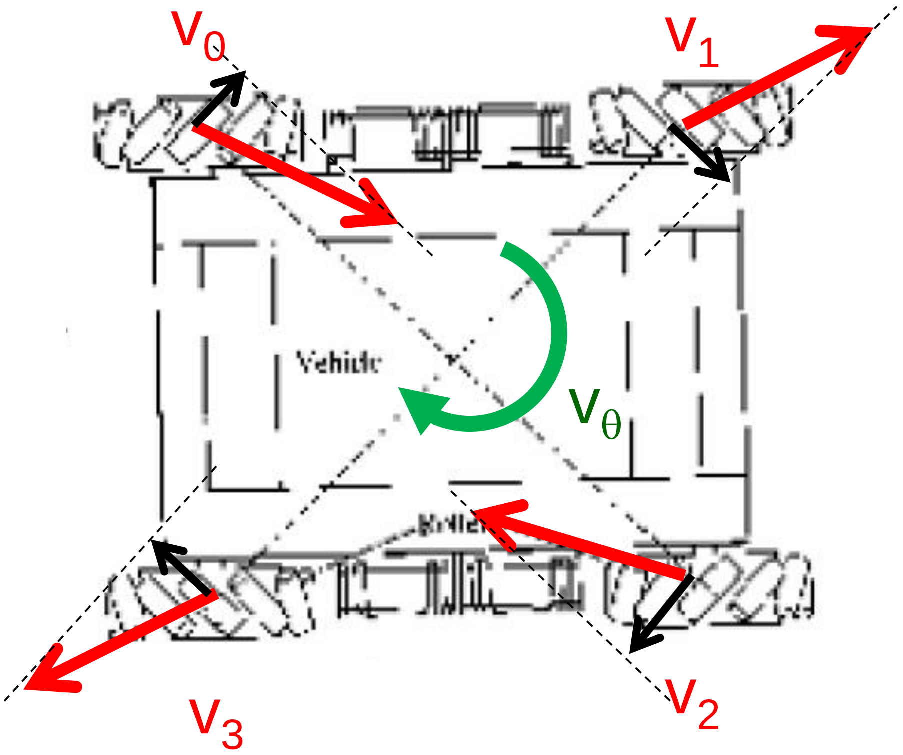


$$v_y = (v_0 + v_1 + v_2 + v_3)/4$$

$$v_x = (v_0 - v_1 + v_2 - v_3)/4$$

$$v_\theta = (v_0 + v_1 - v_2 - v_3)/4$$

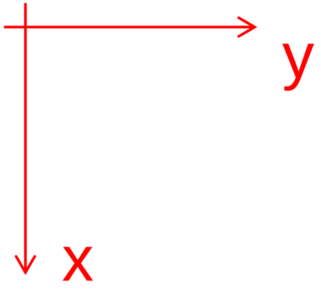
Swedish-wheel omnidirectional drive



$$v_y = (v_0 + v_1 + v_2 + v_3)/4$$

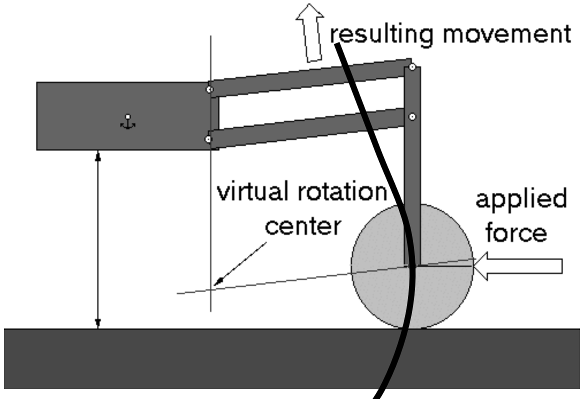
$$v_x = (v_0 - v_1 + v_2 - v_3)/4$$

$$v_\theta = (v_0 + v_1 - v_2 - v_3)/4$$

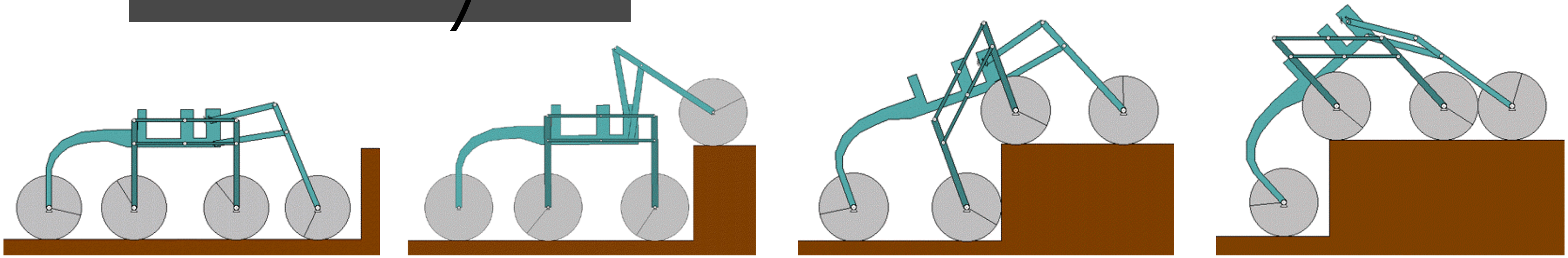


All-terrain wheeled robot: SHRIMP

- The Shrimp
  - Passive locomotion concept for rough terrain
  - 6 wheels
  - overcomes obstacles up to 2 times its wheel diameter



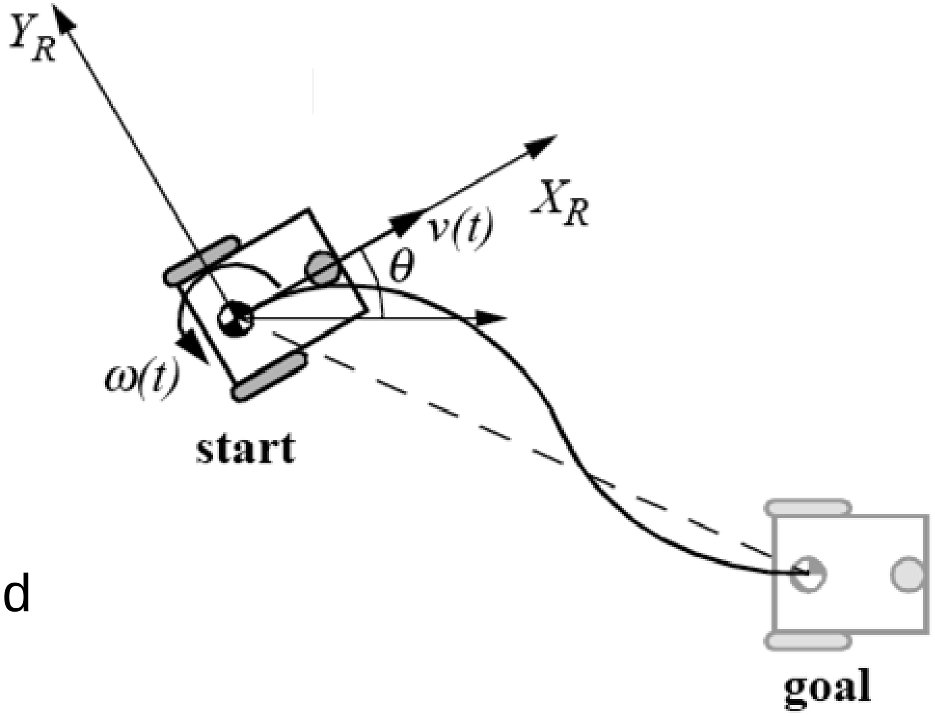
http://www.bluebotics.com/solutions/Shrimp/
https://www.youtube.com/watch?v=ZyVHdbAcTNs



Motion control of a differential drive robot

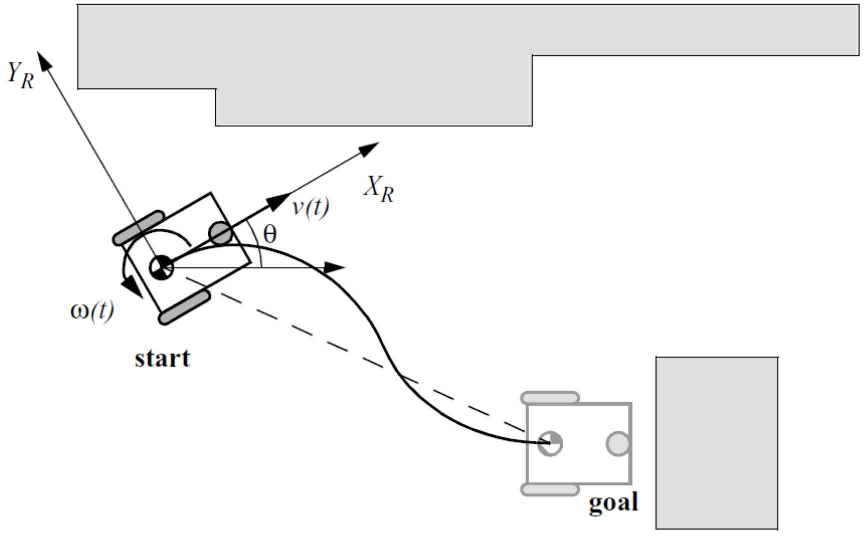
Motion control of a differential-drive robot

- The objective of a **motion controller** for a mobile robot is either to **follow a trajectory** or to **reach a target pose**.
- Motion control is not straight forward because mobile robots are often nonholonomic, nonlinear systems.
- However, it has been studied by various research groups and some adequate solutions for motion control of mobile robot systems are now available.
- Note that most controllers are not considering the dynamics of the system, i.e. forces are not computed and speed is not included in the state vector.



Motion planning for a dif.-drive Astolfi (1995, 1997, 1999)

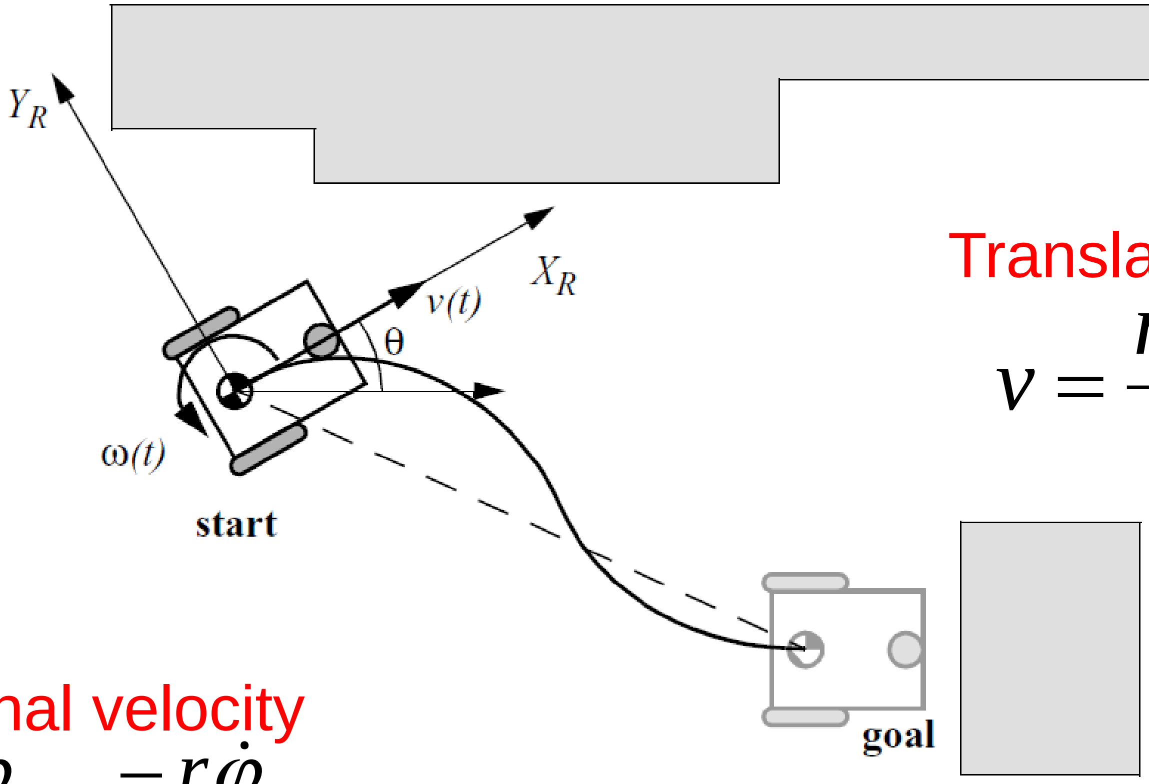
Problem statement: how to control the speed of the two motors to bring the robot to a desired position and orientation?



Option 1: Use combinations of rotations on the spot + straight segments.
Simple method but trajectory is not smooth.

Option 2: Design a control law that smoothly modulates both forward and rotational velocities. Elegant control law proposed by Astolfi and colleagues, see next.

Motion planning for a dif.-drive
Astolfi (1995, 1997, 1999)



Translational velocity

$$v = \frac{r\dot{\varphi}_1}{2} + \frac{r\dot{\varphi}_2}{2}$$

Rotational velocity

$$\omega = \frac{r\dot{\varphi}_1}{2l} + \frac{-r\dot{\varphi}_2}{2l}$$

Where φ_i is the motor speed, r is the wheel radius, l is the axle length, v is translational velocity and ω is the rotational velocity.

Kinematic model of a dif.-drive

First it is useful to link the speed of the two motors to the displacement of the robot in the global reference frame, and to the translational and rotational velocities.

Coordinate transformation from robot frame to the global reference frame:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = R(\theta)^{-1} \begin{bmatrix} \frac{r\dot{\varphi}_1}{2} + \frac{r\dot{\varphi}_2}{2} \\ 0 \\ \frac{r\dot{\varphi}_1}{2l} + \frac{-r\dot{\varphi}_2}{2l} \end{bmatrix} = R(\theta)^{-1} \begin{bmatrix} v \\ 0 \\ \omega \end{bmatrix}$$

Global frame

Local robot frame

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad R(\theta)^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

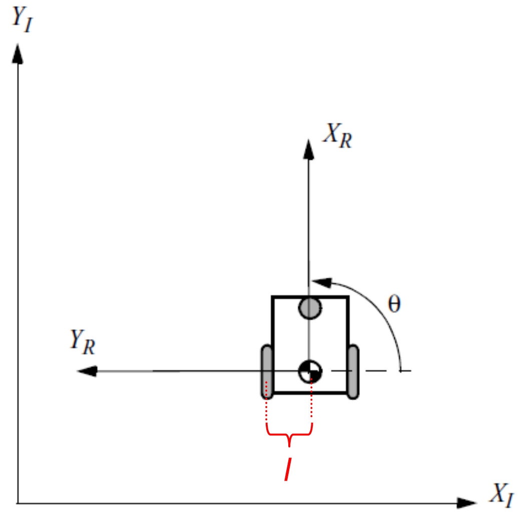


Figure 3.2
The mobile robot aligned with a global axis.

Where φ_i is the motor speed, *r* is the wheel radius, *l* is the axle length, *v* is translational velocity and ω is the rotational velocity.

Kinematic model of a dif.-drive

The kinematics of a differential drive mobile robot described in the inertial frame is given by:

Translational velocity

$$^{I}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\cos\theta & 0\\ \sin\theta & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}v\\ \omega\end{bmatrix}$$

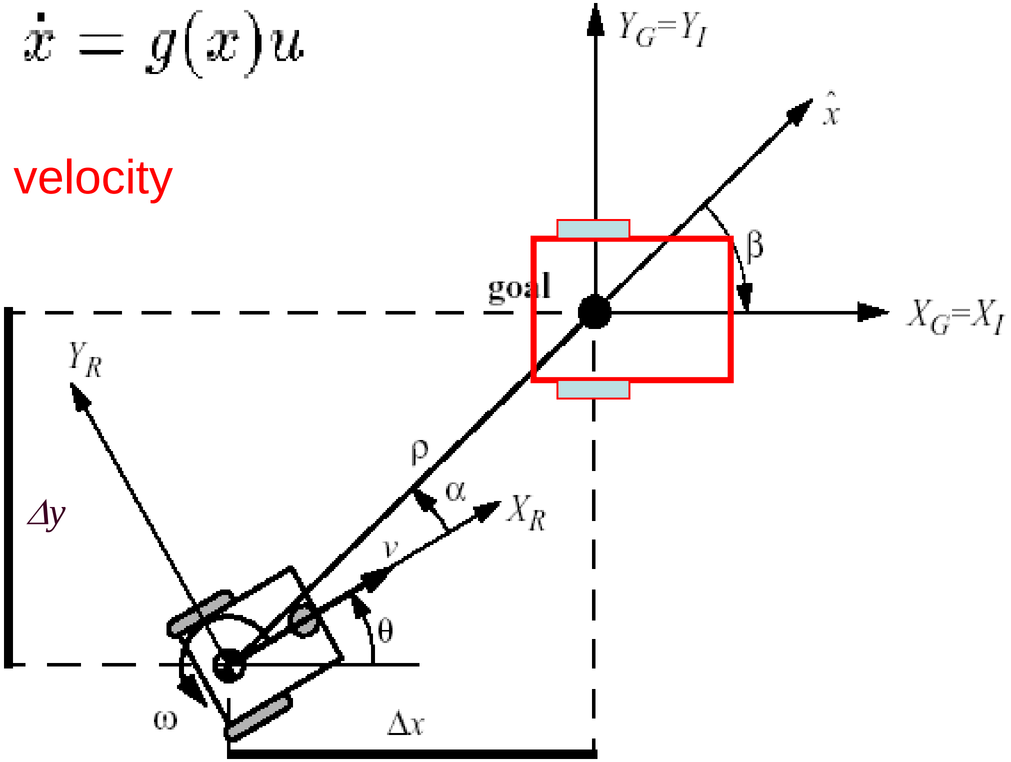
Rotational velocity

of the form:

$$\dot{x} = g(x)u$$

where $\dot{x}$ and $\dot{y}$ are the linear velocities in the direction of X_I and Y_I of the inertial frame.

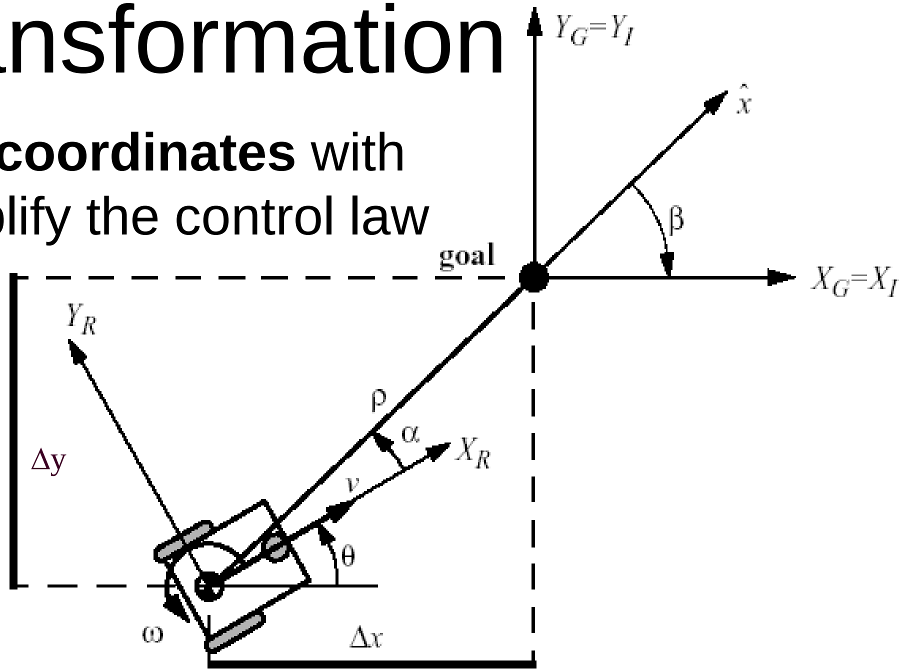
Let α denote the angle between the X_R axis of the robot's reference frame and the vector connecting the center of the axle of the wheels with the final position.



The goal is to reach Δx=0, Δy=0 and β=0

Coordinate transformation

The following transformation into **polar coordinates** with origin at the goal position allows to simplify the control law



$$\begin{cases} \rho = \sqrt{\Delta x^2 + \Delta y^2} \\ \alpha = -\theta + \operatorname{atan2}(\Delta y, \Delta x) \\ \beta = -\theta - \alpha \end{cases}$$

note: $\operatorname{atan2}(a, b) = \arctan\left(a/b\right)$

where the signs of both arguments are used to determine the quadrant of the result.

http://en.wikipedia.org/wiki/Atan2

Target: $(\rho, \alpha, \beta) = (0, 0, 0)$

The kinematic model in the new polar coordinates:

If $\alpha \in I_1 = \left(-\frac{\pi}{2}, \frac{\pi}{2}\right]$ or if $\alpha \in I_2 = (-\pi, -\pi/2] \cup (\pi/2, \pi]$

$$\begin{bmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} -\cos\alpha & 0 \\ \frac{\sin\alpha}{\rho} & -1 \\ -\frac{\sin\alpha}{\rho} & 0 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \qquad \begin{bmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} \cos\alpha & 0 \\ -\frac{\sin\alpha}{\rho} & 1 \\ \frac{\sin\alpha}{\rho} & 0 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}$$

The control law

- It can be shown, that the linear control law:

$$\boxed{v = k_\rho \rho \qquad \omega = k_\alpha \alpha + k_\beta \beta}$$

yields the closed loop system:

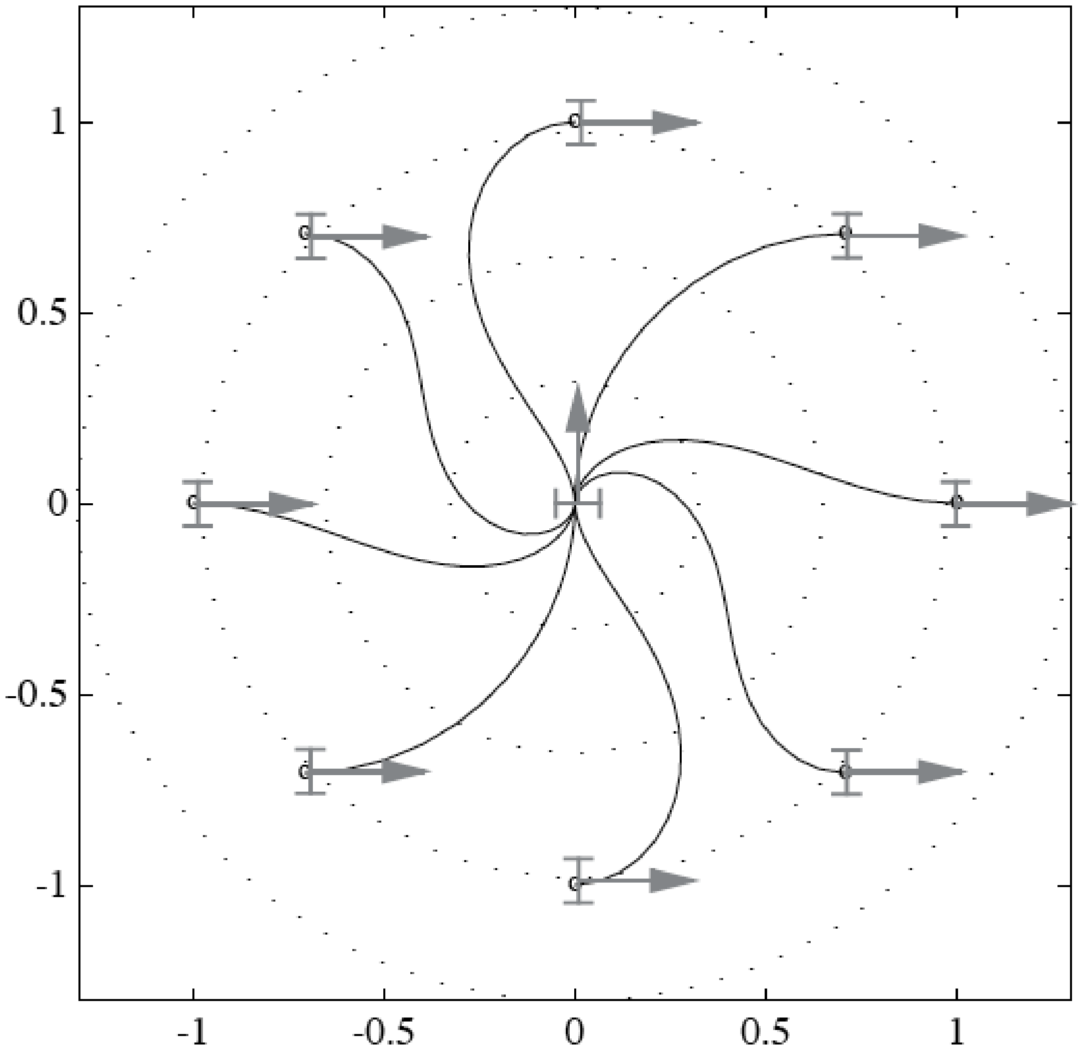
$$\begin{bmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} -k_\rho \rho \cos\alpha \\ k_\rho \sin\alpha - k_\alpha \alpha - k_\beta \beta \\ -k_\rho \sin\alpha \end{bmatrix}$$

which has a **unique equilibrium point** at $(\rho, \alpha, \beta) = (0, 0, 0)$

- Using the Lyapunov theory, it can be shown (Astolfi, 1995, 1997) that the closed loop control system is **exponentially stable** if: $k_\rho > 0$; $k_\beta < 0$; $k_\alpha - k_\rho > 0$

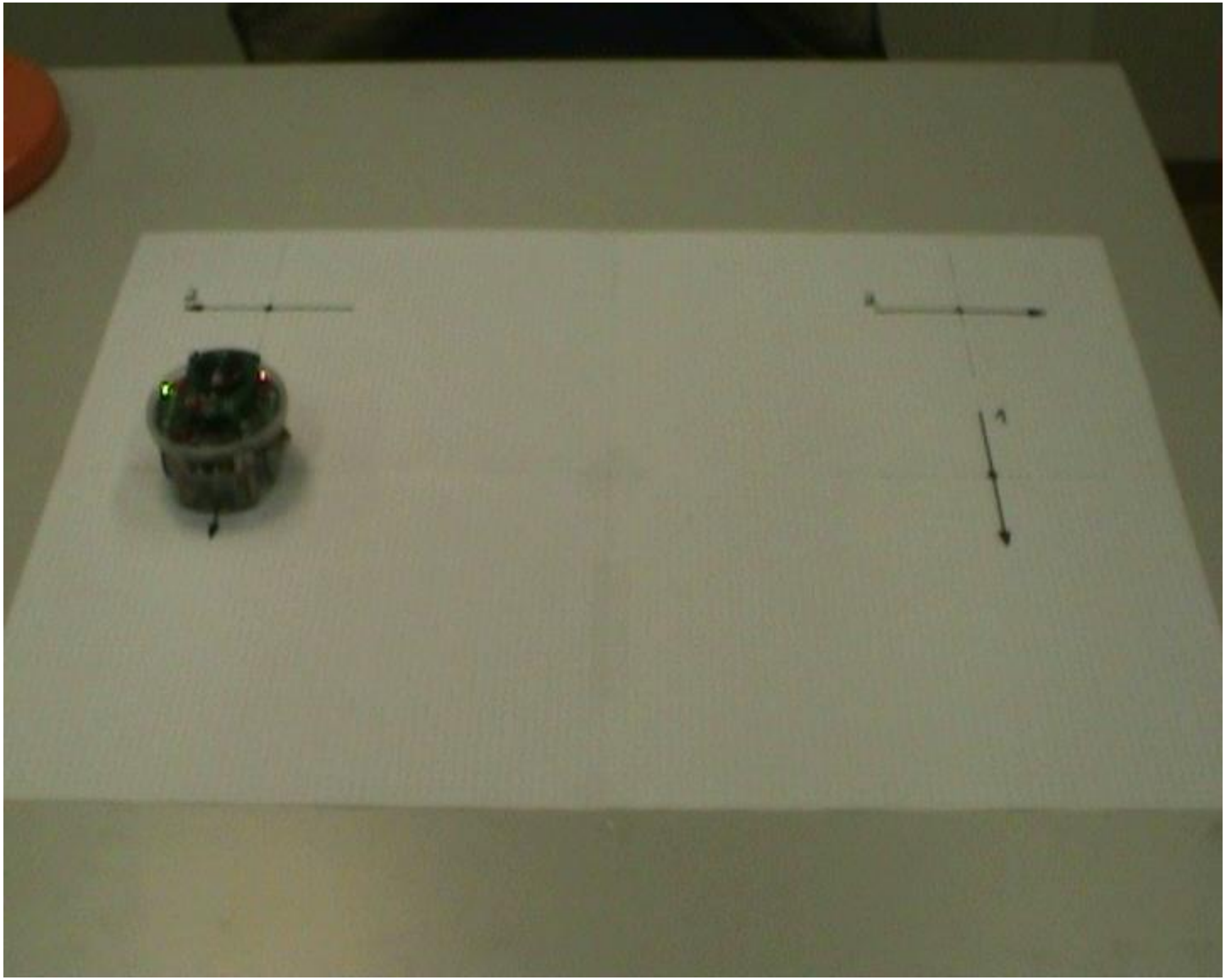
- The control signal v has always constant sign:
  - $\Rightarrow$ the direction of movement is kept positive or negative during the entire movement.
  - $\Rightarrow$ parking maneuver is performed always in the most natural way and without ever inverting its motion.

Resulting paths



differential_drive_motion_control.m

Implementation on e-puck



Reference

Exponential stabilization of a wheeled mobile robot via discontinuous control
A Astolfi - Journal of dynamic systems, measurement, and control, 121 (1), pp 121-126,1999

Wheeled versus legged robots

Pros of wheeled robots:

- Easy to construct
- Easy to control
- Energy efficient (except for soft terrains, see next slides) + no use of power at stand still

Cons:

- Cannot move in complex terrains
- Catastrophic failure when motor damage (if few wheels)

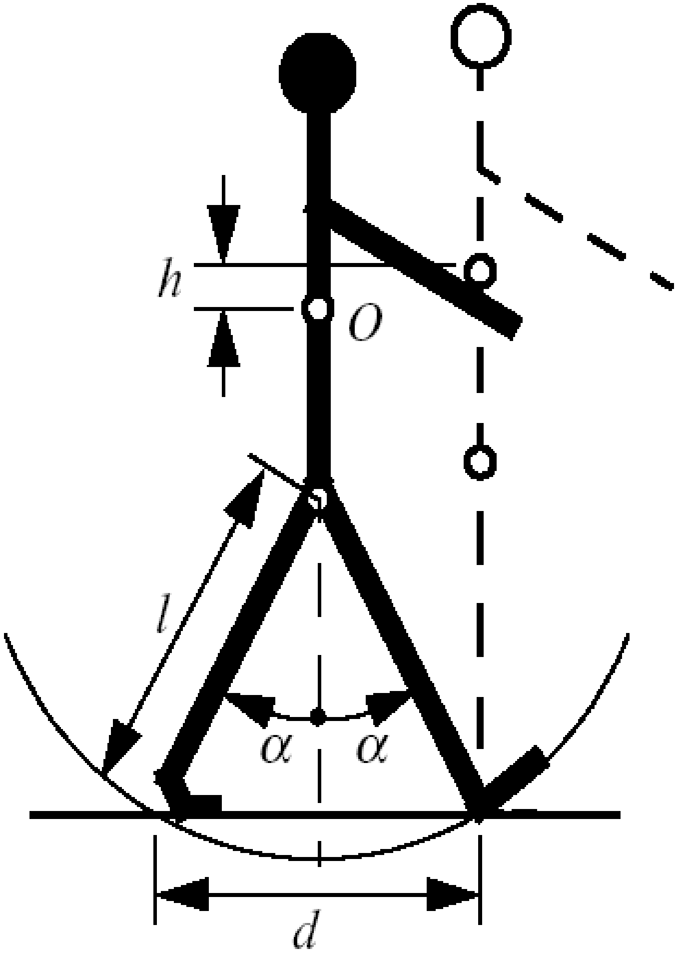
Pros of legged robots:

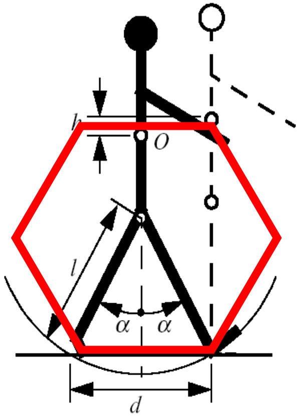
- Discrete contacts with the ground (good for passing obstacles)
- Can tackle a large variety of terrains
- Robustness against motor failure (because of redundancy)

Cons:

- Difficult to design and construct
- Difficult to control (because of many DOFs)
- Control required to keep balance

Walking of a biped





- Biped walking mechanism
  - not to far from rolling
  - rolling of a polygon with side length equal to the length of the step
  - the smaller the step gets, the more the polygon tends to a circle (wheel).
- However, fully rotating joint was not developed in nature. (except flagella in bacteria!)

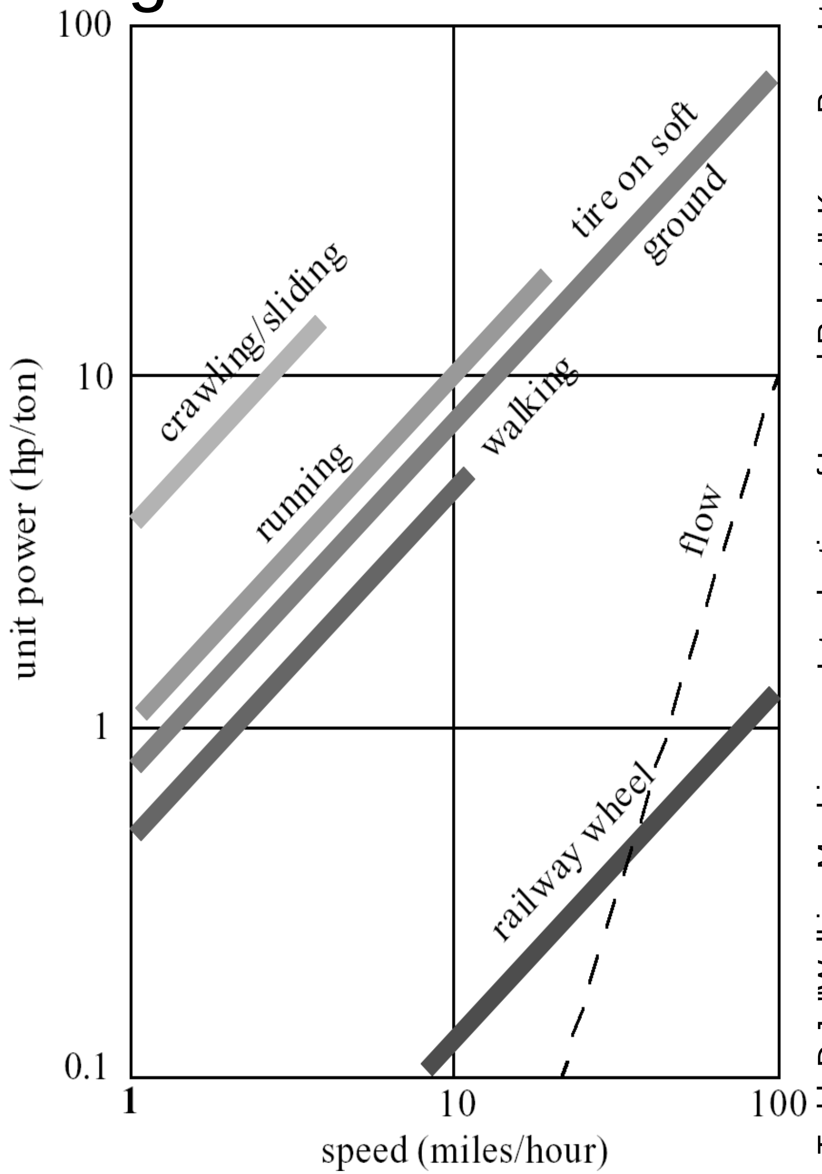
What's most energy efficient? Walking or rolling?

- Energy efficiency depends on:
  - terrain (flat ground, soft ground, climbing..)
  - movement of the involved masses: walking / running includes up and down movement of COG + some extra losses

From an energy point of view:

- Wheels are better on hard and flat terrains
- Walking is better on soft terrains

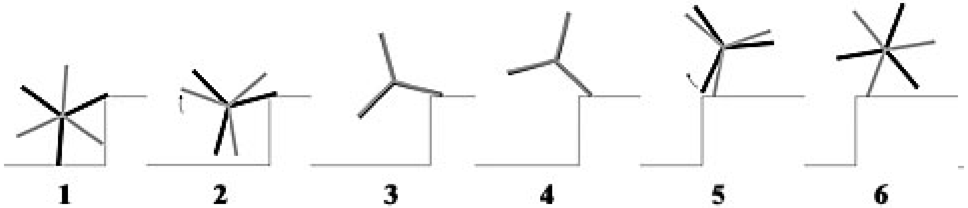
specific power vs attainable speed



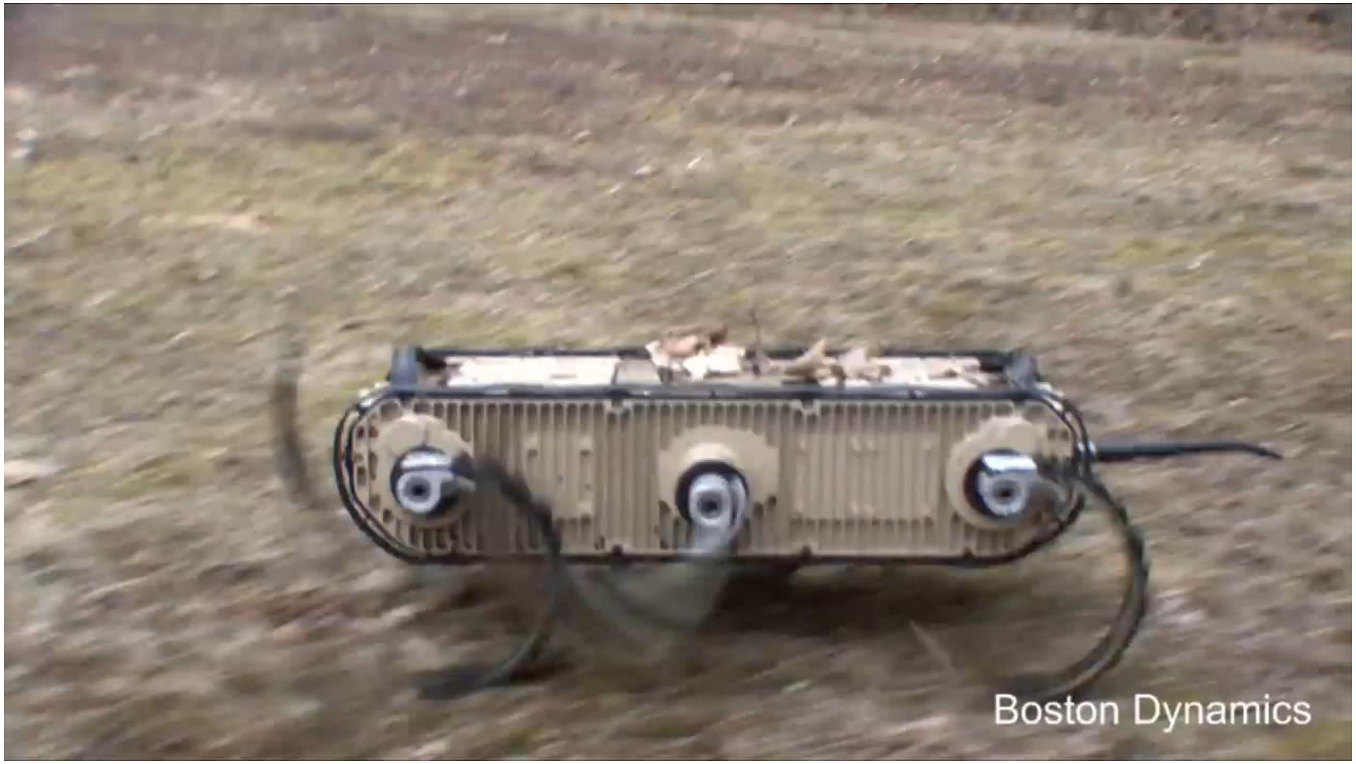
Todd, D.J, "Walking Machines, an Introduction of Legged Robots", Kogan Page Ltd, 1985

Whegs (or rotational legs) are a good compromise between wheels and legs, powerful for handling unstructured terrains

Whegs:



Case Biorobotics Lab



Rhex

https://www.youtube.com/watch?v=ISznqY3kESI

Topics:

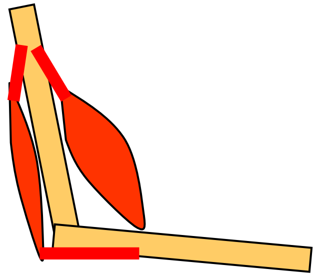
- Wheeled locomotion
- **Animal locomotion**
- Different control approaches in legged robotics
- Examples of projects from the Biorob lab

Biomechanics of animal Locomotion

General principles:

1. To **rhythmically apply forces** to the environment,

2. Use of **antagonist muscles ➔** creation of torques
   + modification of the stiffness of a joint



3. **Storage of mechanical energy** (spring prope
   of muscles and tendons)

4. **Multiple degrees of freedom**

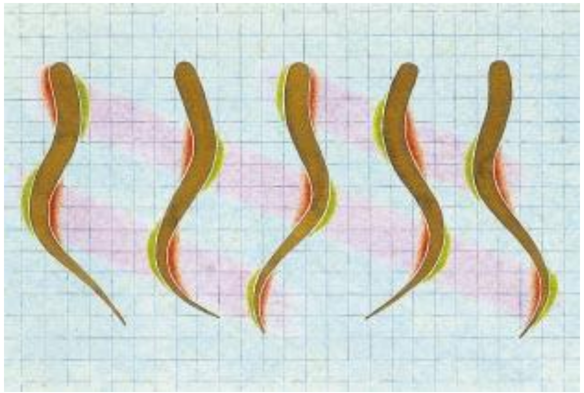
Biomechanics of animal Locomotion

Generation of forces:

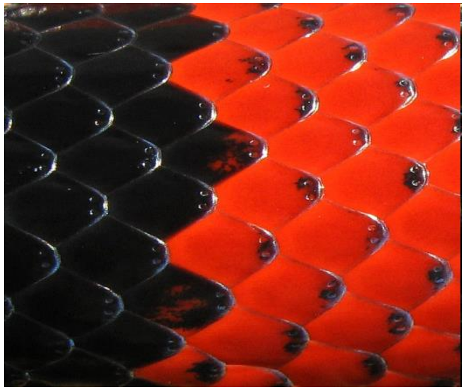
5. Animals use the **principles of action-reaction**

6. Key feature: **creation of asymmetries in the external forces due to the environment** (little resistance in the direction of locomotion compared to the other directions)

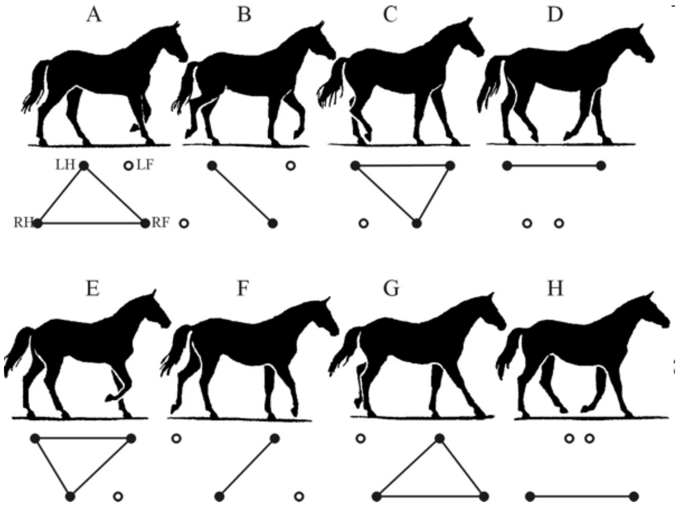
- Examples: elongated form of the body, scales on snake skin, legs (transition between swing and stance)



Asymmetric drag



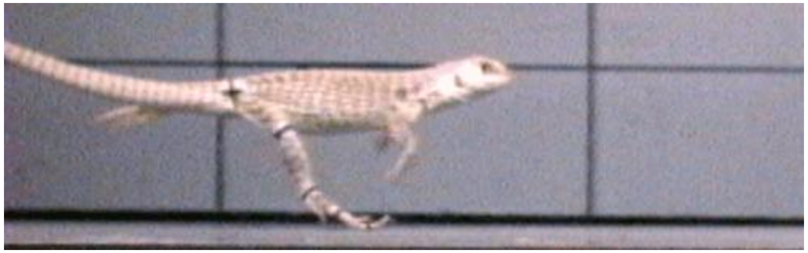
Scales:
Asymmetric friction



Swing-stance alternation

Biomechanics of animal Locomotion

Large diversity of different types of locomotion:swimming, crawling, walking, hoping, burrowing, flying,… but **all use the same principles**.



The beauty of animal movement control

Coordination of
multiple degrees of freedom

Adaptation to complex terrain

Visuomotor coordination
Switching between motor tasks

Learning new skills

Multiple redundancies

Control of locomotion is a difficult and « ill-posed » problem:

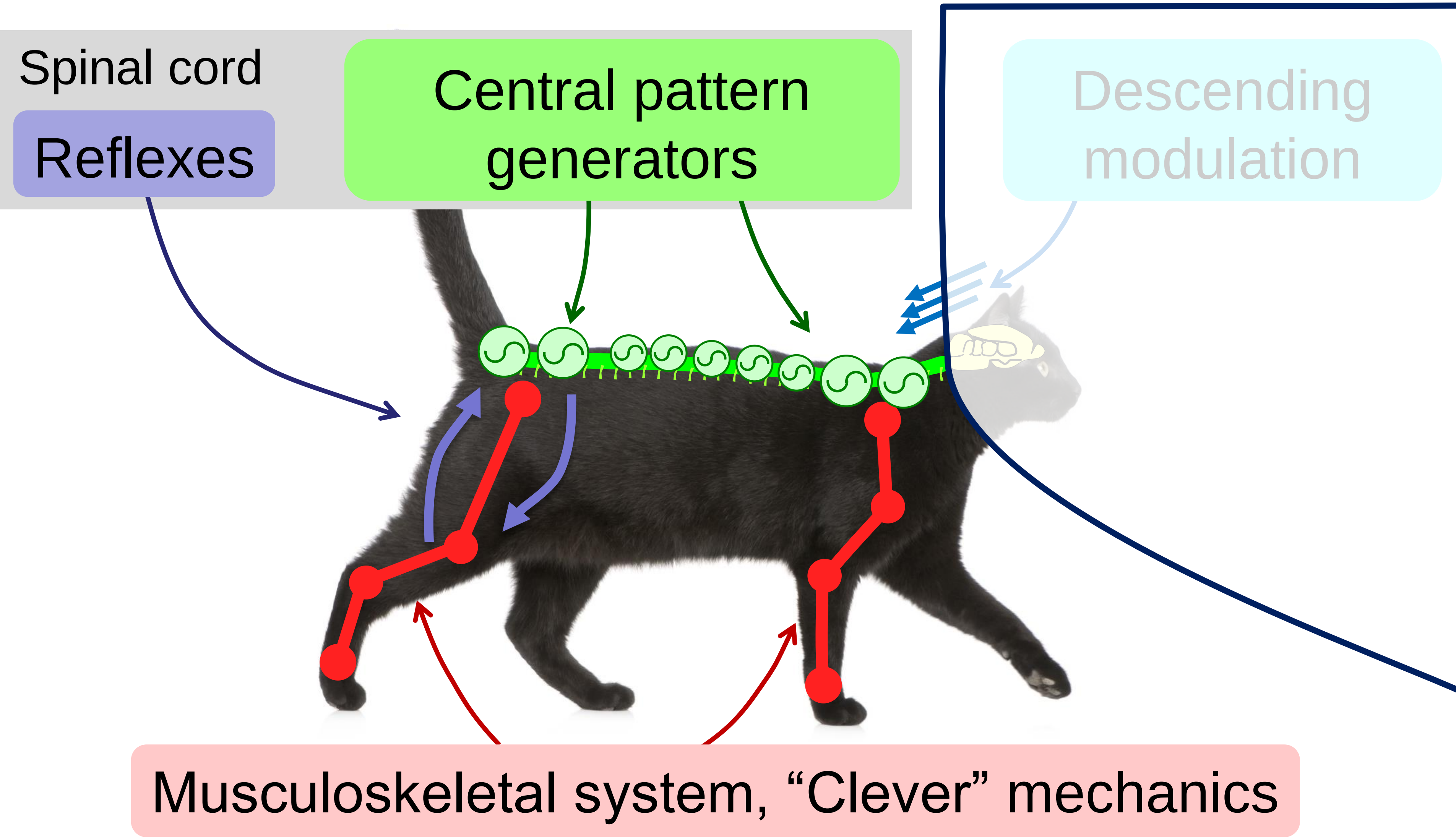
Requires good **coordination** (right frequencies, phases, signal shapes,…) of multiple degrees of freedom,

despite the multiple **redundancies**:

- Many possible **end-point trajectories**
- Many possible **postures** for a given end-point
- Many possible **muscle activations** for a given posture
- Many possible **motor unit** activations for a given muscle activation

We will see that most of these redundancy problems are solved by the spinal cord

Four essential ingredients in animal motor control



Spinal cord

Reflexes

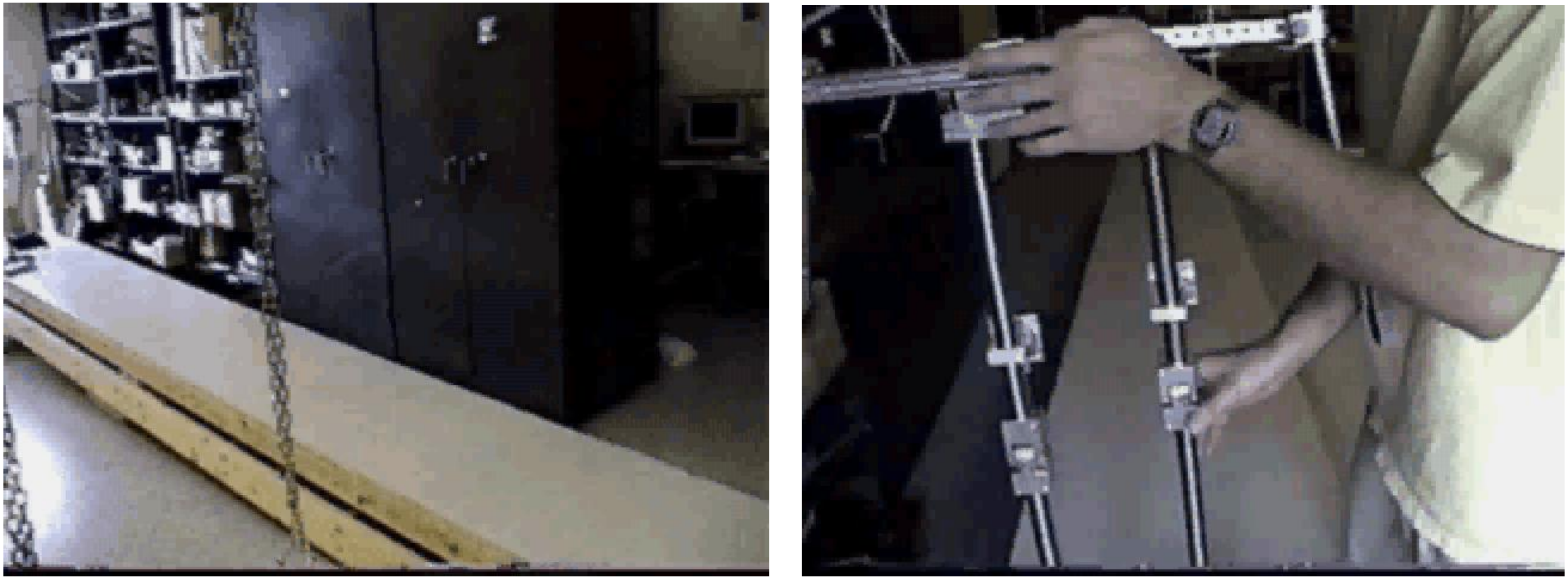
Central pattern generators

Descending modulation

Musculoskeletal system, “Clever” mechanics

Intelligent mechanics:

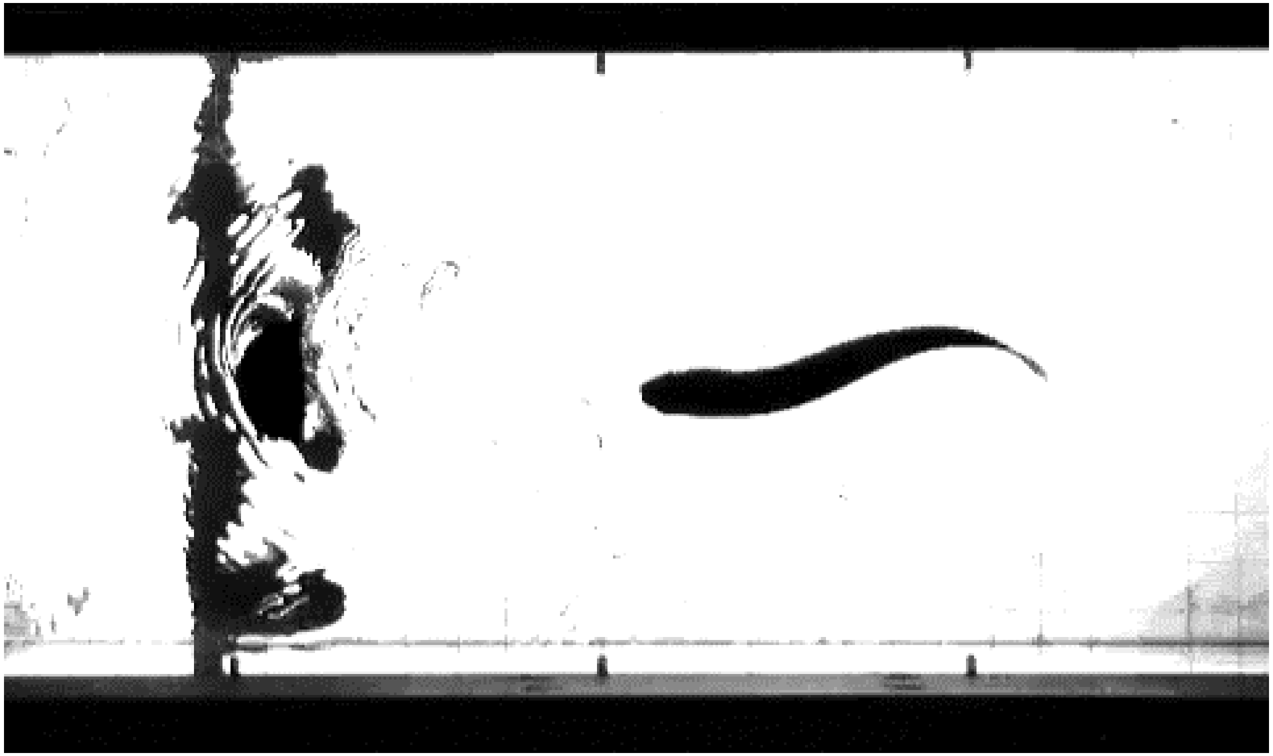
Walking without control and without battery!!



A Three-Dimensional Passive-Dynamic Walking Robot with Two Legs and Knees, Collins, S. H., Wisse, M., Ruina, A. International Journal of Robotics Research, Vol. 20, No. 2, Pages 607-615, 2001

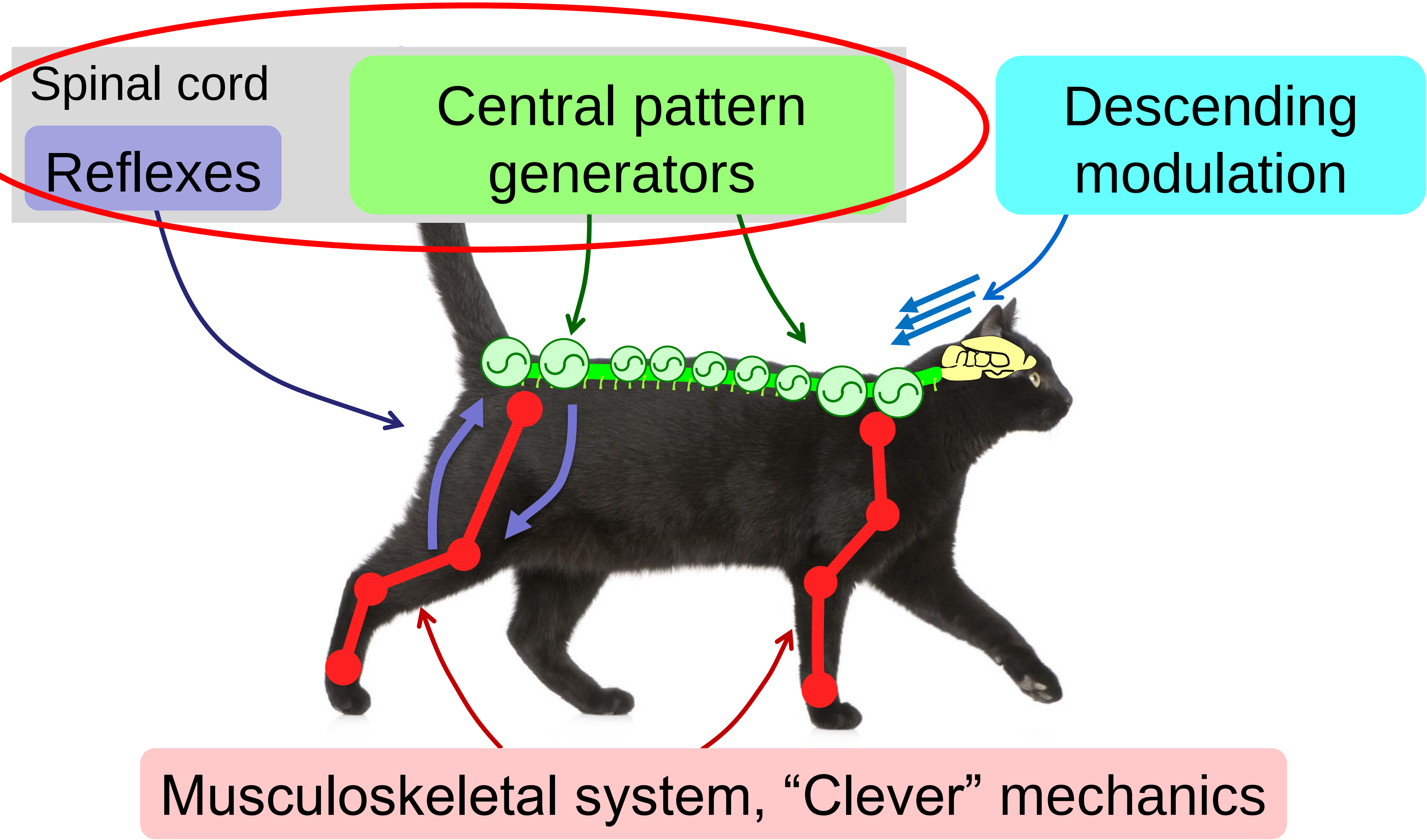
Intelligent mechanics:

Dead ! trout swimming



Liao, J. C. (2004).
Journal of Experimental Biology,
Vol. *207*(20), 3495-3506.
MIT tow tank, Lauder Lab Harvard
http://web.mit.edu/towtank/www/

Four essential ingredients in animal motor control



Spinal cord

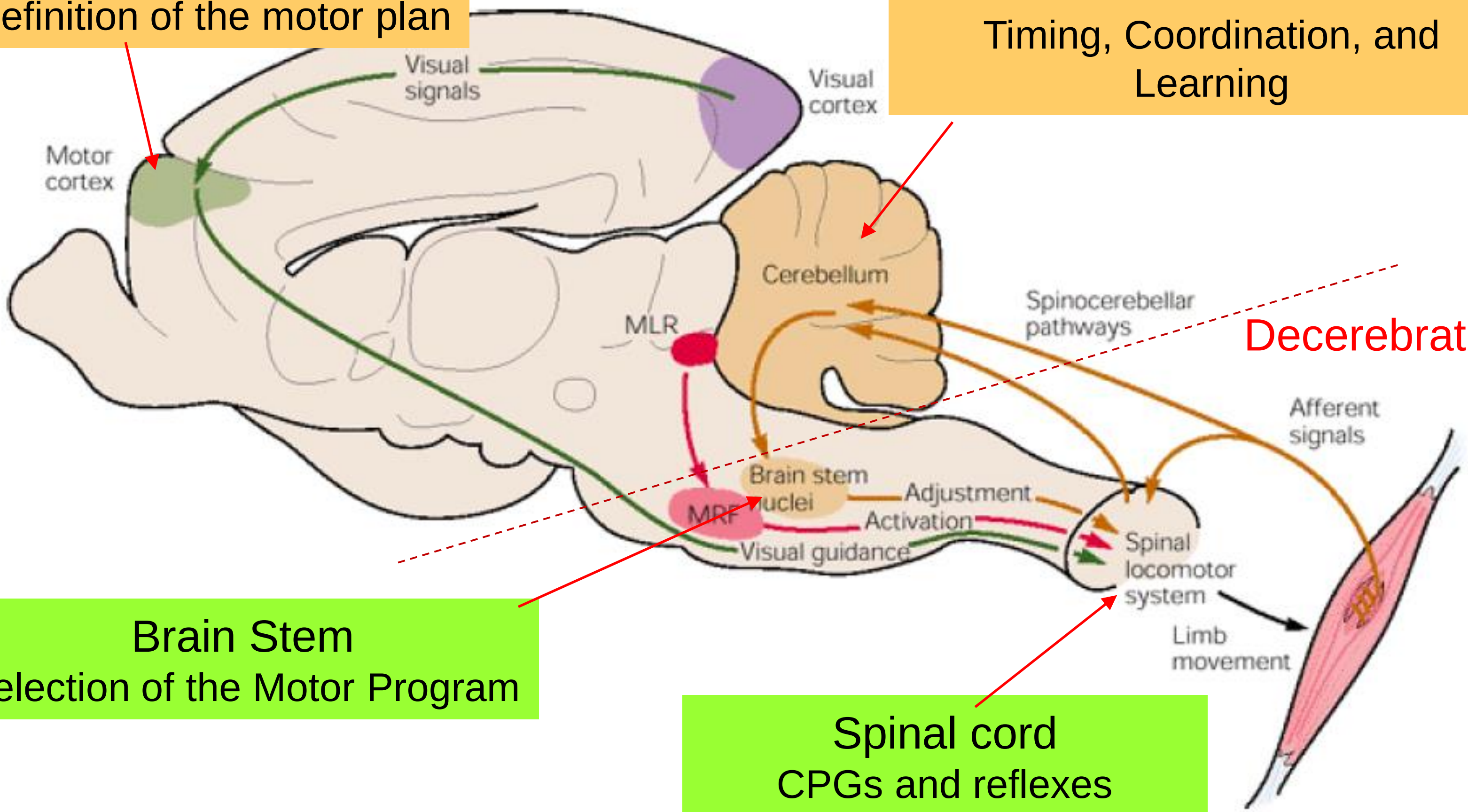
Reflexes

Central pattern generators

Descending modulation

Musculoskeletal system, “Clever” mechanics

Brain centers involved in vertebrate motor control



Cerebral cortex
Definition of the motor plan

Cerebellum
Timing, Coordination, and Learning

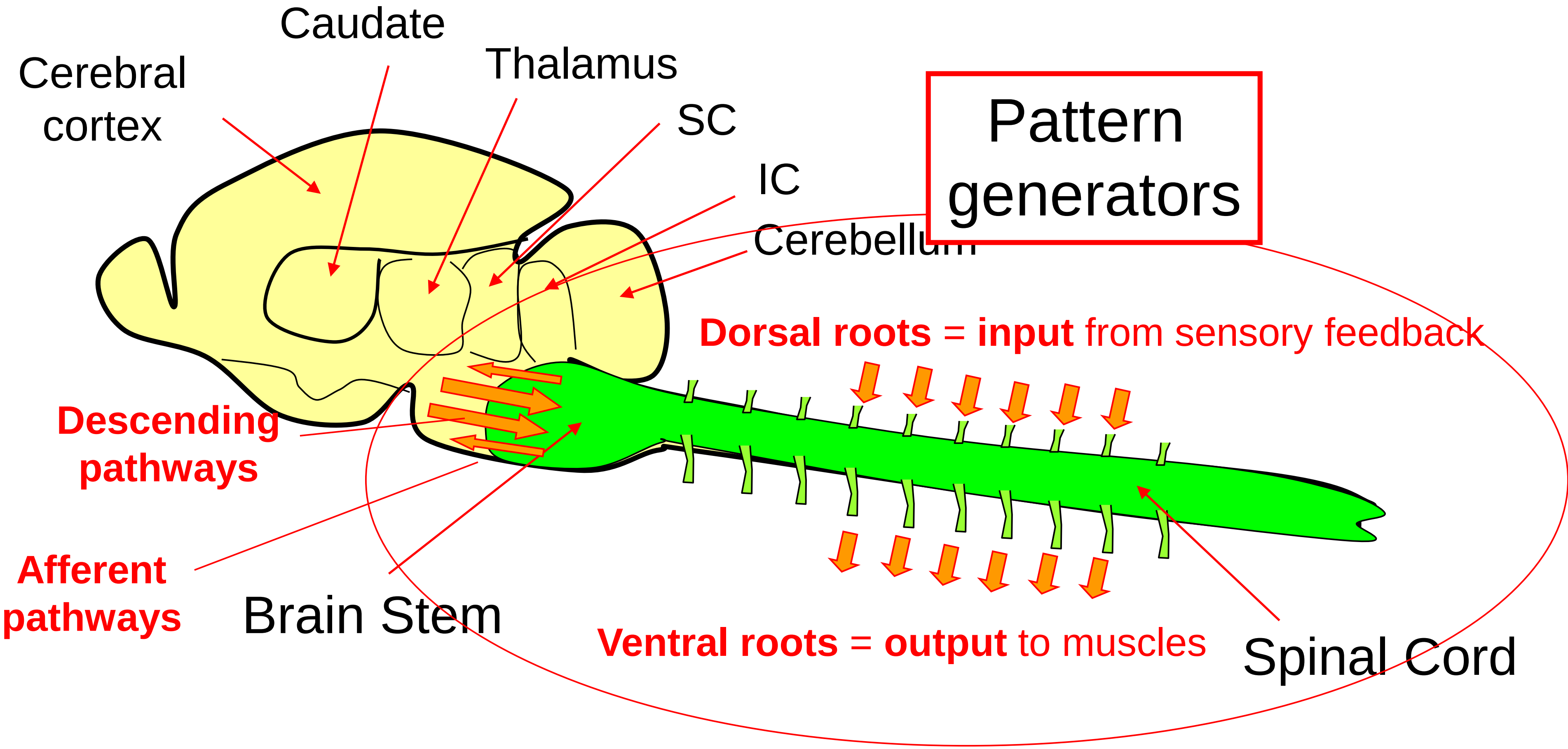
Decerebrated animal

Brain Stem
Selection of the Motor Program

Spinal cord
CPGs and reflexes
Spatiotemporal Sequences
Activation of muscles

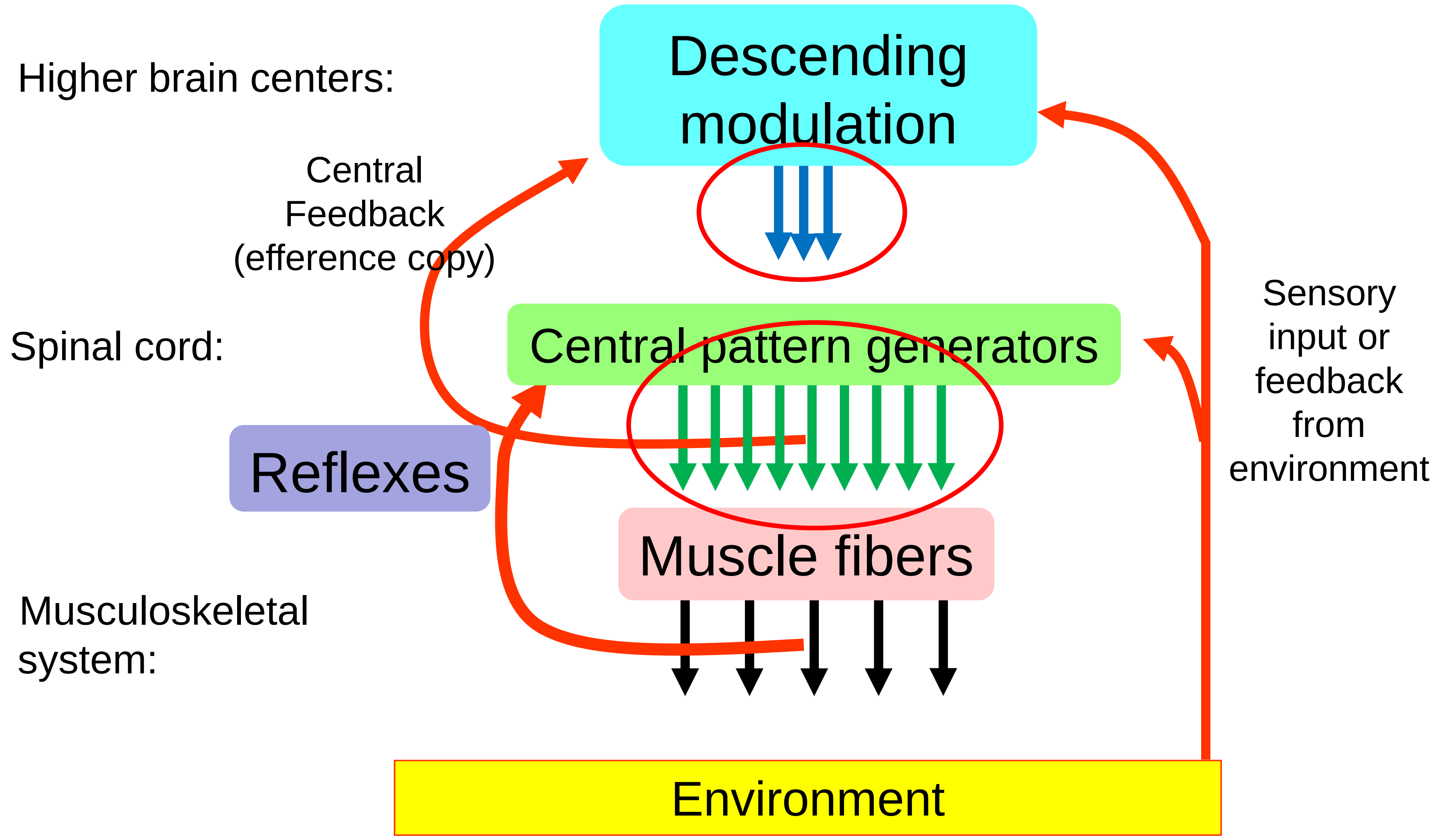
From: *Principles of Neural Science*. 4th edition. Edited by E.R. Kandel, J.H. Schwartz and T.M. Jessell. Appleton & Lange, New York.

Building bricks for motor control: **pattern generators**

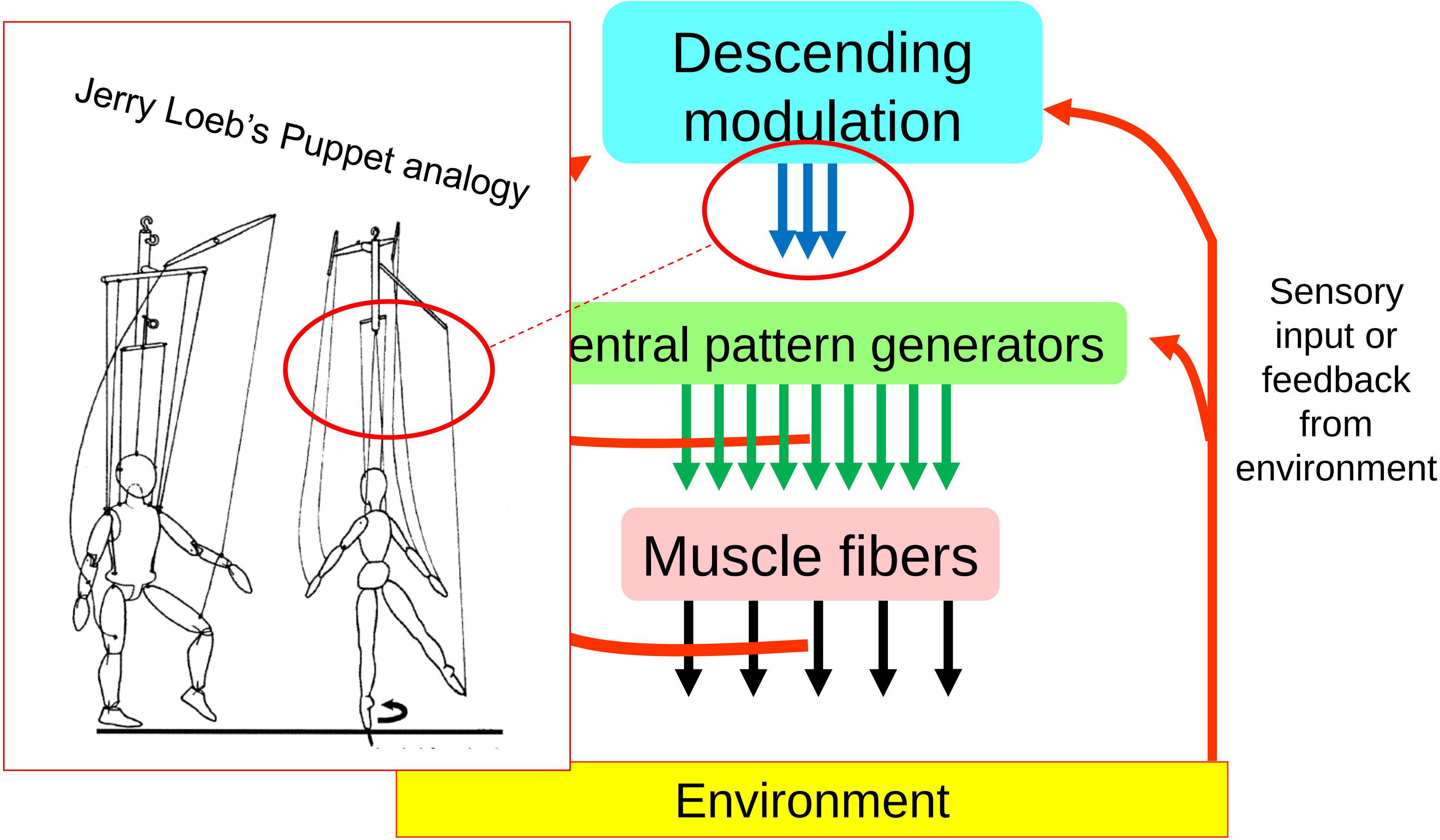


Simple inputs ➔ complex outputs. E.g gait transition by electrical stimulation of the brain stem (Shik and Orlosky 1966)

Central pattern generators in the spinal cord



Central pattern generators in the spinal cord



Jerry Loeb's Puppet analogy

Descending modulation

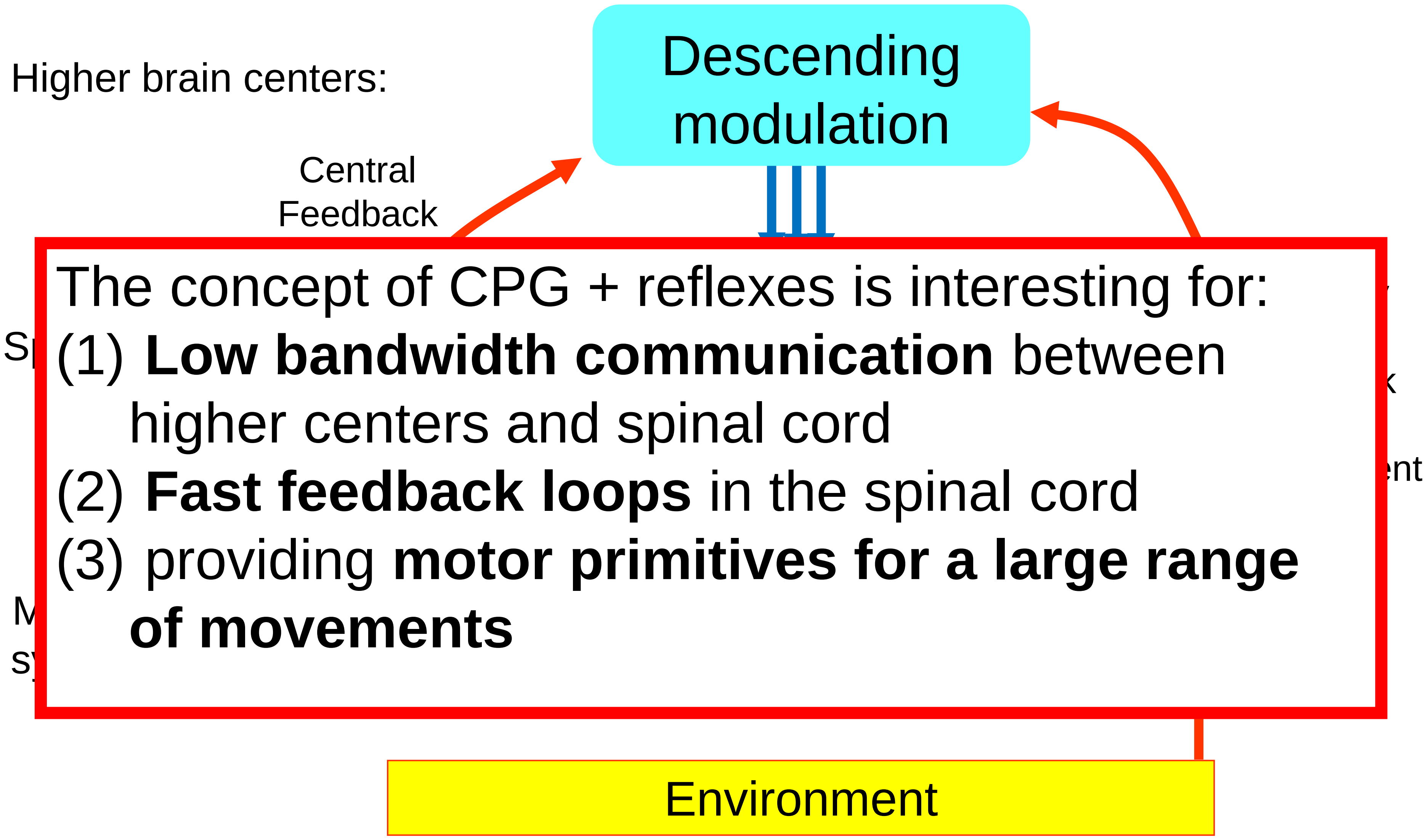
entral pattern generators

Muscle fibers

Sensory input or feedback from environment

Environment

Central pattern generators in the spinal cord



The concept of CPG + reflexes is interesting for:

(1) **Low bandwidth communication** between higher centers and spinal cord

(2) **Fast feedback loops** in the spinal cord

(3) providing **motor primitives for a large range of movements**

Animals = good source of inspiration

Due to the efficiency and agility of animals, robotics has naturally taken inspiration from biology:

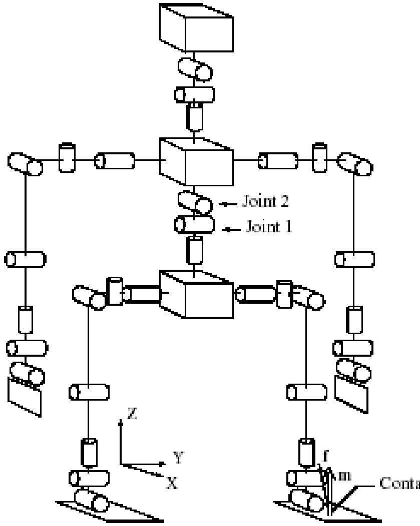
- In **their structure** (e.g. snake, hexapod, quadruped, biped robots)
- In their **modes of locomotion** (walking, running, …)
- In their **control methods** (e.g. CPG-based controllers, see next slides)

Note: It would be a mistake for engineers to blindly copy animals, better **only re-implement some key principles**

Topics:

- Wheeled locomotion
- Animal locomotion
- **Different control approaches in legged robotics**
- Examples of projects from the Biorob lab

The problems of legged locomotion control



- **Underactuated problem**: a robot cannot follow arbitrary motion commands (because it is not attached to the ground)
- **Need to keep balance**. Many robots are only dynamically stable (e.g. quadruped and biped robots) and require careful control for staying upright.
- **Need to coordinate multiple degrees of freedom**, most legged robots are **redundant robots** (i.e. more controllable DOFs than the state DOFs)
- Legged robots are **highly nonlinear systems**, with complex relationships between joint motor commands and robot posture.
- The control of legged robots has to **take into account the robot dynamics** (not only the kinematics, as in wheeled robots).

Different approaches to legged robot locomotion control in current robots

Model-based control:

1. **trajectory based methods (ZMP)**
2. heuristic control methods
    - A. Virtual leg control (Raibert)
    - B. Virtual model control (Pratt et al)
3. Planning methods (Little dog project)
4. Inverse dynamics and optimization

Biologically-inspired approaches:

1. Passive and dynamic walkers
2. Sensory-driven methods,
3. CPG-and-reflex based methods

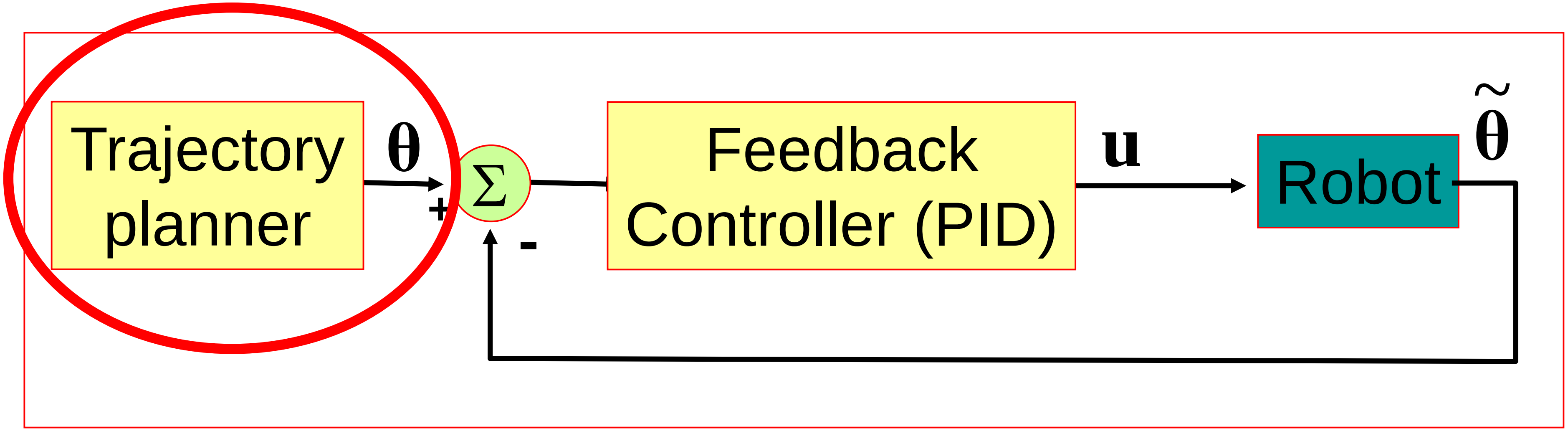
Trajectory based methods

- Main idea: design walking kinematic trajectories, and use the dynamic equations to test and prove that locomotion is stable

- Trajectories are designed by trial-and-error, or from human recordings

- Most used stability criterion: Zero Moment Point (ZMP) (Vukobratovic 1990)

Minimalistic control diagram

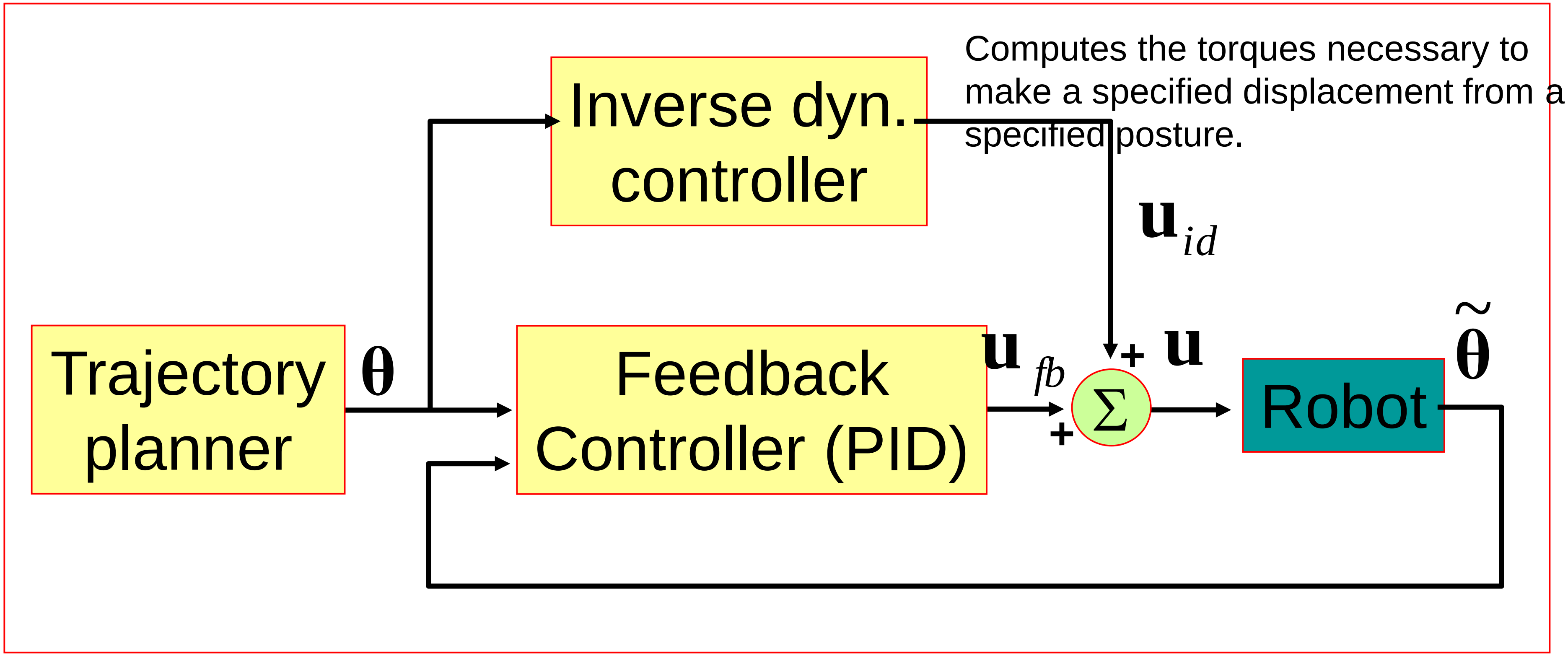


$\boldsymbol{\theta}$ Desired robot posture

$\tilde{\boldsymbol{\theta}}$ Actual robot posture

$\mathbf{u}$ Command (torque)

More sophisticated: Inverse dynamics



Computes the torques necessary to make a specified displacement from a specified posture.

Inverse dyn. controller

Trajectory planner

$\boldsymbol{\theta}$

Feedback Controller (PID)

$\mathbf{u}_{fb}$

$\mathbf{u}_{id}$

$+$

$+$

Σ

$\mathbf{u}$

Robot

$\tilde{\boldsymbol{\theta}}$

$\boldsymbol{\theta}$ Desired robot posture

$\tilde{\boldsymbol{\theta}}$ Actual robot posture

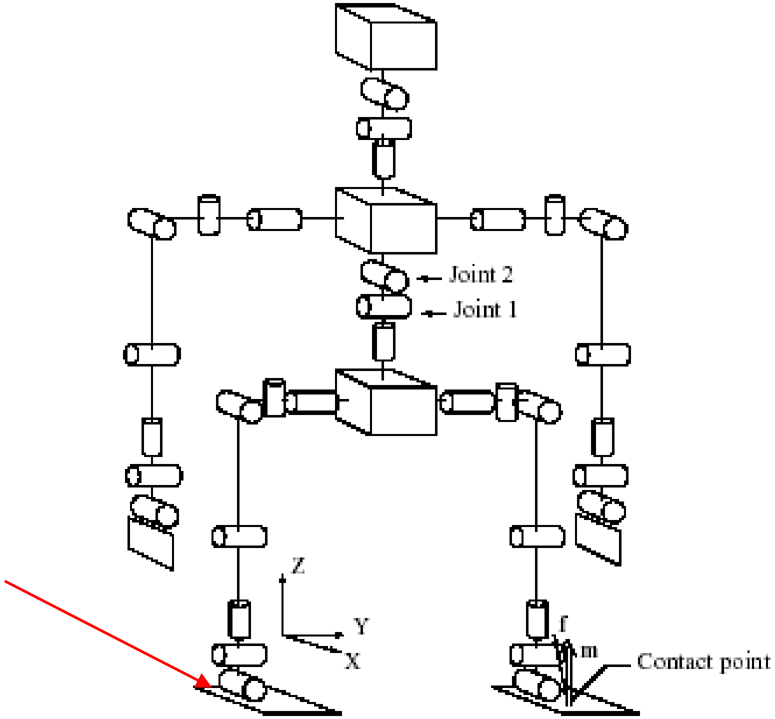
$\mathbf{u}$ Command (torque)

A PID does not know anything about the physics of the body (e.g. gravity, inertias).

The inverse dynamics uses knowledge of the configuration and characteristics of the robot to compute the exact torques necessary to make a displacement

Trajectory-based with ZMP

Foot-print polygon



Locomotion is stable if the ZMP remains within the foot-print polygons over time

Trajectory-based with ZMP

- Example: (early) Honda robot

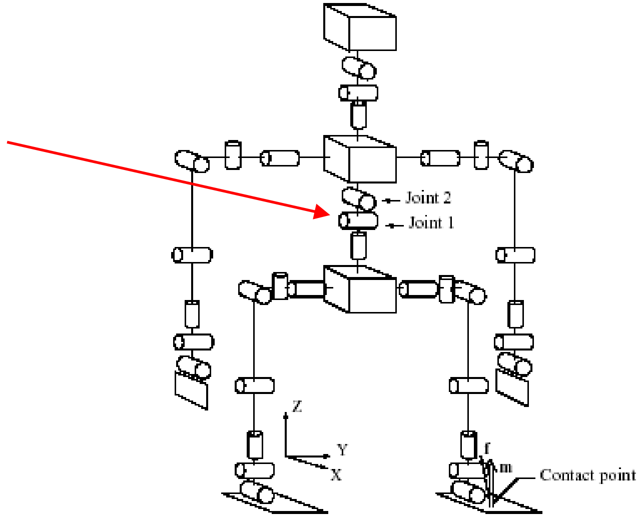
Trajectory-based with ZMP

Most used method:

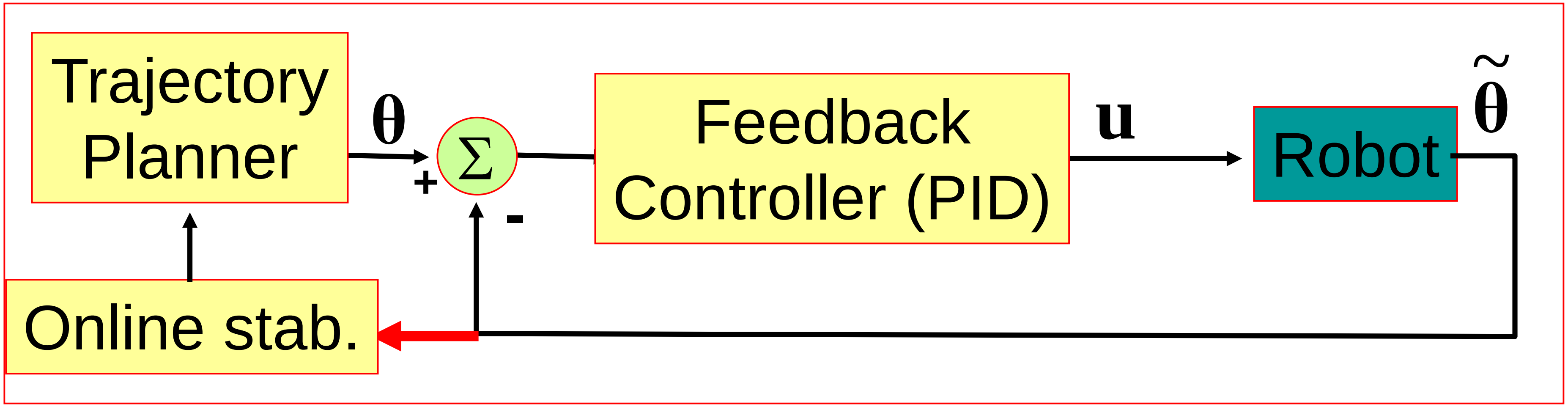
1. Human motion capture for getting trajectories,
2. Modify trajectories such that locomotion is stable according to the ZMP criterion
3. Add online stabilization to deal with perturbations.

Example of online stabilization:

- Use of two hip actuators to manipulate the ZMP



Control diagram: ZMP + online stabilization



θ Desired robot posture

$\tilde{\theta}$ Actual robot posture

$\mathbf{u}$ Command (torque)

Trajectory-based with ZMP: conclusions

Pros:

- Well-defined methodology for proving stability
- Well-suited for expensive robots that should never fall

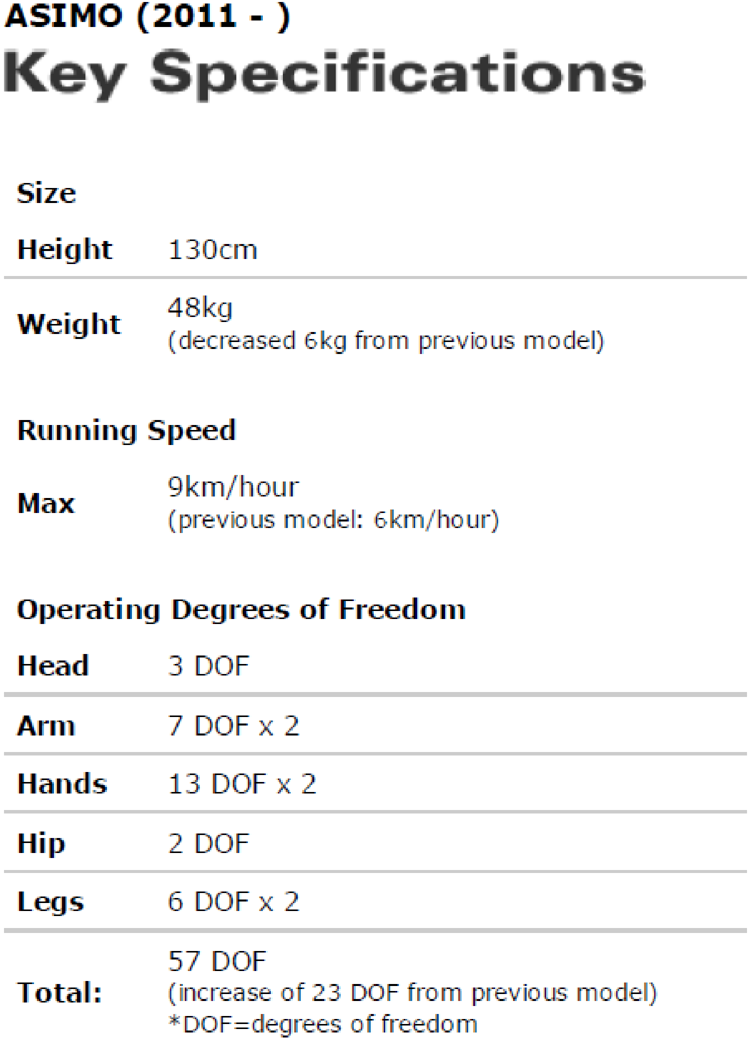
Cons:

- Requires a perfect knowledge of the robot’s dynamics and of the environment
- Requires additional online control to deal with perturbations
- Defining good trajectories can be time-consuming
- Energetically inefficient (requires stiff actuation)

Note: There exist other criteria than ZMP, e.g Foot Rotation Indicator, Centroidal Moment Pivot, …

Reference: Vukobratovic, M. and Borovac, B. (2004). Zero-moment point - thirty five years of life. International Journal of Humanoid Robotics, 1(1):157–173.

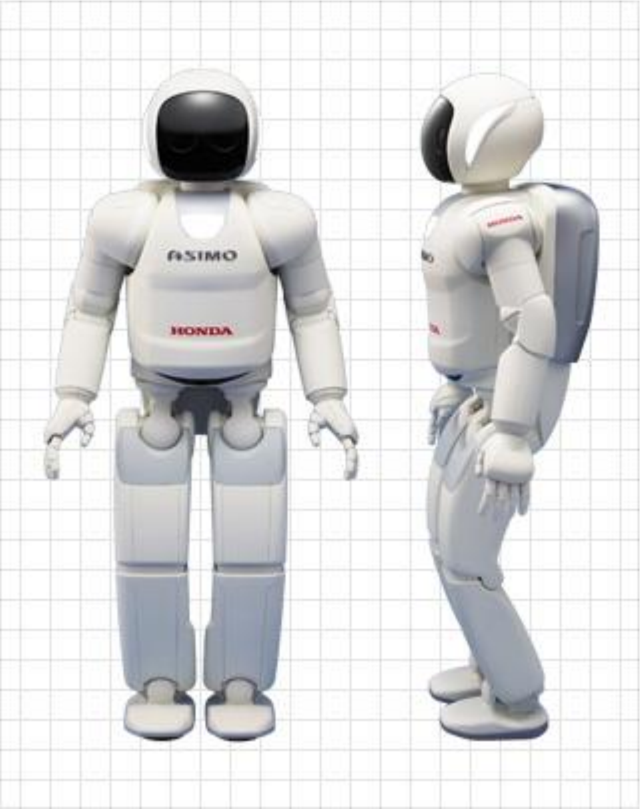
Note the huge progress with Honda’s Asimo



ASIMO (2011 -)

Key Specifications

Size	
Height	130cm
Weight	48kg (decreased 6kg from previous model)
Running Speed	
Max	9km/hour (previous model: 6km/hour)
Operating Degrees of Freedom	
Head	3 DOF
Arm	7 DOF x 2
Hands	13 DOF x 2
Hip	2 DOF
Legs	6 DOF x 2
Total:	57 DOF (increase of 23 DOF from previous model) *DOF=degrees of freedom



- http://world.honda.com/ASIMO/
- http://world.honda.com/ASIMO/video/index.html

Different approaches to legged robot locomotion control in current robots

Model-based control:

1. trajectory based methods (ZMP)
2. heuristic control methods
   - **A. Virtual leg control (Raibert)**
   - B. Virtual model control (Pratt et al)
3. Planning methods (Little dog project)
4. Inverse dynamics and optimization

Biologically-inspired approaches:

1. Passive and dynamic walkers
2. Sensory-driven methods,
3. CPG-and-reflex based methods

Virtual Leg Control

- Developed by Marc Raibert and colleagues (CMU, MIT, Boston Dynamics) for hopping/running robots (i.e. with short flight phases). Closely related to the SLIP model.

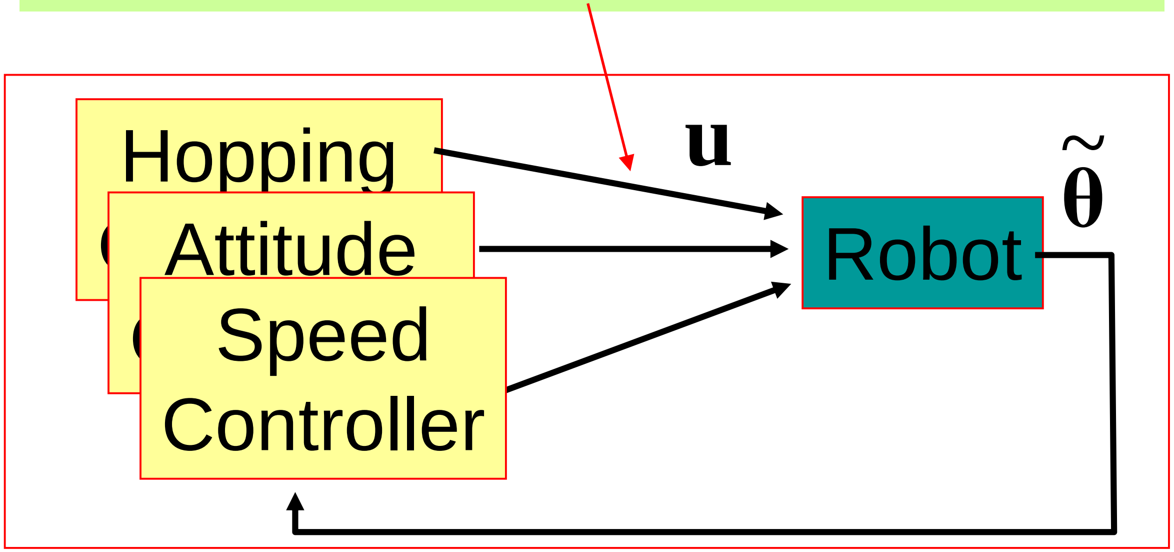
- One- two- and four-legged robots controlled by a similar approach

- Key idea: to decompose the problem into three (independent) parts:

1. *Hopping control*: Supporting the body with a vertical bouncing motion
2. *Attitude control*: Controlling the attitude of the body by servoing the body through hip torques during stance
3. *Speed control:* Placing the feet in key locations on each step using symmetry principles

Control diagram: Virtual Leg Control

Directly produces torques,
no tracking of a desired trajectory



Hopping

Attitude

Speed Controller

$\mathbf{u}$

Robot

$\tilde{\boldsymbol{\theta}}$

$\tilde{\boldsymbol{\theta}}$ Actual robot posture

$\mathbf{u}$ Command (torque and force)

Robots at MIT LegLab

© The Leg Laboratory

Similarities between 1, 2, and 4 legs

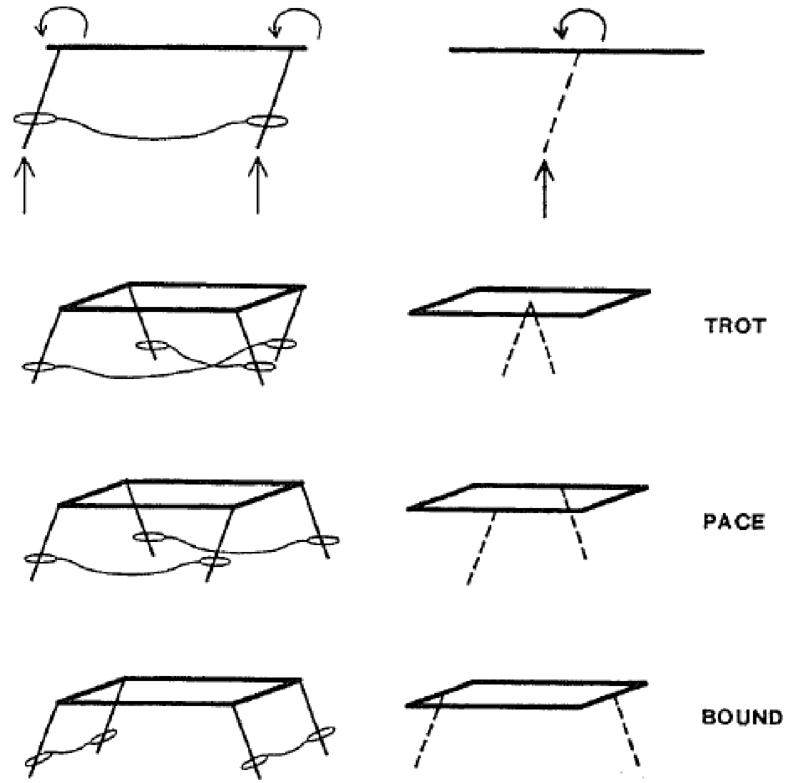


Fig. 3. Virtual legs. When two legs are coordinated to act in unison, they can be represented by a functionally equivalent *virtual leg*. The virtual leg and the original pair of physical legs both exert the same forces and moments on the body, so they both result in the same behavior. When each pair of legs is replaced by a virtual leg, the trot, the pace, and the bound are transformed into equivalent virtual biped gaits. One virtual leg is used for support at a time. Sutherland first introduced the concept of the virtual leg to simplify the design of a six-legged walking machine (Sutherland and Ullner, 1984).

Raibert, 1990, Trotting, pacing and bounding by a quadruped robot, Journal of Biomechanics Volume 23, Supplement 1, 1990, Pages 79–81, 83–98

Virtual Leg Control: summary

Pros:

- The most impressive locomotion skills in current robots (e.g. BigDog)
- Quite simple to implement (e.g. no complex models needed)

Cons:

- Needs very powerful actuators (hydraulic)
- No (analytical) proof of stability
- Only applicable to hopping/running robots (no walking)

References:

- Raibert, M. H. and Hodgins, J. K. (1993). Legged robots. In Beer, R. D., Ritzmann, R. E., and McKenna, T. M., editors, Biological Neural Networks in Invertebrate Neuroethology and Robotics, pages 319–354. Academic Press.
- M.H. Raibert, M. Chepponis, and H. Benjamin Brown, "Running on Four Legs As Though They Were One," IEEE Journal of Robotics and Automation, Vol. RA-2, No. 2, June, 1986, pp. 70 - 82.

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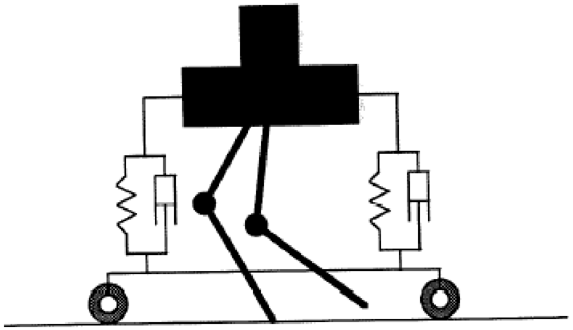
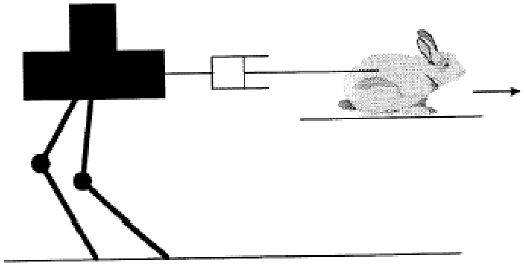
Virtual Model Control

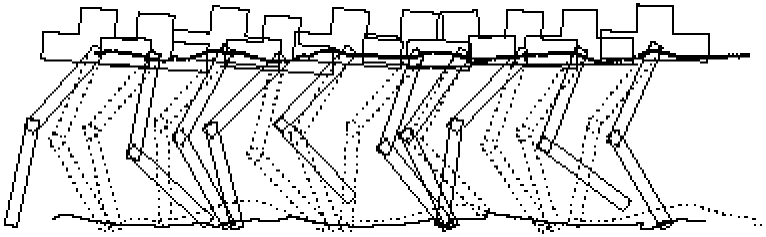
- One of the most successful examples: Virtual Model Control (G.Pratt)
- Idea: create virtual elements to keep the robot upright and have it move forward
- Then compute the necessary torques such that the robot motors replicate the effect of those virtual elements



Virtual granny walker
for balance control



Virtual bunny
for velocity control



Virtual Model Control

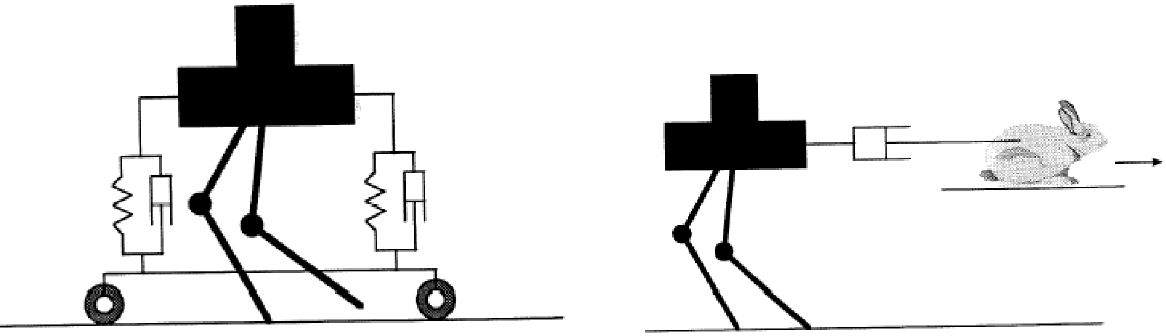
- For each virtual element producing a force F, the joint torque needed to produce that virtual force can be computed with:

$$\vec{T} = \mathbf{J}^T \vec{F}$$

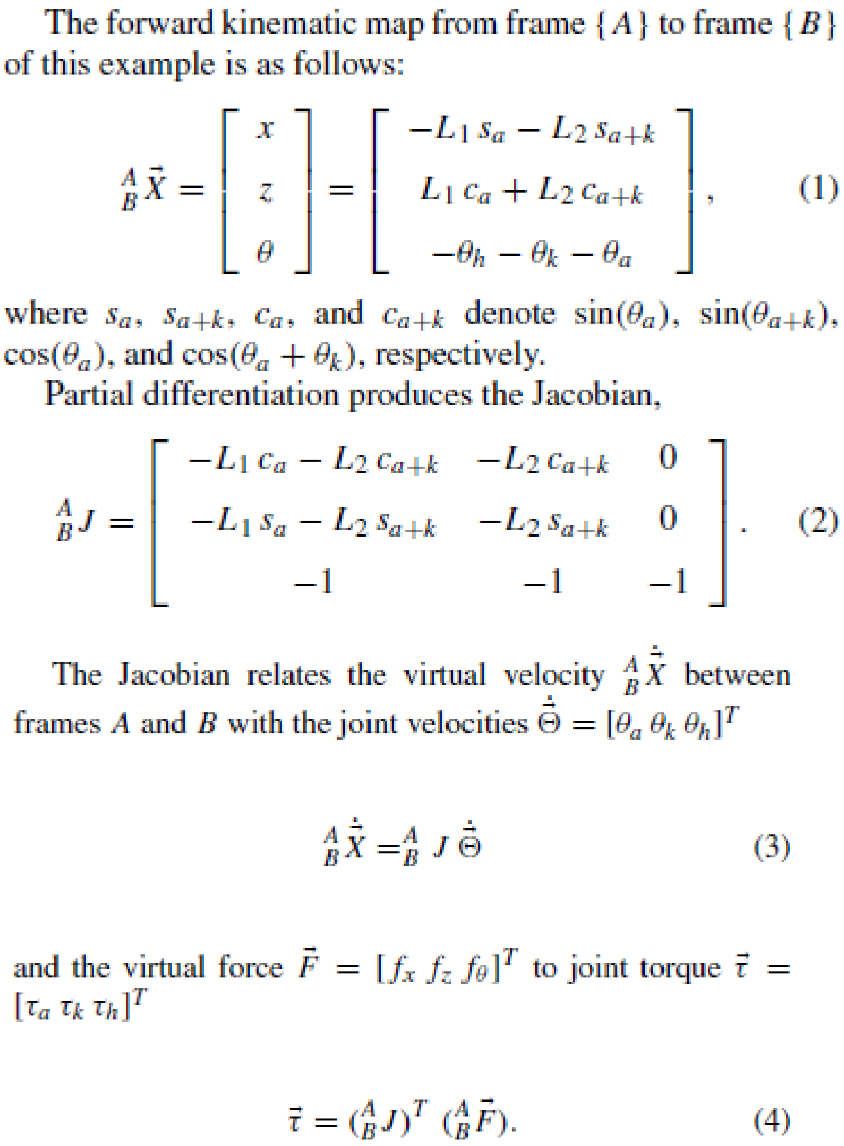
- **J** is the *Jacobian* relating the reference frame of the virtual element to the robot

$$\vec{x} = f(\vec{\theta})$$

$$J = \begin{pmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{pmatrix}$$



Example



The forward kinematic map from frame $\{A\}$ to frame $\{B\}$ of this example is as follows:

$$ {}^{A}_{B}\vec{X} = \begin{bmatrix} x \\ z \\ \theta \end{bmatrix} = \begin{bmatrix} -L_1\, s_a - L_2\, s_{a+k} \\ L_1\, c_a + L_2\, c_{a+k} \\ -\theta_h - \theta_k - \theta_a \end{bmatrix}, \qquad (1)$$

where s_a, s_{a+k}, c_a, and c_{a+k} denote $\sin(\theta_a)$, $\sin(\theta_{a+k})$, $\cos(\theta_a)$, and $\cos(\theta_a + \theta_k)$, respectively.

Partial differentiation produces the Jacobian,

$$ {}^{A}_{B}J = \begin{bmatrix} -L_1\, c_a - L_2\, c_{a+k} & -L_2\, c_{a+k} & 0 \\ -L_1\, s_a - L_2\, s_{a+k} & -L_2\, s_{a+k} & 0 \\ -1 & -1 & -1 \end{bmatrix}. \qquad (2)$$

The Jacobian relates the virtual velocity ${}^{A}_{B}\dot{\vec{X}}$ between frames A and B with the joint velocities $\dot{\vec{\Theta}} = [\theta_a\ \theta_k\ \theta_h]^T$

$$ {}^{A}_{B}\dot{\vec{X}} = {}^{A}_{B}J\ \dot{\vec{\Theta}} \qquad (3)$$

and the virtual force $\vec{F} = [f_x\ f_z\ f_\theta]^T$ to joint torque $\vec{\tau} = [\tau_a\ \tau_k\ \tau_h]^T$

$$ \vec{\tau} = ({}^{A}_{B}J)^T\ ({}^{A}_{B}\vec{F}). \qquad (4)$$

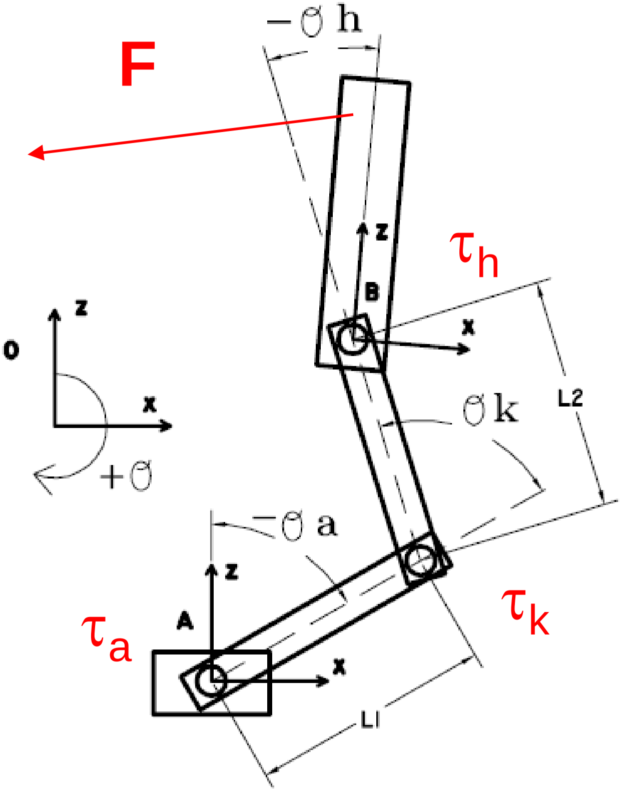
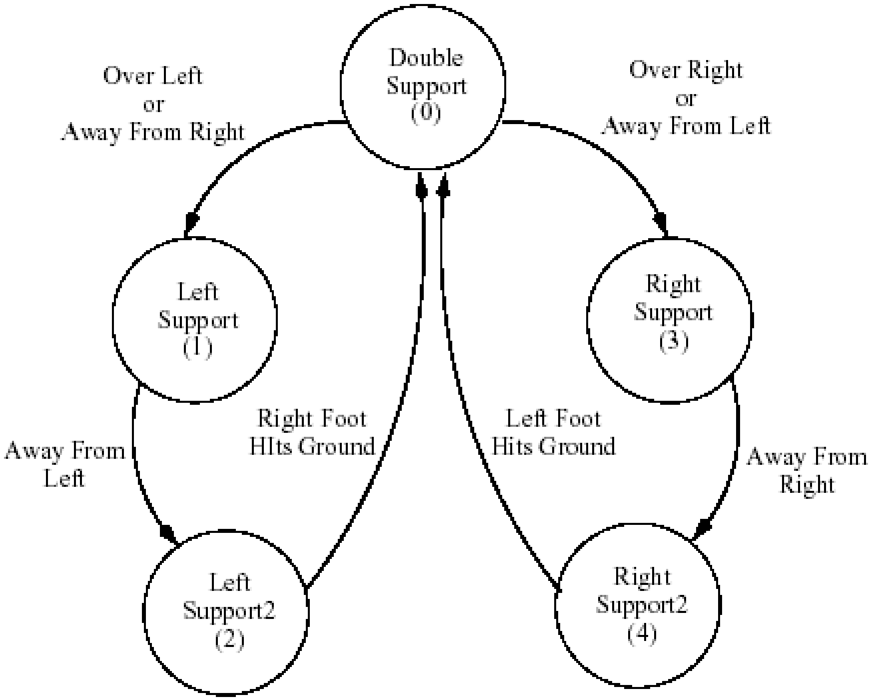


Fig. 3. Single-leg implementation. Reaction frame $\{A\}$ is assumed to be in the same orientation as reference frame $\{O\}$ so that ${}^{O}_{A}R = I$.

Virtual Model Control

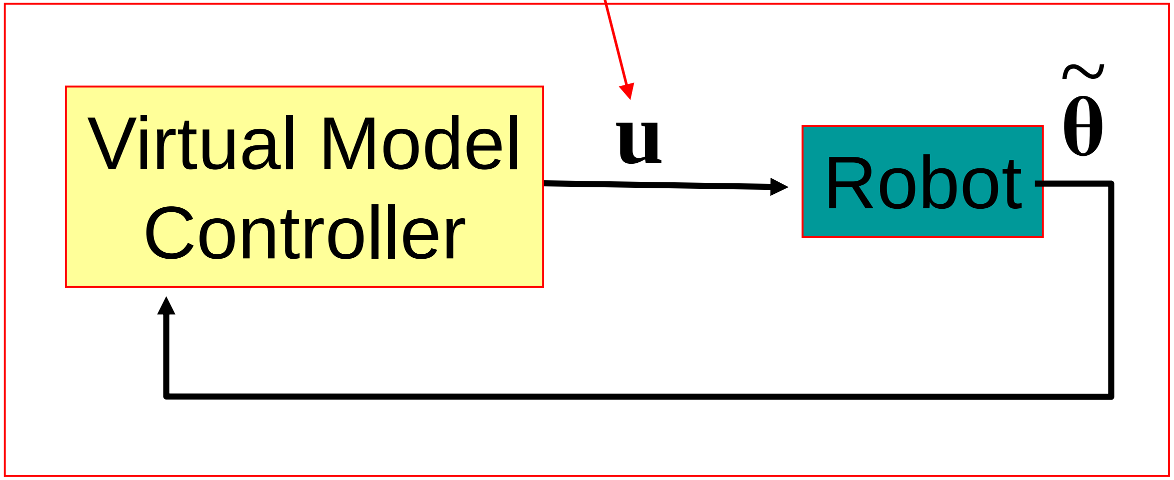
Only some motors should be activated at particular phases in the locomotor cycle



Finite state machine (set of if-then rules) for cycling through different actuation phases

Control diagram:
Virtual Model Control

Directly produces torques,
no tracking of a desired trajectory



$\tilde{\boldsymbol{\theta}}$ Actual robot posture

$\mathbf{u}$ Command (torque)

Virtual Model Control

- Example: Flamingo robot at MIT Leg LAB

Virtual Model Control: summary

Pros:

- Intuitive way of designing a controller
- Does not need an accurate model of the environment
- Robust against pertubations
- No need of a dynamic model

Cons:

- Need to make sure that the virtual forces can actually be generated by the robot’s motors
- Cannot be used for running gaits??

Reference: Pratt et al, Virtual Model Control: An intuitive approach for bipedal locomotion, The International Journal of Robotics Research, Vol. 20, No. 2, 129-143 2001 .

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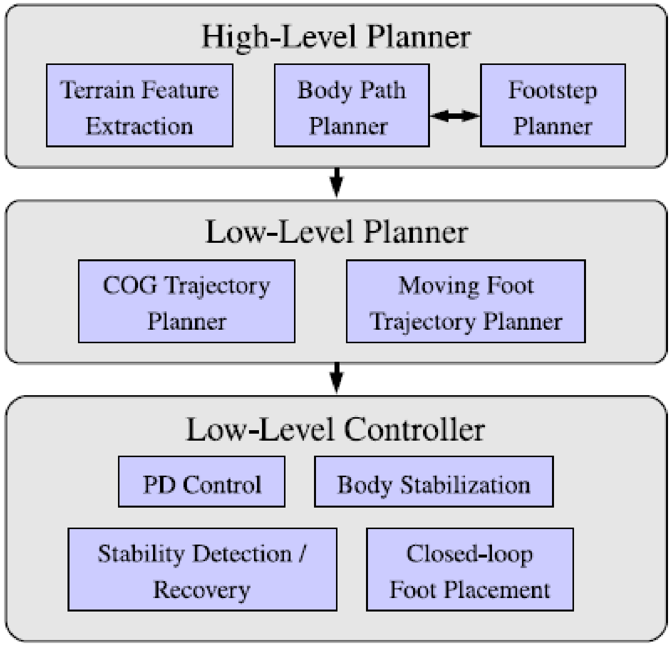
Planning methods

Buchli et al 2009

- DARPA's Little Dog project
- Main idea: control locomotion on very rough terrain by **providing very accurate 3D information about the ground** and the **robot absolute position and orientation**
- Competition with 5 US teams
- Most teams highly depend on **planning methods**
- Several use learning, e.g. for foot placement

Planning methods

- Example: Stanford’s team (Ng and colleagues)



High-Level Planner

Terrain Feature Extraction

Body Path Planner

Footstep Planner

Low-Level Planner

COG Trajectory Planner

Moving Foot Trajectory Planner

Low-Level Controller

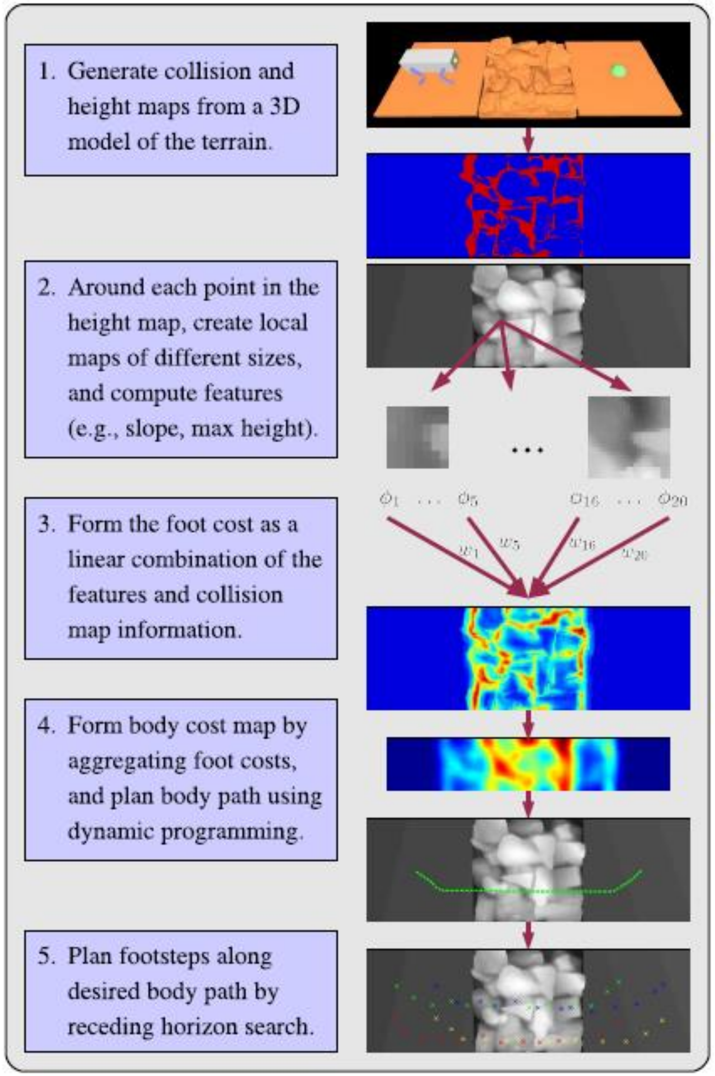
PD Control

Body Stabilization

Stability Detection / Recovery

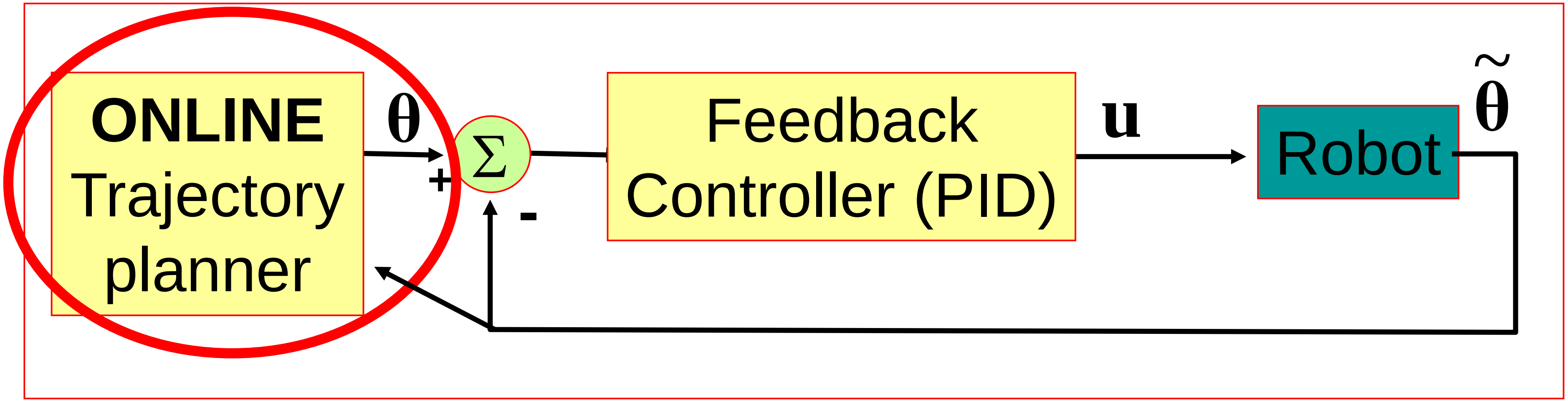
Closed-loop Foot Placement

Kolter et al 2008



1. Generate collision and height maps from a 3D model of the terrain.
2. Around each point in the height map, create local maps of different sizes, and compute features (e.g., slope, max height).
3. Form the foot cost as a linear combination of the features and collision map information.
4. Form body cost map by aggregating foot costs, and plan body path using dynamic programming.
5. Plan footsteps along desired body path by receding horizon search.

Minimalistic control diagram



θ Desired robot posture

$\tilde{\theta}$ Actual robot posture

$\mathbf{u}$ Command (torque)

Planning methods

- Example: USC’s team (Schaal, Buchli and colleagues)

Learning Locomotion with LittleDog

http://www-clmc.usc.edu

Mrinal Kalakrishnan, Jonas Buchli,
Peter Pastor, and Stefan Schaal

Planning methods: summary

- Pros:
  - Ability to handle very complex terrain that requires careful foot holds.
- Cons:
  - Requires very accurate 3D maps of the ground.
  - It is not clear how performance degrades with less good sensory input
  - Not well suited for biped locomotion (except slow statically stable locomotion)

References:

Buchli, J.;Kalakrishnan, M.;Mistry, M.;Pastor, P.;Schaal, S. (2009). Compliant quadruped locomotion over rough terrain, Proceedings of IROS 2009, pp.814-820.

Kalakrishnan, M.;Buchli, J.;Pastor, P.;Schaal, S. (2009). Learning locomotion over rough terrain using terrain templates, Proceedings of IROS 2009 pp.167-172.

J. Zico Kolter, Mike P. Rodgers, and Andrew Y. Ng. A Control Architecture for Quadruped Locomotion over Rough Terrain. In Proceedings of ICRA2008, 2008.

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Inverse dynamics and optimization

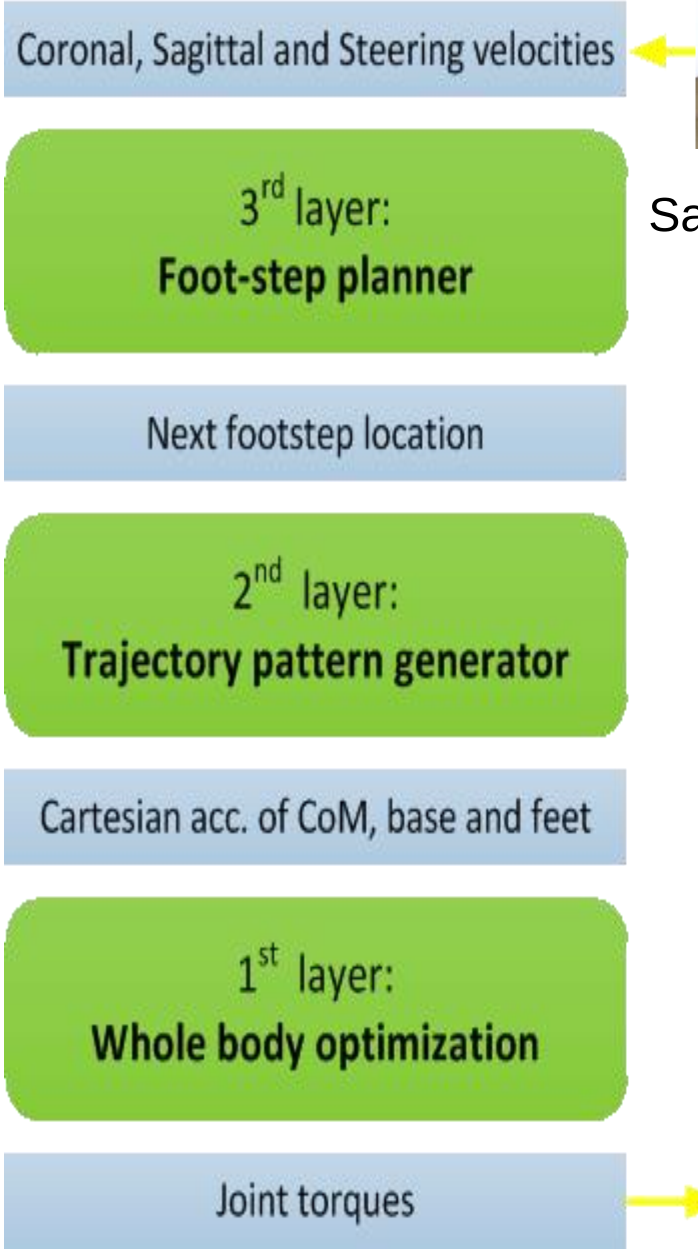
- For **torque-controlled** robots for which an **accurate dynamical model** exists:

- Possibility:
  - To **compute the inverse-dynamics of the robot**, i.e. finding the torques needed to perform specific movements)
  - To **run optimizations** to find torques that optimize some objective functions and that respect some constraints (optimal control)

  - And therefore to obtain highly versatile gaits and whole body control.

Optimization of
footsteps,
Model predictive control
Linear Inverted
Pendulum model
(see Salman’s slides)

Inverse dynamics,
Online optimization
Torques for all DOFs



Coronal, Sagittal and Steering velocities

3^{rd} layer:
Foot-step planner

Next footstep location

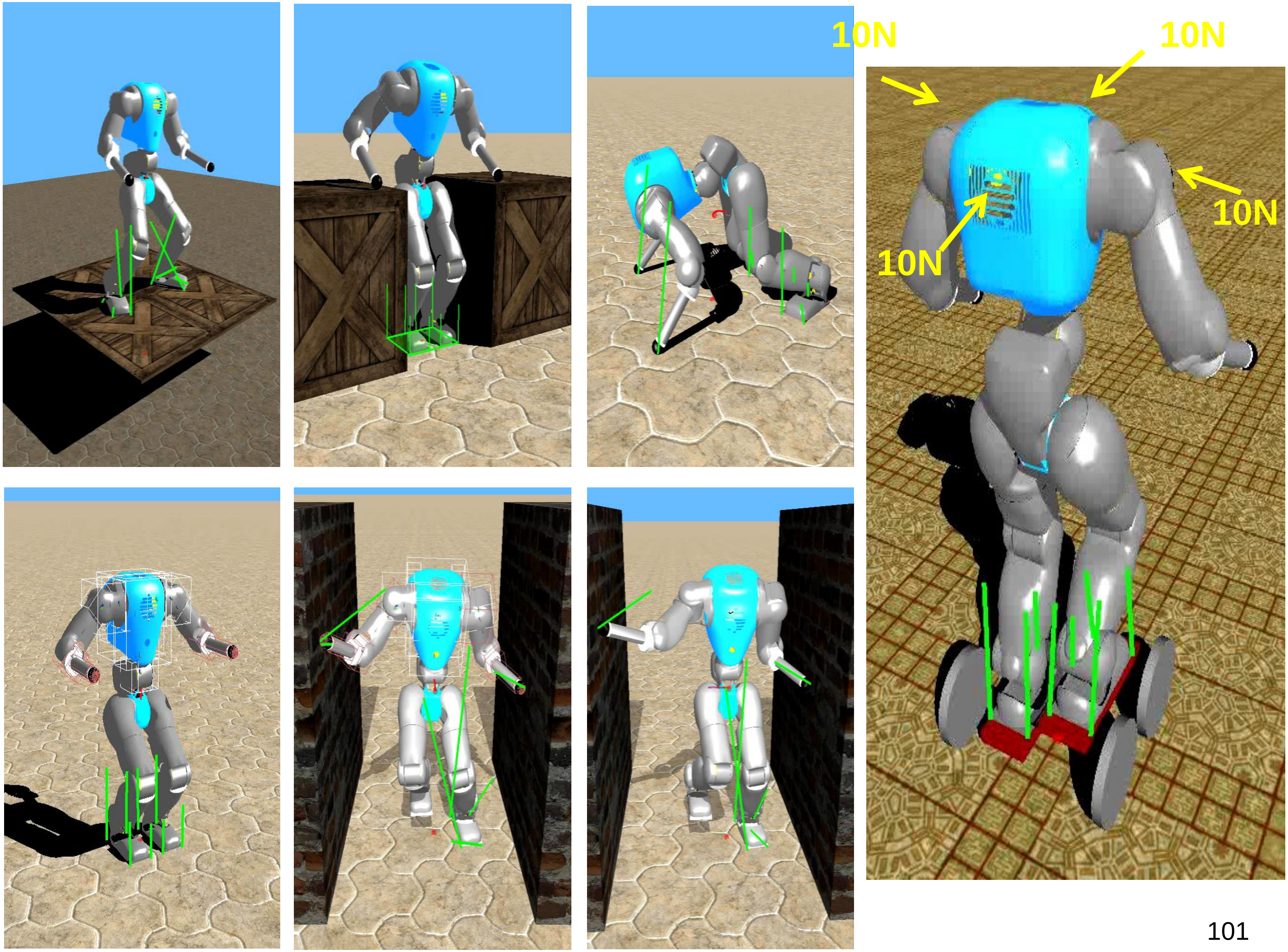
2^{nd} layer:
Trajectory pattern generator

Cartesian acc. of CoM, base and feet

1^{st} layer:
Whole body optimization

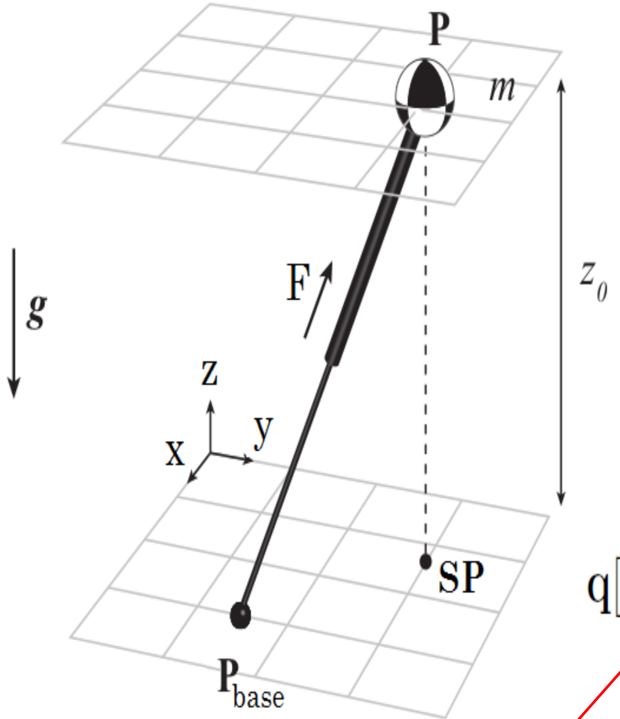
Joint torques

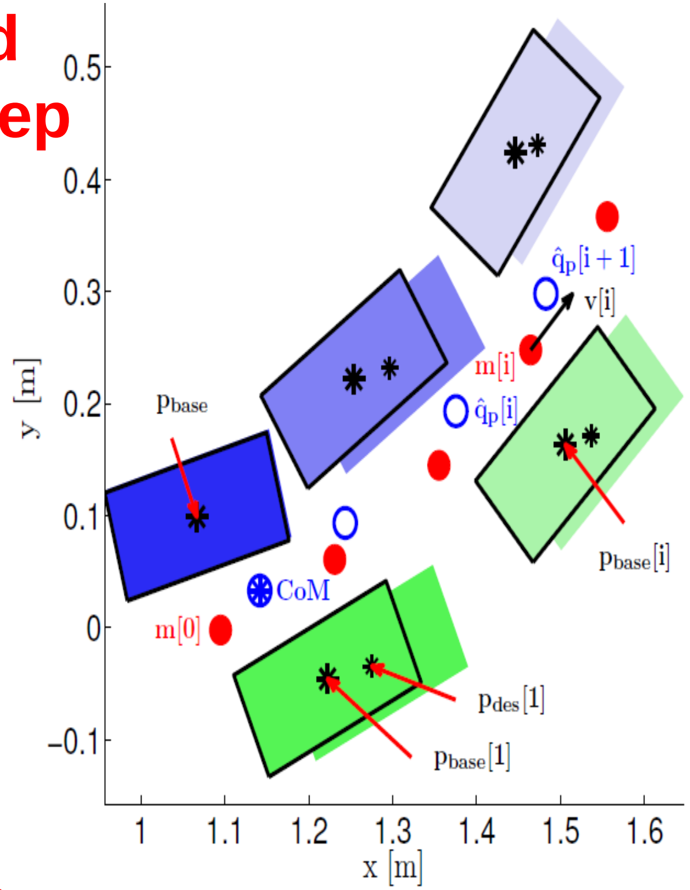
Salman Faraji


10N
10N
10N
10N

Linear Inverted Pendulum for step planning

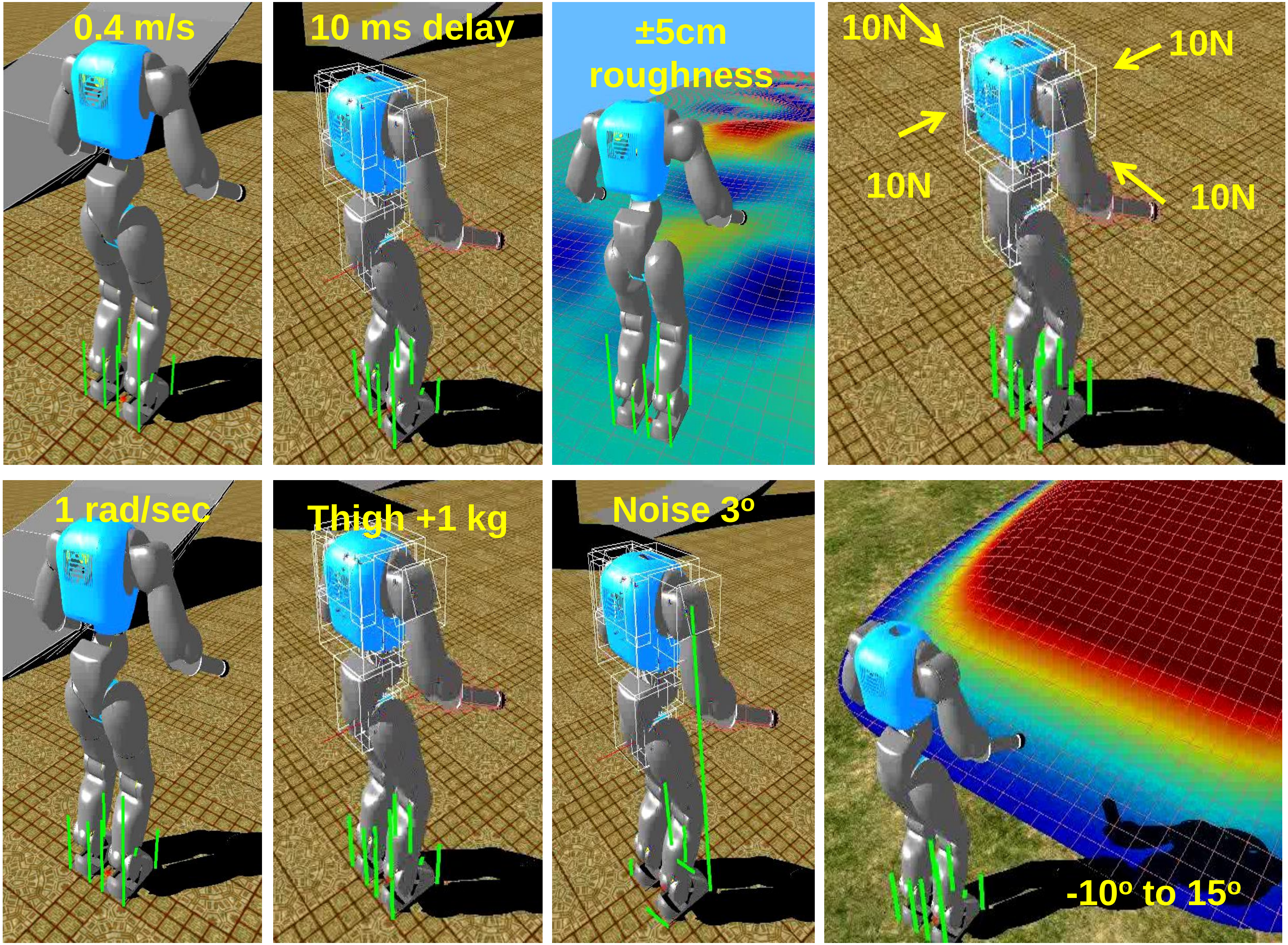
$$\ddot{x} = \frac{g}{z_0}(x - x_{base})$$





$$q[N+1] = Aq[N] + BP[N]$$

$$\begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{bmatrix}(T) = \begin{bmatrix} a_1 & 0 & a_2 & 0 \\ 0 & a_1 & 0 & a_2 \\ a_3 & 0 & a_4 & 0 \\ 0 & a_3 & 0 & a_4 \end{bmatrix} \begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{bmatrix}(0) + \begin{bmatrix} b_1 & 0 \\ 0 & b_1 \\ b_2 & 0 \\ 0 & b_2 \end{bmatrix} \begin{bmatrix} x_{base} \\ y_{base} \end{bmatrix}$$


0.4 m/s
10 ms delay
±5cm roughness
10N
10N
10N
10N
1 rad/sec
Thigh +1 kg
Noise 3°
-10° to 15°

Inverse dynamics and optimization

- Pros:
  - Ability to generate a large class of movements: walking + many others
  - Allows one to design controllers in task space, as opposed to joint space

- Cons:
  - Requires (very) good torque control
  - Heavy computation

References:

A Herzog, L Righetti, F Grimminger, P Pastor, S Schaal (2014) Momentum-based Balance Control for Torque-controlled Humanoids, arXiv preprint arXiv:1305.2042

Salman Faraji, Soha Pouya, Christopher G. Atkeson‡, and Auke Jan Ijspeert (2014) Versatile and Robust 3D Walking with the Humanoid Robot Atlas: a Model Predictive Control Approach. ICRA 2014.

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Biologically-inspired approaches:

1. **Passive and dynamic walkers**
2. Sensory-driven methods,
3. CPG-and-reflex based methods

Passive walkers

- The laws of physics should be exploited: passive walkers, i.e. walking machines with actuators nor control

A Three-Dimensional Passive-Dynamic Walking Robot with Two Legs and Knees, Collins, S. H., Wisse, M., Ruina, A. International Journal of Robotics Research, Vol. 20, No. 2, Pages 607-615, 2001

Passive walkers

- The **laws of physics can be exploited** to produce relatively **robust control-less walking**

- Instead of cancelling-out the natural dynamics of the robot (by using high-power electric motors), takes advantage of the natural frequencies of the robot

- **Self-stabilizing phenomenon**

- **Requires little energy** when actuated E.g. robot Mike at Delft Univ. with McKnibben muscles

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Runbot project

Exploitation of natural dynamics

Sensor driven controller implemented with a neural network, **locomotion as a chain of reflexes**

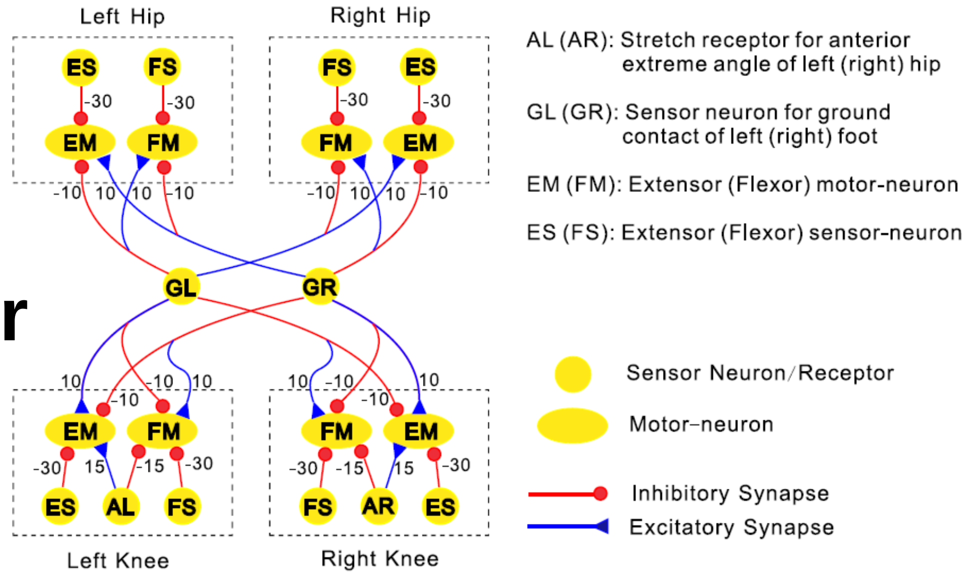
Policy gradient reinforcement learning algorithm to tune the parameters in real time

Reference: Gen, Porr, and Wörgötter, Fast Biped Walking with a Sensor-driven Neuronal Controller and Real-time Online Learning, The International Journal of Robotics Research, Vol. 25, No. 3, 243-259, 2006.

Runbot project

Exploitation of natural dynamics

Sensor driven controller (like Geyer’s model) implemented with a neural network



AL (AR): Stretch receptor for anterior extreme angle of left (right) hip

GL (GR): Sensor neuron for ground contact of left (right) foot

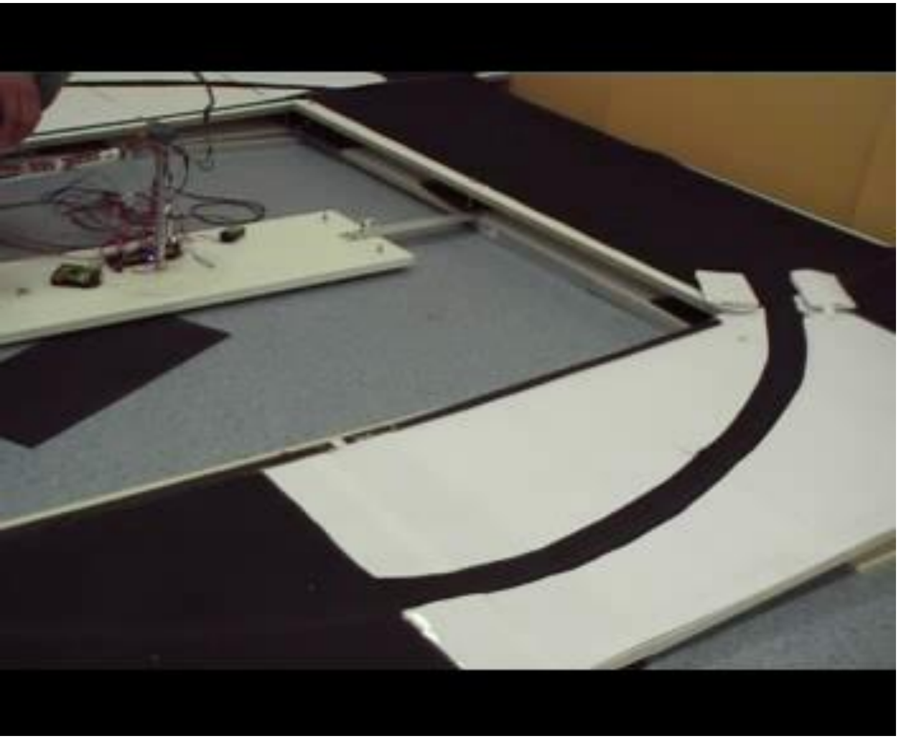
EM (FM): Extensor (Flexor) motor-neuron

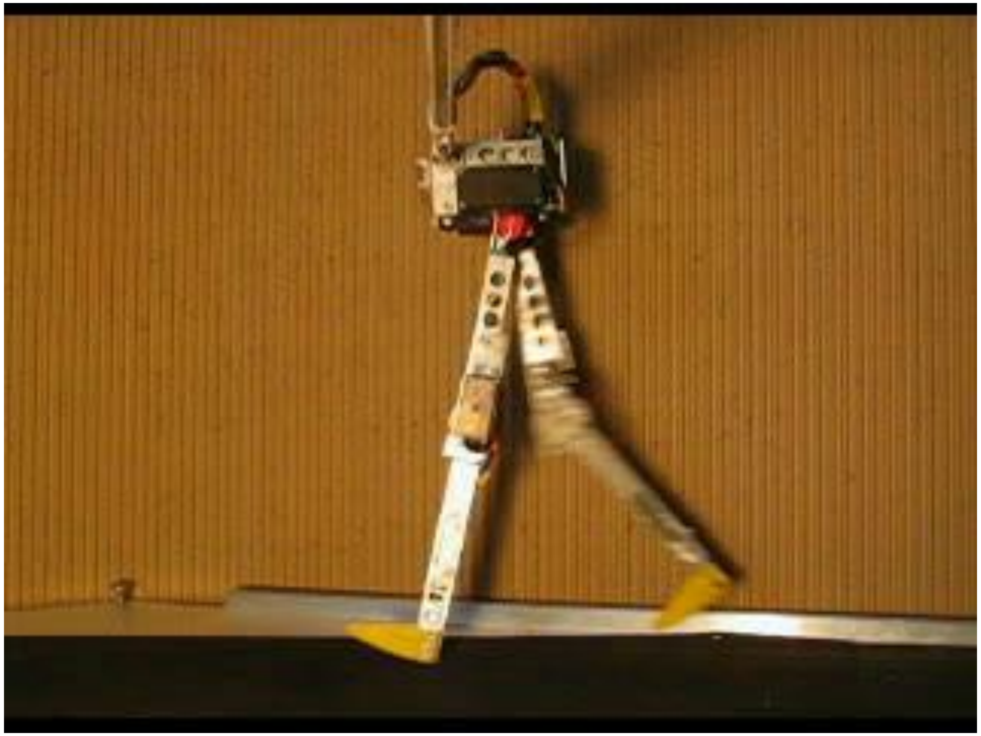
ES (FS): Extensor (Flexor) sensor-neuron

Policy gradient **reinforcement learning algorithm** to tune the parameters in real time

Gen, Porr, and Wörgötter, Fast Biped Walking with a Sensor-driven Neuronal Controller and Real-time Online Learning, The International Journal of Robotics Research, Vol. 25, No. 3, 243-259, 2006.

Runbot project





Sensory-driven control: summary

Pros:

- Very close link between the controller and what the robot actual does
- Can be very energy efficient by benefiting from passive dynamics (as opposed to stiff actuation)

Cons:

- because of the lack of a centrally generated rhythm, non-negligible risk that locomotion might be completely stopped because of damage in the sensors and/or external constraints that force the robot in a particular posture.

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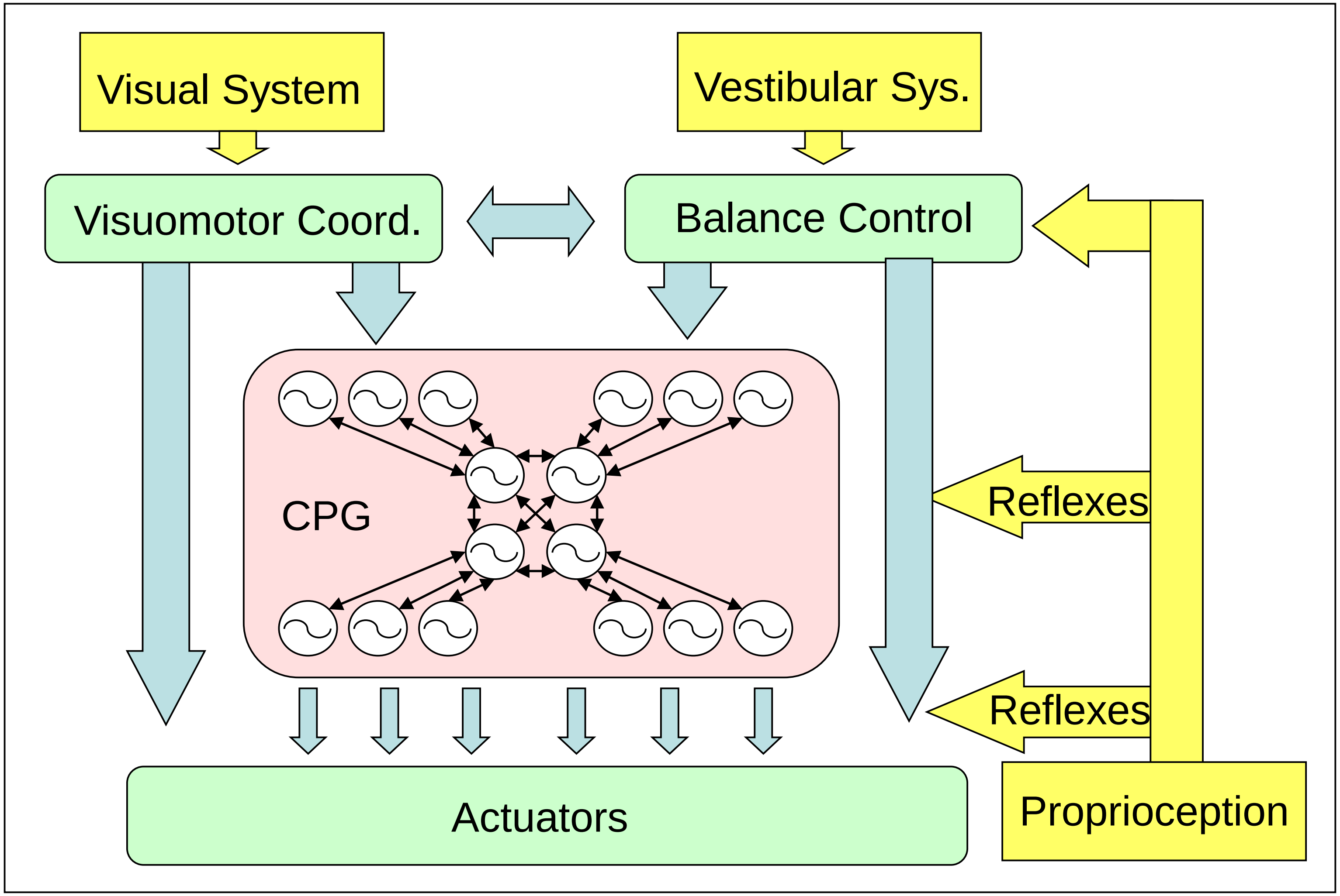
3. **CPG-and-reflex based methods**

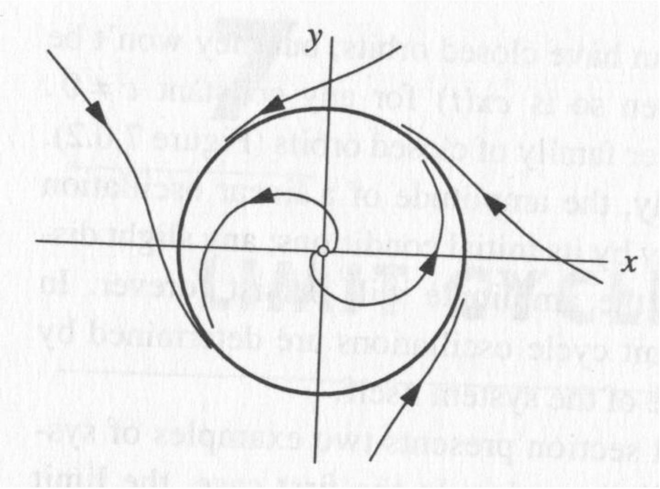
CPG-and-reflex control

- Main idea: to use oscillators and to replicate the distributed control mechanisms found in vertebrates



Concept of Limit Cycle

- A *limit cycle* is an oscillatory regime in a dynamical system:



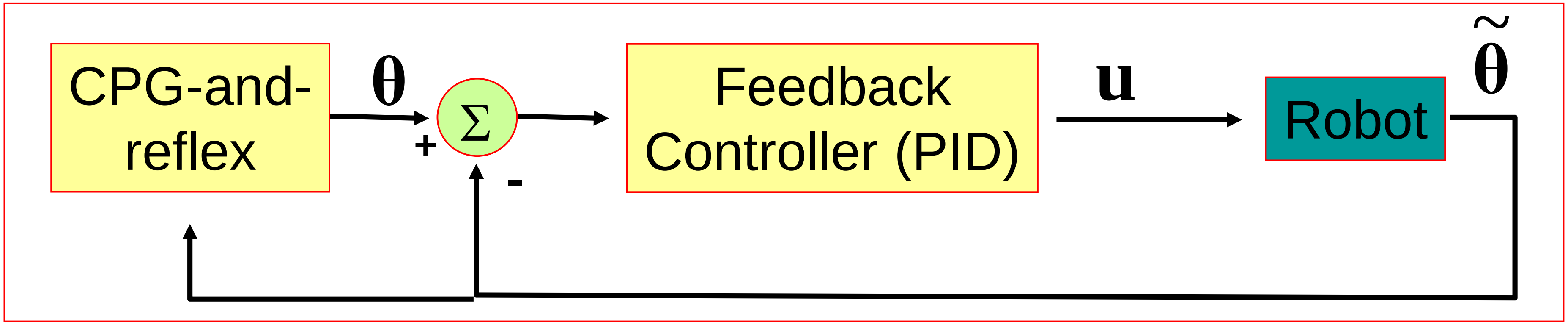
Limit cycles

- If the limit cycle is stable, the states of the system will return to it after perturbations

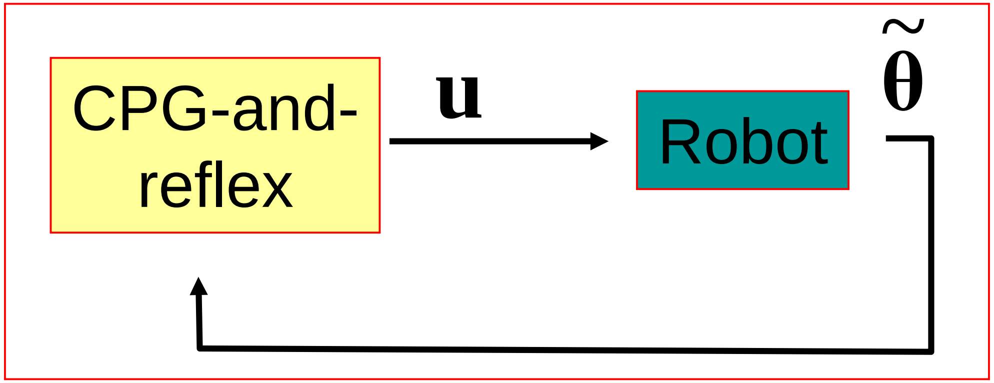
CPG-and-reflex control

Two types of implementations:

CPG produces **desired positions**:



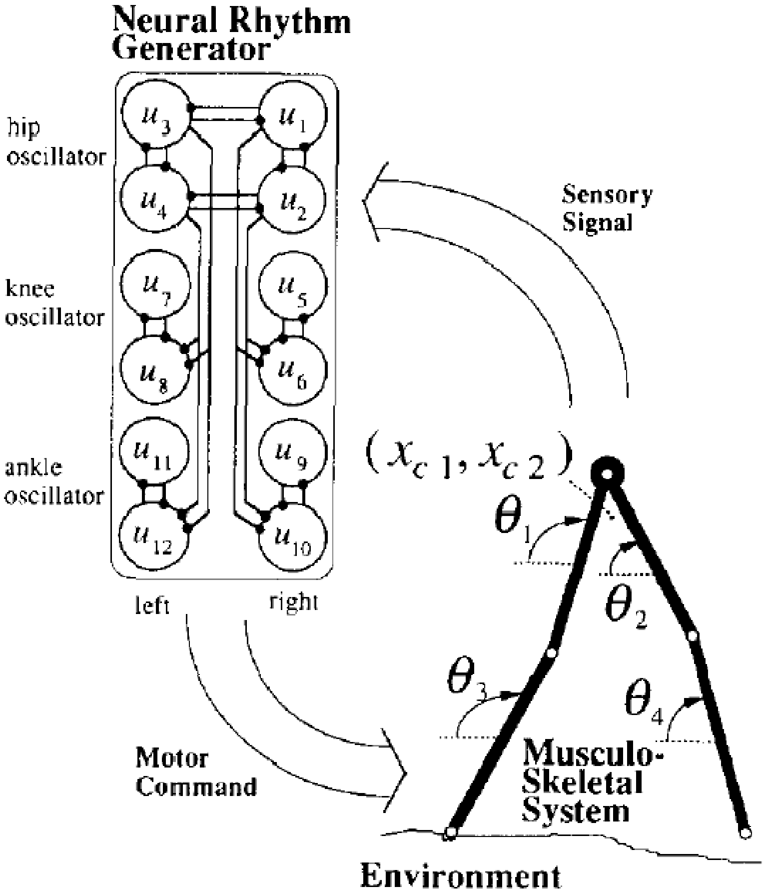
CPG directly produces **torques**:



Taga’s neuromechanical simulation

This approach has been strongly influenced by Taga’s models that we saw last week.

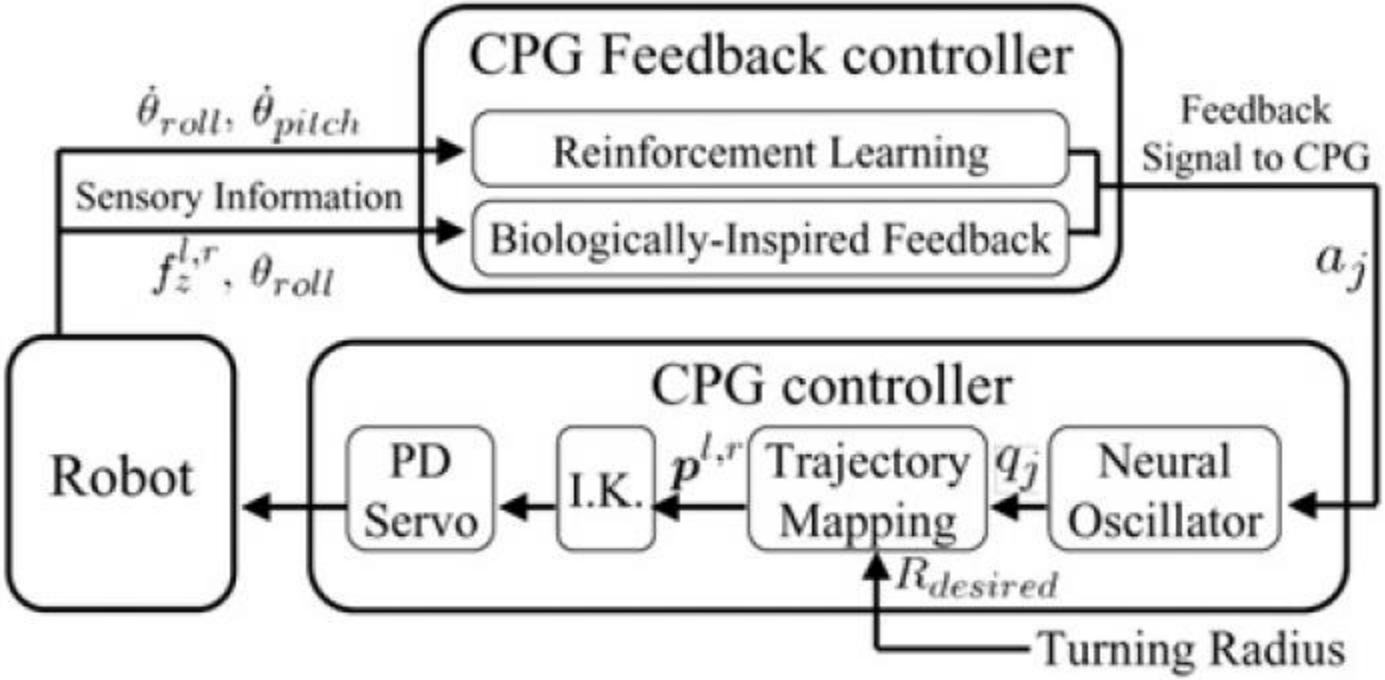
Quite a few labs have taken a similar approach



G. Taga. Emergence of bipedal locomotion through entrainment among the neuro-musculo-skeletal system and the environment. *Physica D: Nonlinear Phenomena*, 75(1-3):190-208, 1994

G. Taga. A model of the neuro-musculo-skeletal system for human locomotion. i. emergence of basic gait. *Biological Cybernetics*, 73(2):97-111, 1995

Biped robots and CPGs



Endo, G., Morimoto, J., Matsubara, T., Nakanishi, J., & Cheng, G. (2008). Learning CPG-based biped locomotion with a policy gradient method: Application to a humanoid robot. *The International Journal of Robotics Research*, *27*(2), 213-228.

Biped robots and CPGs

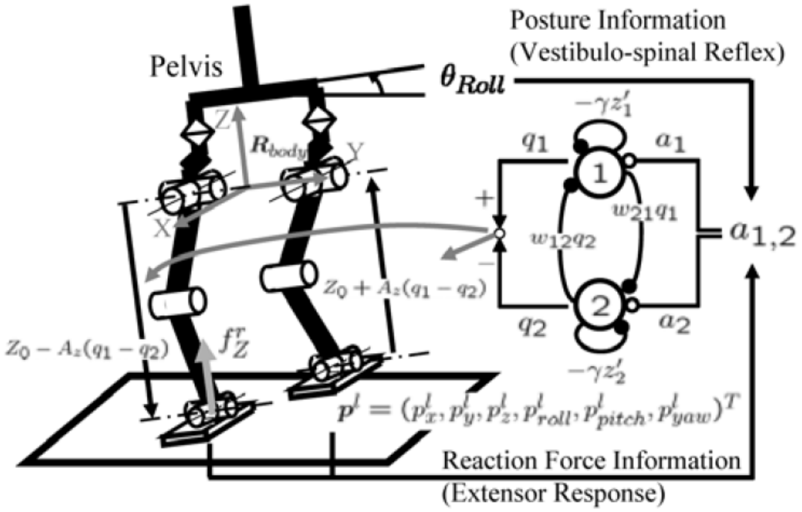


Fig. 5. Neural oscillator allocation and biologically inspired feedback pathways for a stepping motion in place. The neural oscillator output, $(q_1 - q_2)$, symmetrically controls the left and right leg position in the vertical direction Z with respect to the body-fixed coordinates $\boldsymbol{R}_{\text{body}}$ where Z_0, A_x are an initial offset and a gain, respectively. The reaction force information in the Z direction, $f_Z^{\text{l,r}}$, is used as the extensor response and the posture inclination in the roll direction, θ_{Roll}, is used as the vestibulospinal reflex. Here $a_{1,2}$ are feedback signals derived from (14).

Endo, G., Morimoto, J., Matsubara, T., Nakanishi, J., & Cheng, G. (2008). Learning CPG-based biped locomotion with a policy gradient method: Application to a humanoid robot. *The International Journal of Robotics Research*, *27*(2), 213-228.

Biped robots and CPGs

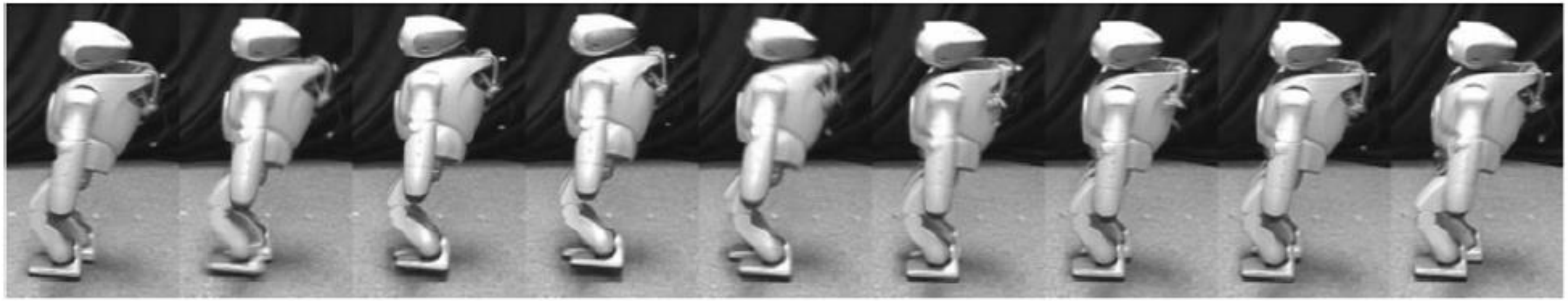
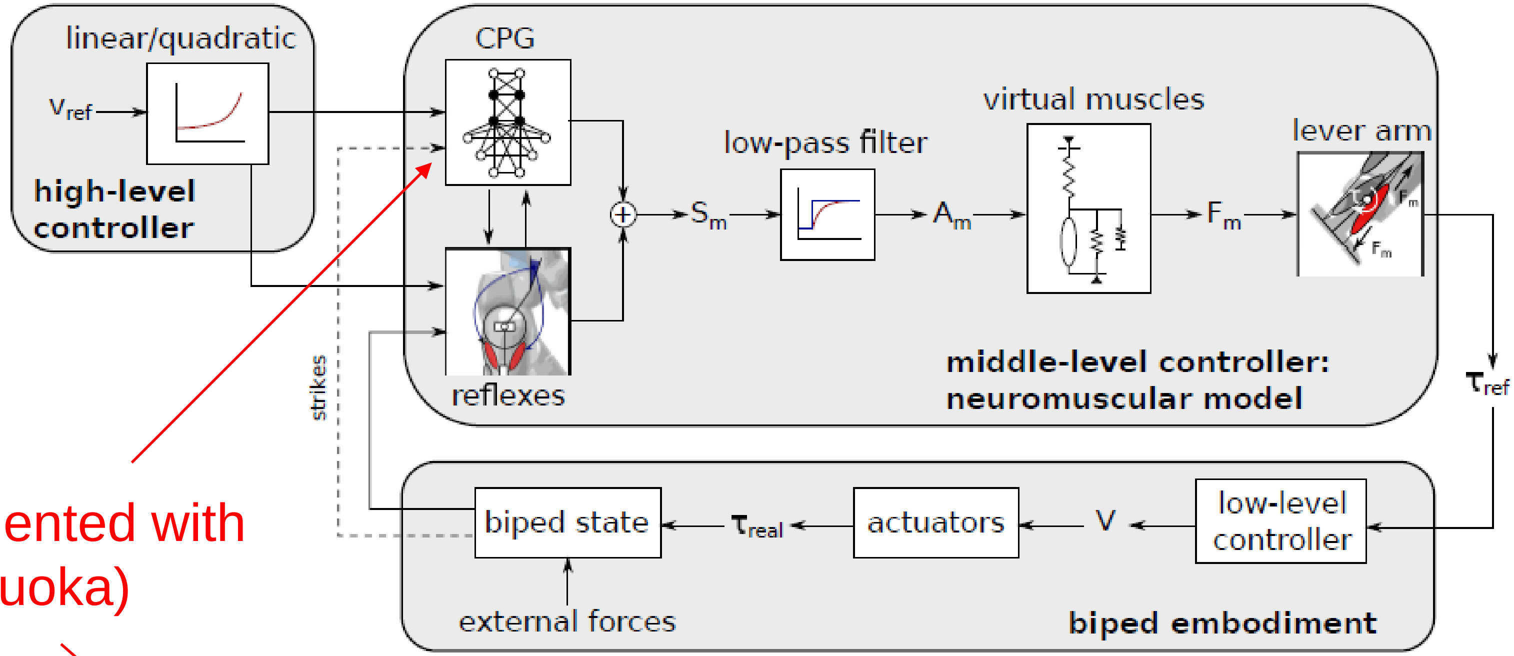


Fig. 11. Snapshots of straight steady walking with the acquired feedback controller ($A_x = 0.015$ m, $A_z = 0.005$ m, $v_x = 0.077$ m s^{-1}. Photos were captured every 0.1 s.)

Endo, G., Morimoto, J., Matsubara, T., Nakanishi, J., & Cheng, G. (2008). Learning CPG-based biped locomotion with a policy gradient method: Application to a humanoid robot. *The International Journal of Robotics Research*, *27*(2), 213-228.

EPFL: CPG control of the CoMan robot

Nicolas
Van der Noot



linear/quadratic

V_{ref}

high-level controller

CPG

reflexes

strikes

S_m

low-pass filter

A_m

virtual muscles

F_m

lever arm

τ_{ref}

middle-level controller: neuromuscular model

biped state

τ_{real}

actuators

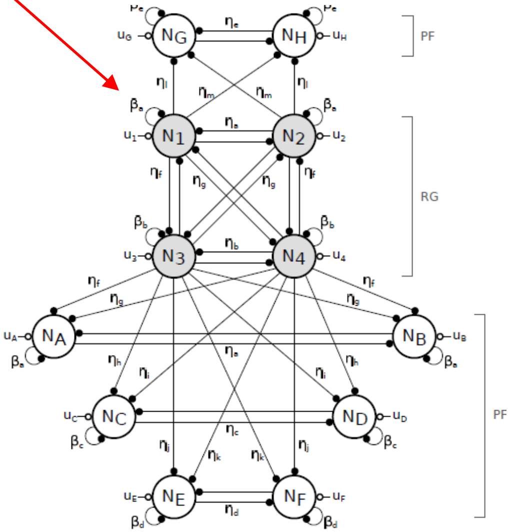
V

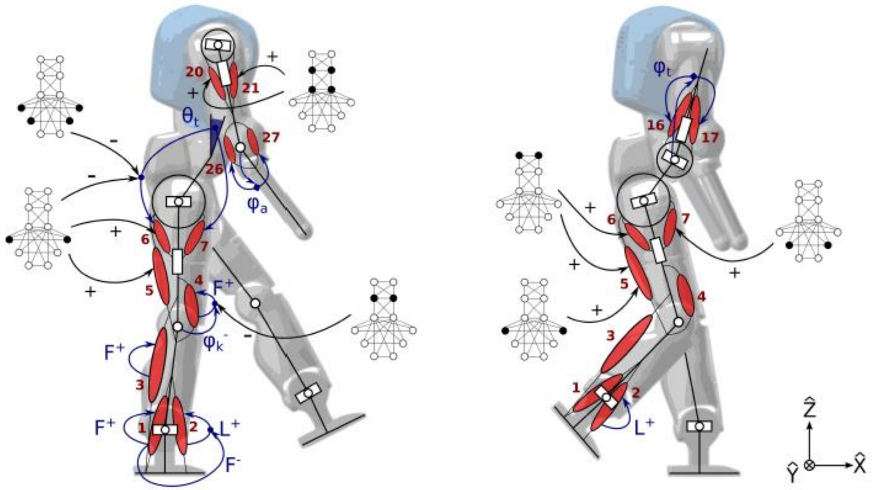
low-level controller

external forces

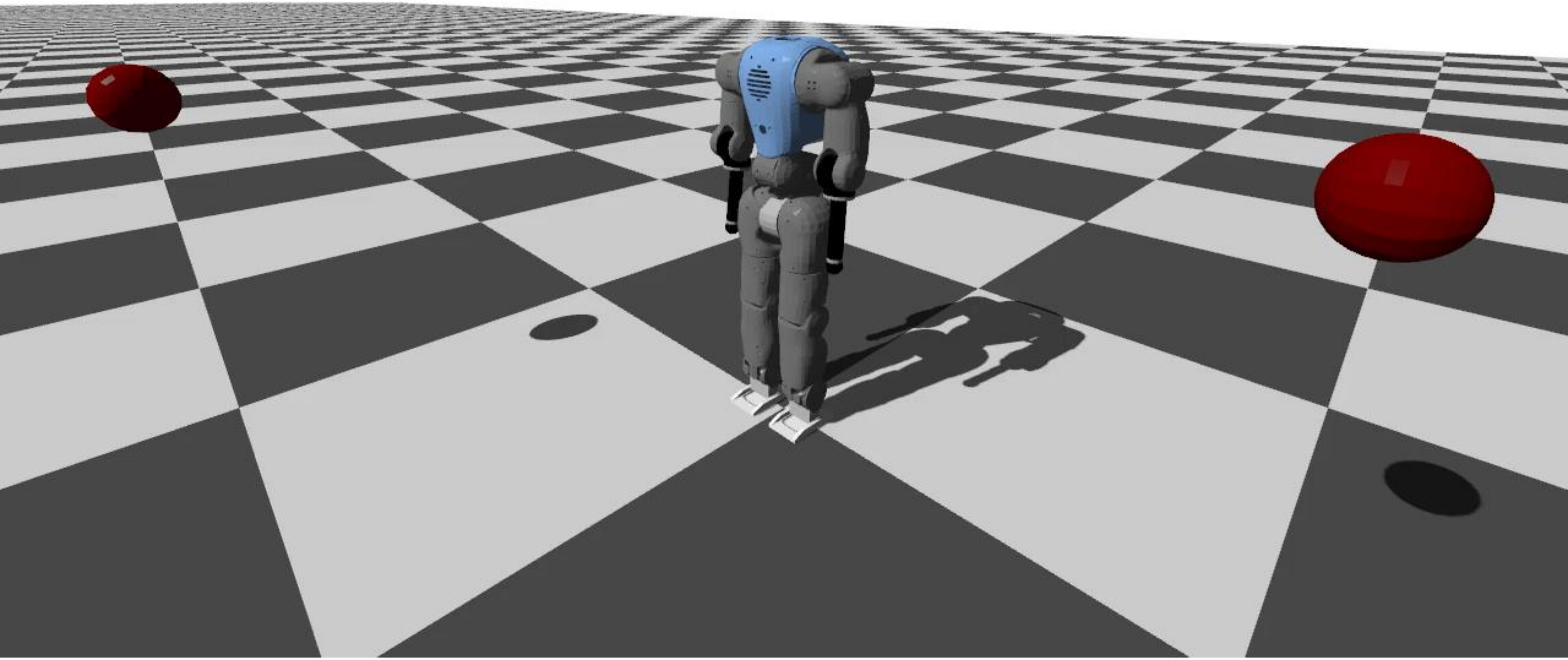
biped embodiment

CPG implemented with neural (Matsuoka) oscillators



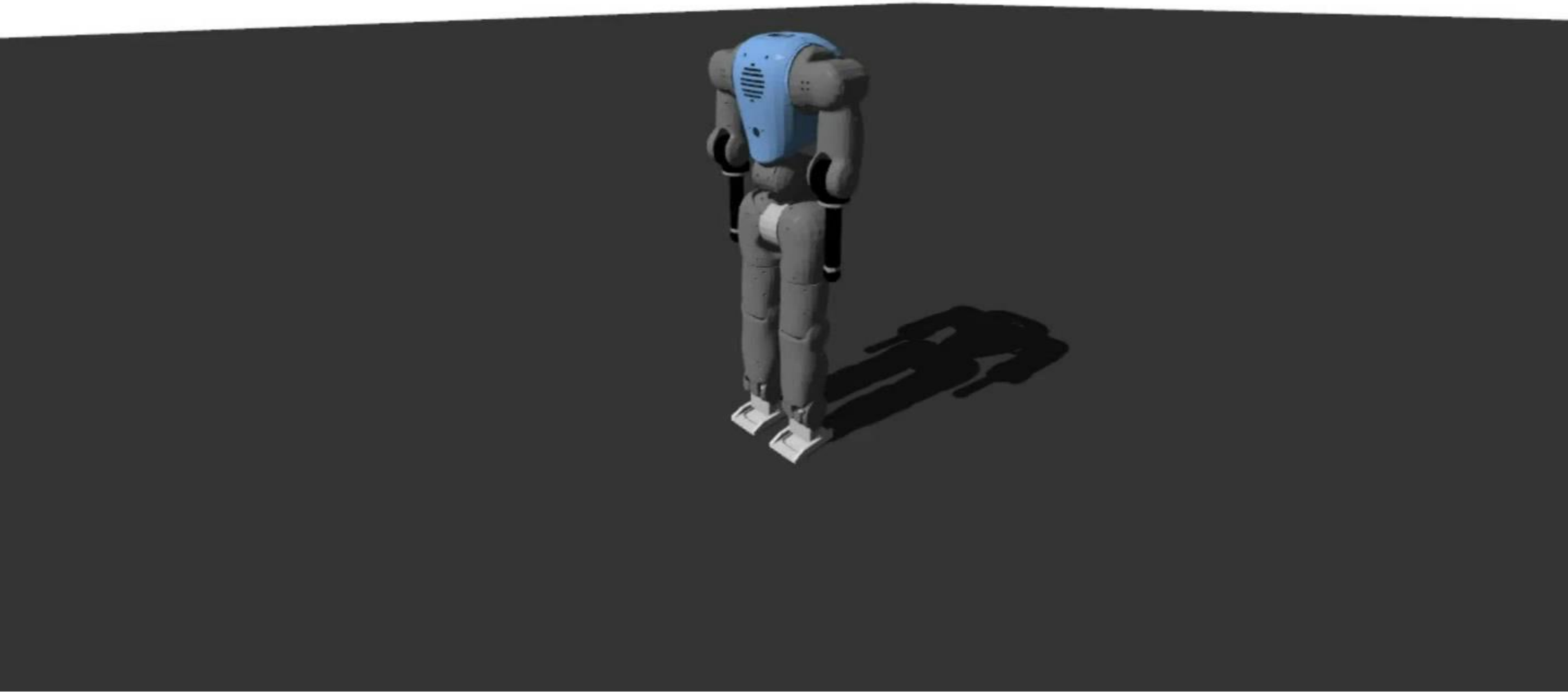


3D CPG-based controller



N Van der Noot, AJ Ijspeert, R Ronsse
The International Journal of Robotics Research 37 (1), 168-196, 2018.

3D CPG-based controller



CPG-and-reflex Control: summary

- Pros:
  - Distributed control
  - Limit cycle behavior (controller-body-environment)
  - Robust against pertubations
  - Smooth trajectories due to the oscillators

- Cons:
  - Fewer mathematical tools than model-based methods

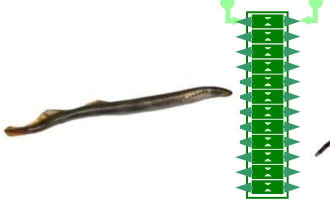
  - Not (yet) a clear design methodology, it is recommended to use reinforcement learning or optimization algorithms

Topics:

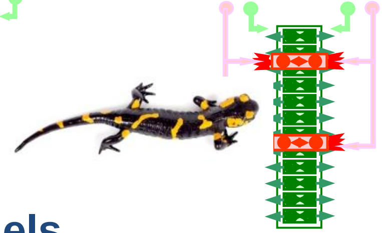
- Wheels versus legged locomotion
- Animal locomotion
- Different control approaches in legged robotics
- **Examples of projects from the Biorob lab**

Biological models

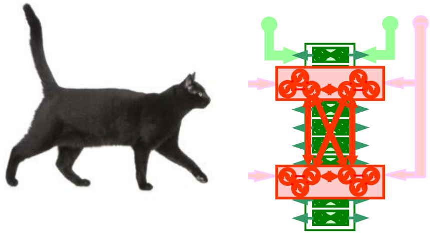
Lamprey



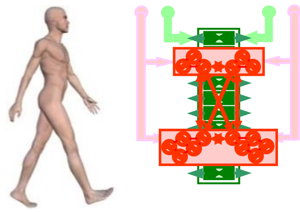
Salamander



Cat



Human



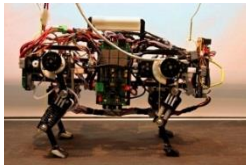
Biorobots

Amphibot

Salamandra robotica

Pleurobot

Cheetah-Cub



Oncilla

iCub

CoMan

Dynamical systems

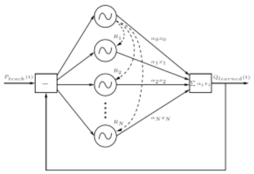
$$\tau \dot{z} = \alpha_z(\beta_z(g - y) - z) + f + C_t$$

$$\tau \dot{y} = z$$

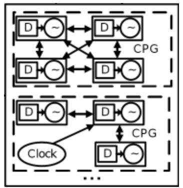
$$\tau \dot{x} = -\alpha_x x + C_c$$

$$f(x) = \frac{\sum_{i=1}^{N} \Psi_i(x) w_i}{\sum_{i=1}^{N} \Psi_i(x)} x(g - y_0)$$

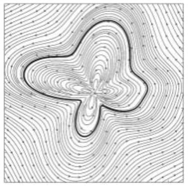
Dyn. movement primitives



Adaptive frequency oscillators



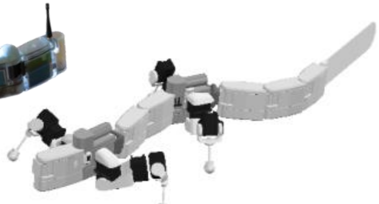
Discrete and rhythmic pattern generator



Morphed oscillators

Applications

Pollution detection
Envirobot



Search-and-rescue
NCCR

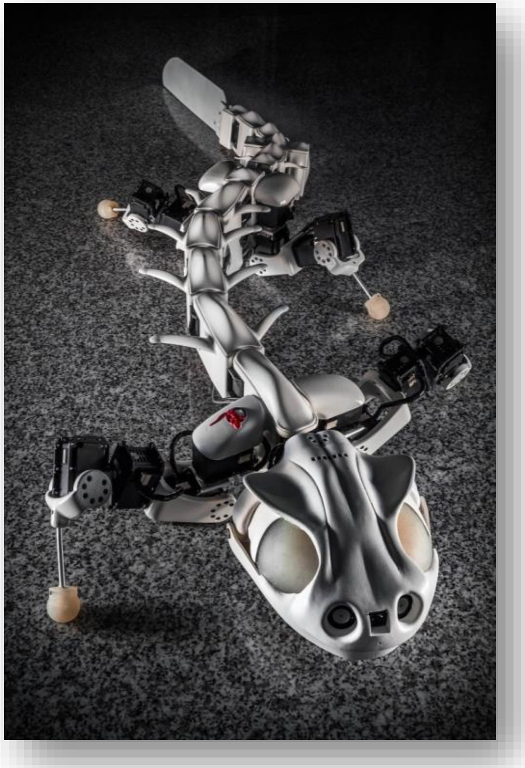
Roombots: assistive furniture

Control of Exoskeletons
Symbitron

Biorobotics

Robotics applications

Inspection
Monitoring
Search and rescue
Transport
Pollution monitoring
Agriculture
Service robotics



Scientific applications

Neuroscience
Biomechanics
Sport science
Ethology
Prosthetics
Neuroprosthetics
Paleontology

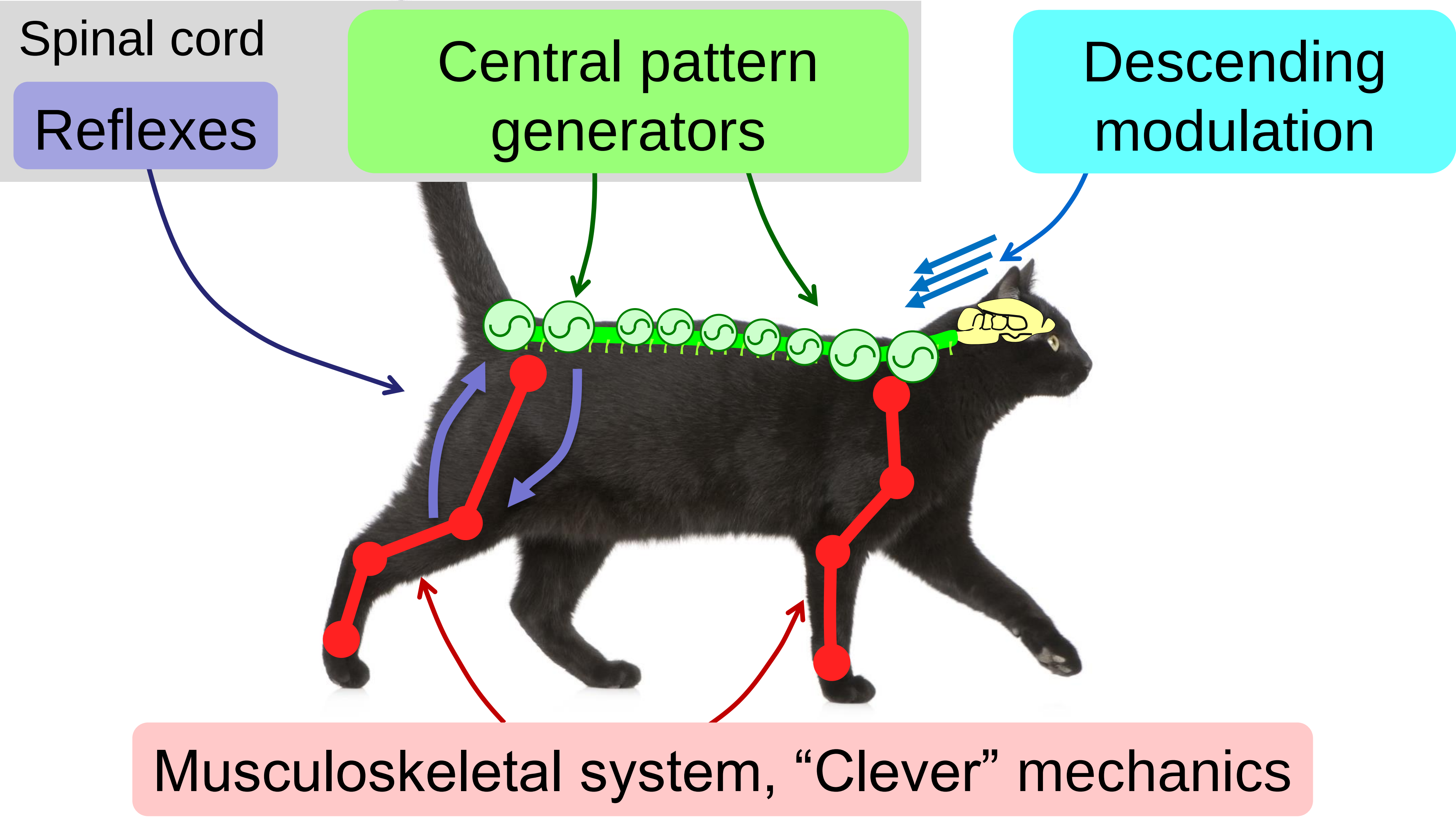
Edutainment applications

Toys
Animatronics
Artificial pets

Filming wild life
Museums
Recreating extinct animals

The beauty of animal movement control

Four essential ingredients in animal motor control



Spinal cord

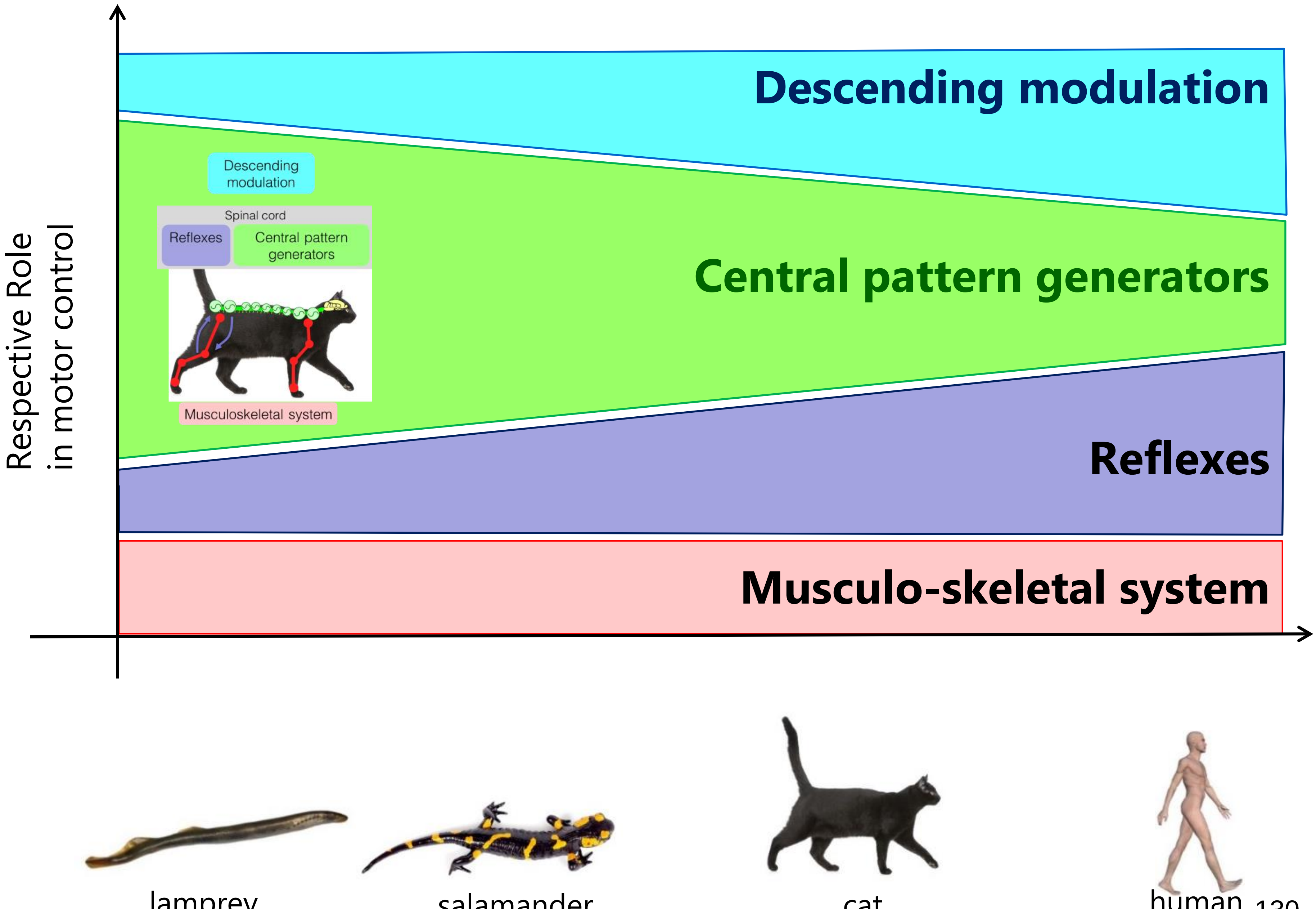
Reflexes

Central pattern generators

Descending modulation

Musculoskeletal system, “Clever” mechanics

Modeling spinal cord circuits



Descending modulation

Central pattern generators

Reflexes

Musculo-skeletal system

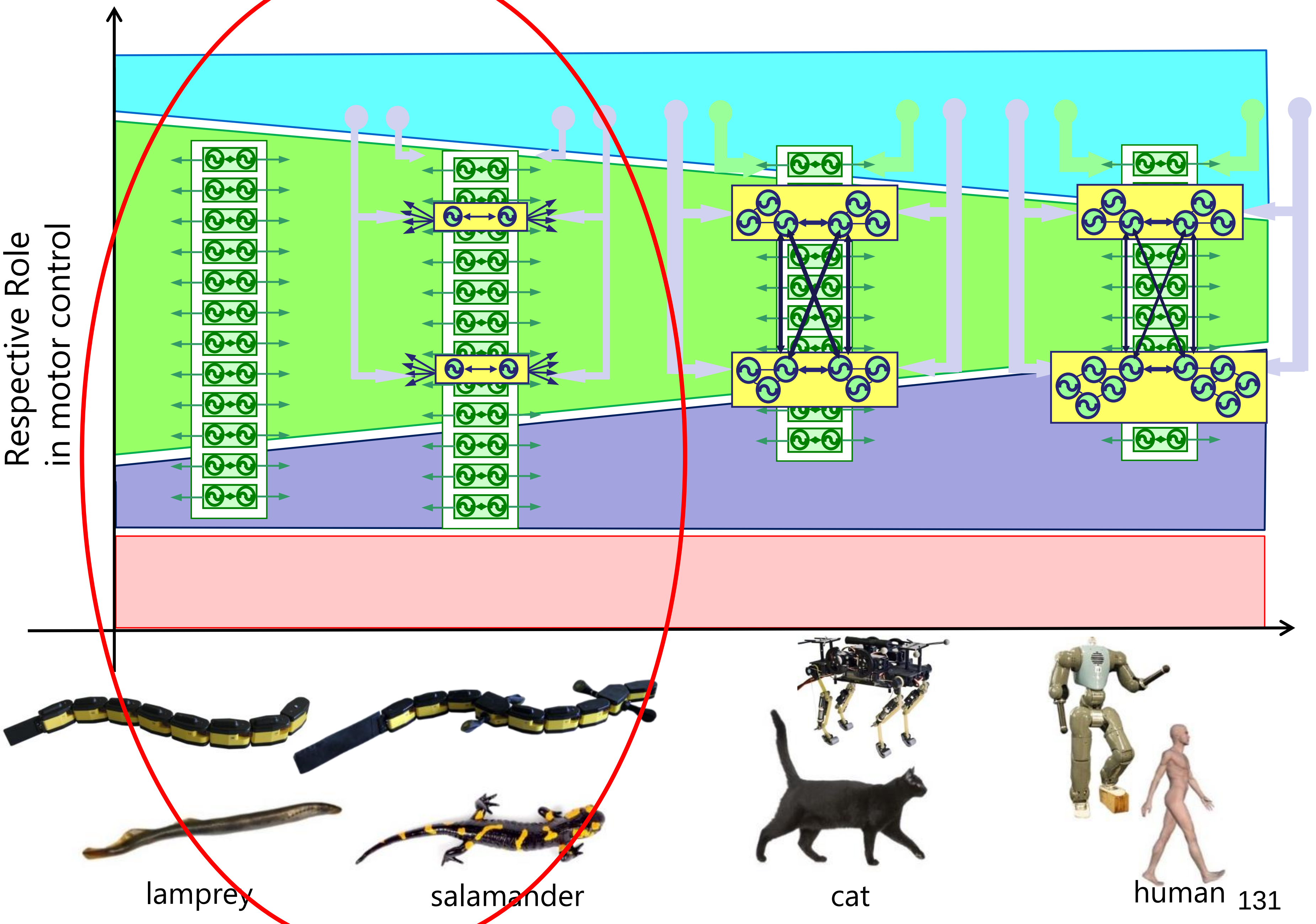
lamprey

salamander

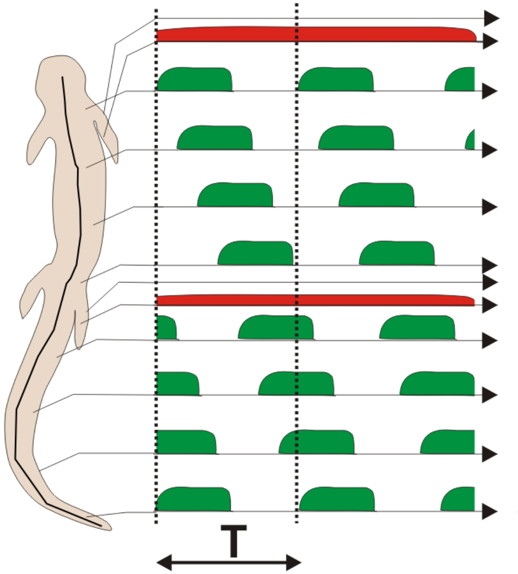
cat

human

Modeling spinal cord circuits



Bimodal locomotion (cartoon)



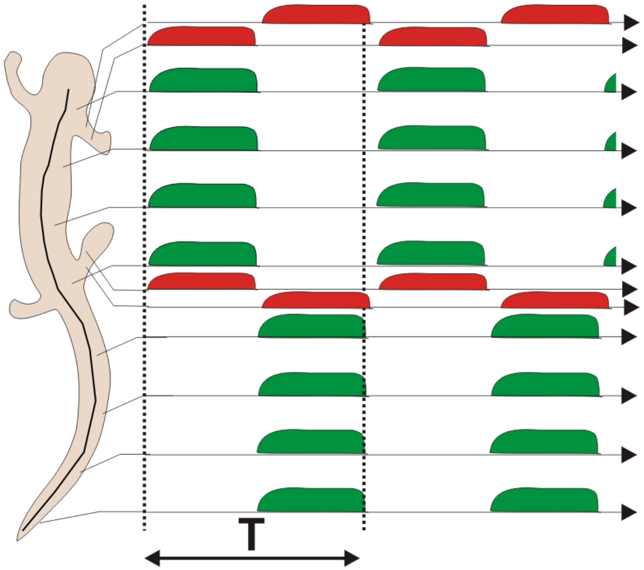
Swimming:

Traveling wave in axial muscles

Wavelength ≈ body length

Limb retractors are tonic

Short cycle durations



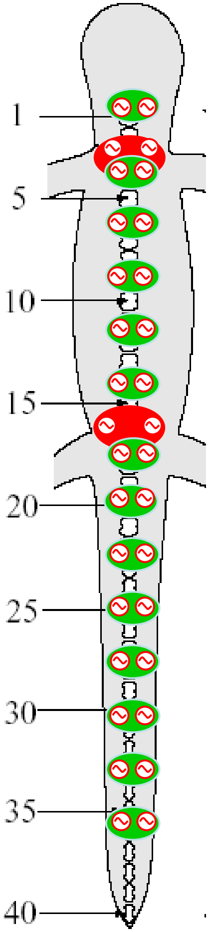
Walking:

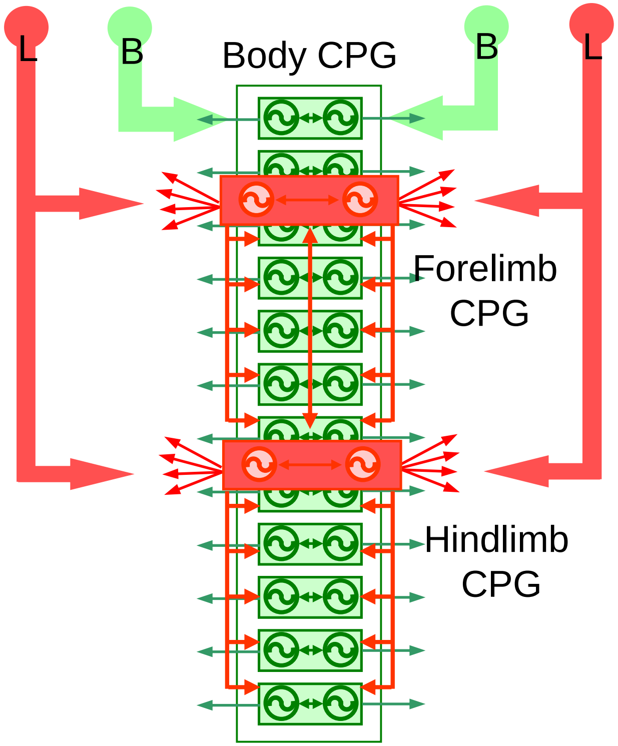
Standing wave

Limb retractors/protactors are phasic

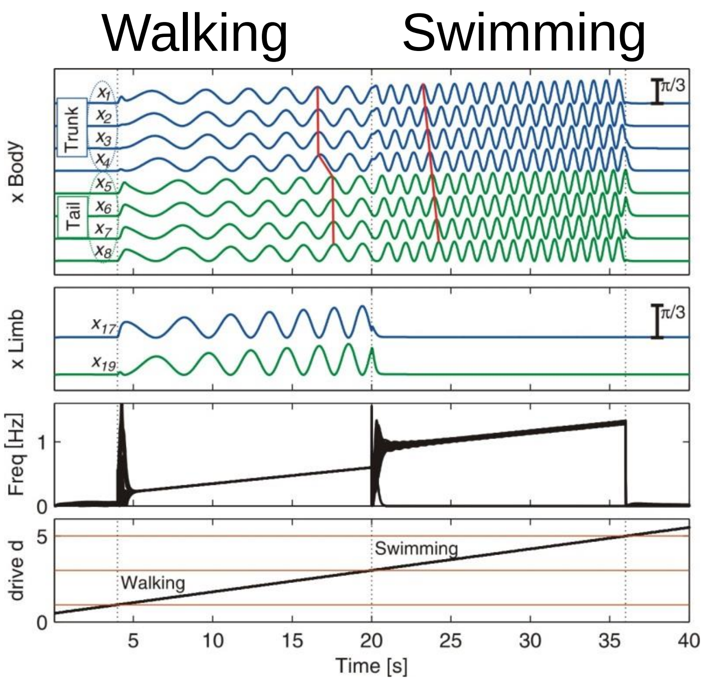
Longer cycle durations

A mathematical model to study the transition from swimming to walking





System of coupled oscillators



Gait transition due to an increase of the descending drive

[Ijspeert *et al*, *Science*, March 2007].

Oscillator model

A segmental oscillator is modeled as an amplitude-controlled phase oscillator as used in (Cohen, Holmes and Rand 1982, Kopell, Ermentrout, and Williams 1990) :

Phase:

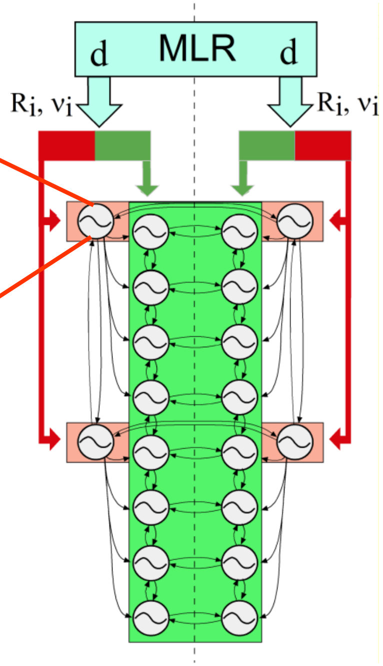
$$\dot{\theta}_i = 2\pi \nu_i + \sum_j r_j w_{ij} \sin(\theta_j - \theta_i - \phi_{ij})$$

Amplitude:

$$\ddot{r}_i = a_i\left(\frac{a_i}{4}(R_i - r_i) - \dot{r}_i\right)$$

Output:

$$x_i = r_i(1+\cos(\theta_i))$$



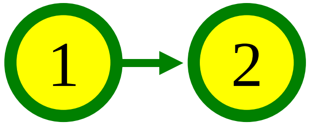
Setpoints:

$$\varphi_i = x_i - x_{N+i} \quad \textit{for the axial motors}$$

$$\varphi_i = f(\theta_i) \quad \textit{for the (rotational) limb motors}$$

[Ijspeert *et al*, *Science*, March 2007].

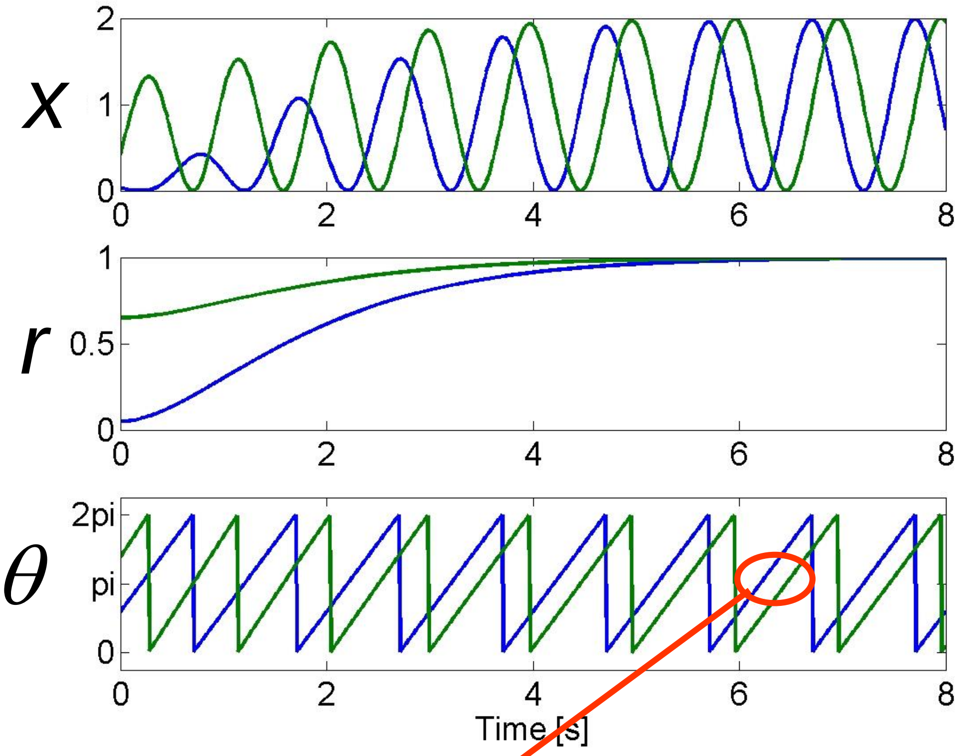
Example with two oscillators



$$\dot{\theta}_i = 2\pi\nu_i + \sum_j \left(r_j w_{ij} \sin(\theta_j - \theta_i - \phi_{ij})\right)$$

$$\ddot{r}_i = a_i\left(\frac{a_i}{4}(R_i - r_i) - \dot{r}_i\right)$$

$$x_i = r_i(1 + \cos(\theta_i))$$



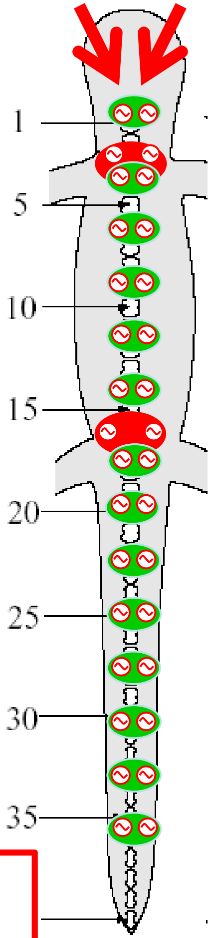
The phase difference $\phi = \theta_1 - \theta_2$ between two oscillators converges to

$$\phi_\infty = \arcsin\left(\frac{2\pi(\nu_1 - \nu_2)}{R_1 w_{21}}\right) - \phi_{21}$$

[Ijspeert *et al*, *Science*, March 2007].

Gait transition in the salamander by modulating descending drive

J.M. Cabelguen
U. of Bordeaux



CPGs can modulate speed, heading, and type of gait under the modulation of a few drive signals

CPG and sensory feedback in amphibious locomotion

Collaborators:


L. Paez


A. Crespi


B. Bayat


Akio Ishiguro
Tohoku U.


Emily Standen
Ottawa U.


K. Melo


T. Horvat


J. Arreguit O'Neil


R. Thiandiackal


Astrid Petitjean

HFSP

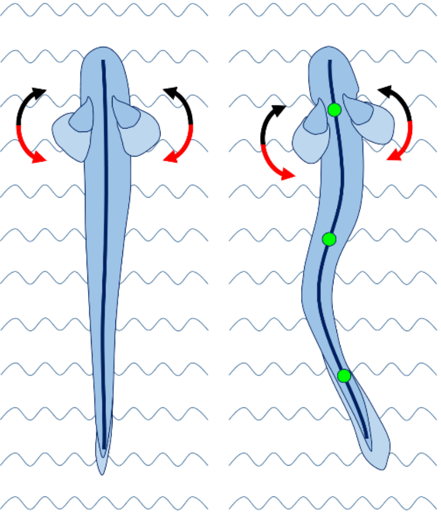

J.M. Cabelguen
U. of Bordeaux


Fred Boyer
Ecole des Mines
Nantes

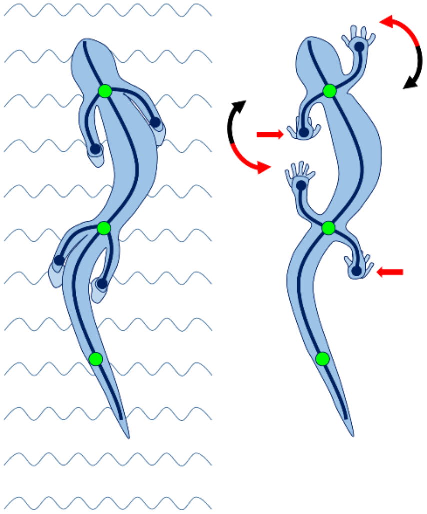
Alumni:
A. Bicanski, J. Knuesel,
K. Karakasiliotis, R. Thandiackal

Gait comparison

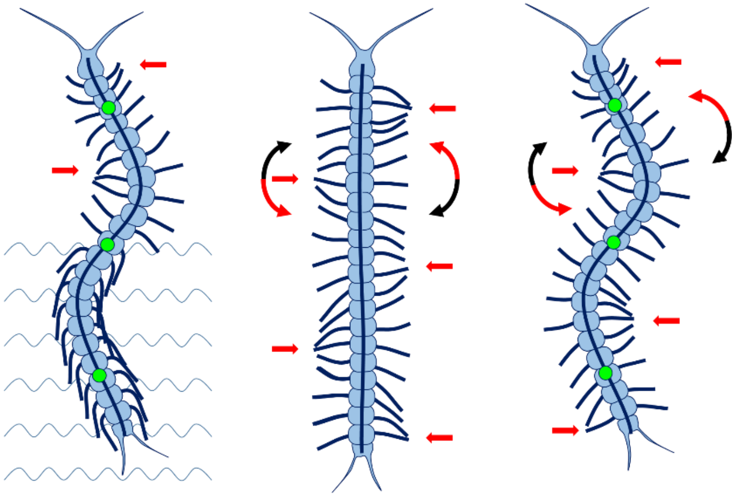
Polypterus



Salamander

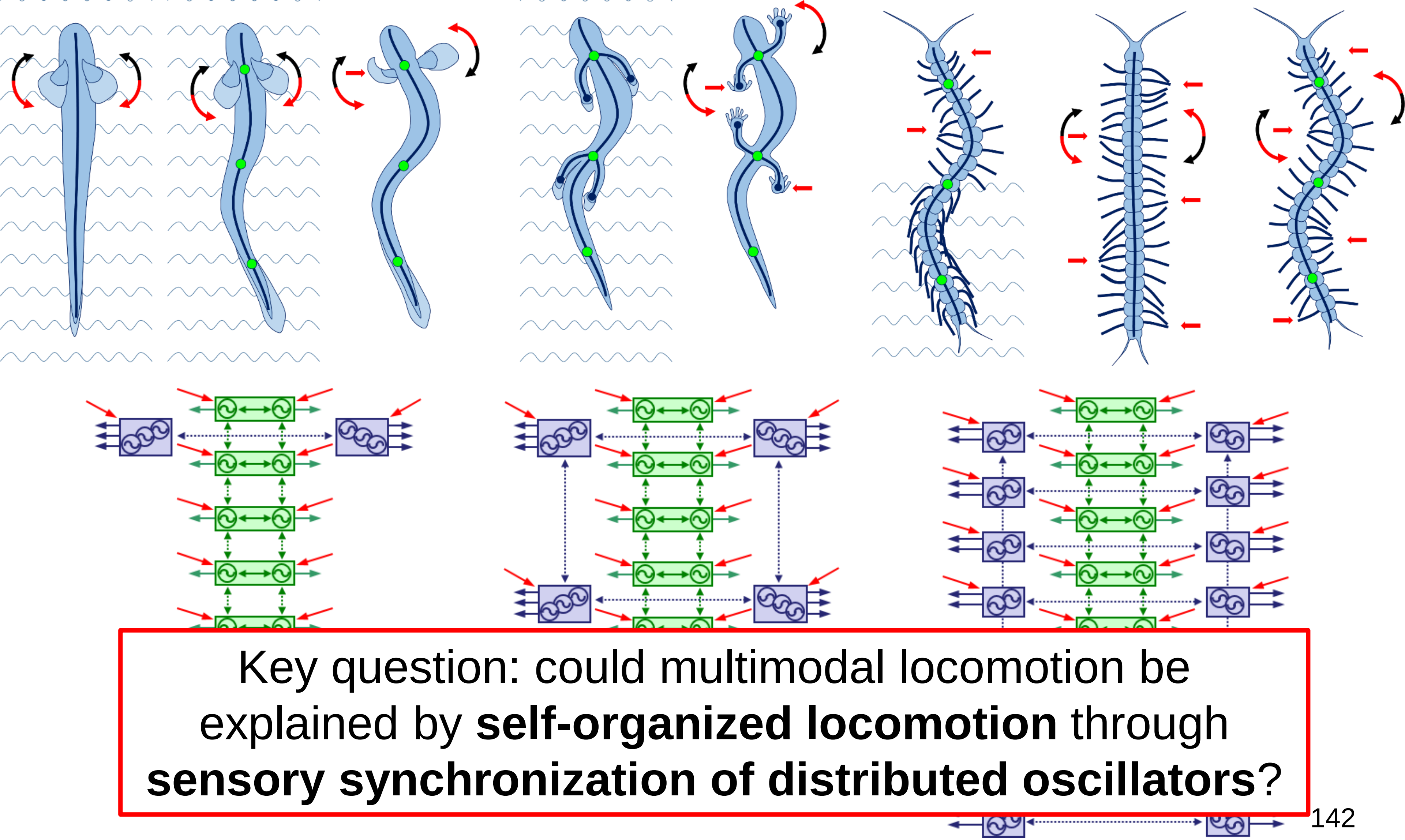


Centipede



Gait comparison

Polypterus **Salamander** **Centipede**



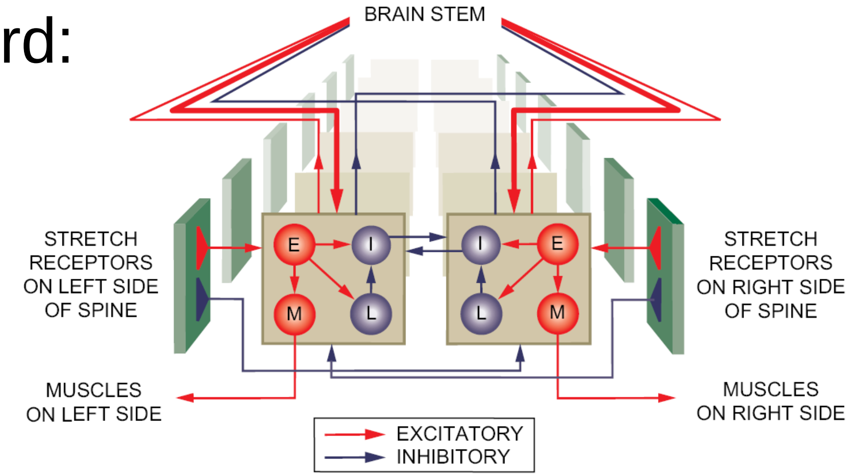
Key question: could multimodal locomotion be explained by **self-organized locomotion** through **sensory synchronization of distributed oscillators**?

Stretch receptors in the lamprey

Stretch receptors within the spinal cord:

- Participate to **burst termination**.

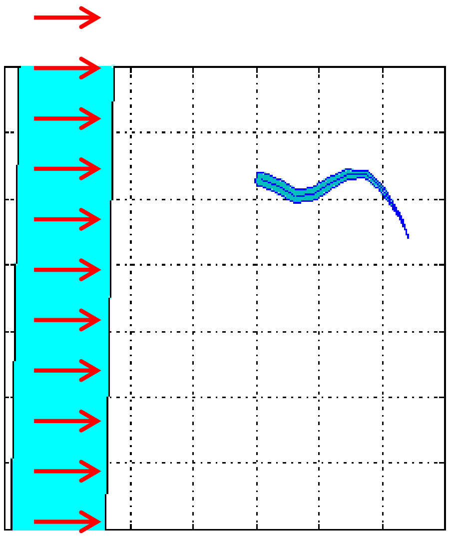
- Help **handle perturbations**, e.g. a speed barrier.



Grillner, Sci. Am. 1996

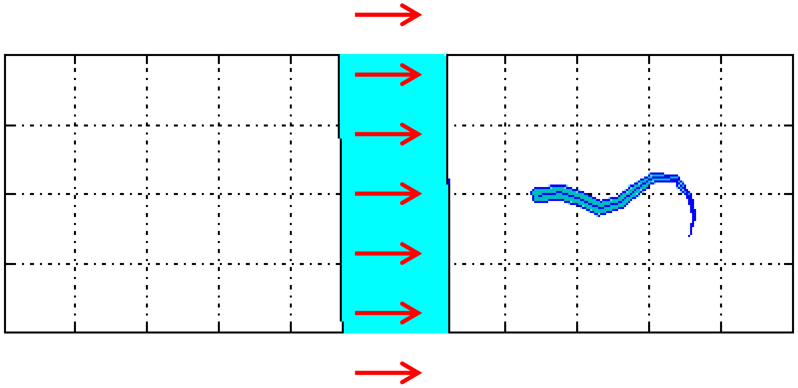
Swimming through a speed barrier

without sensory feedback (only CPG)



Swimming through a speed barrier

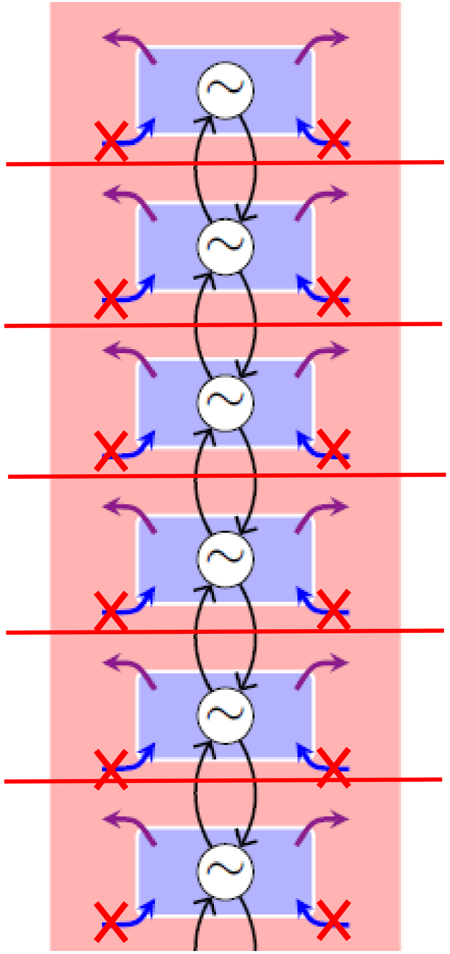
with sensory feedback



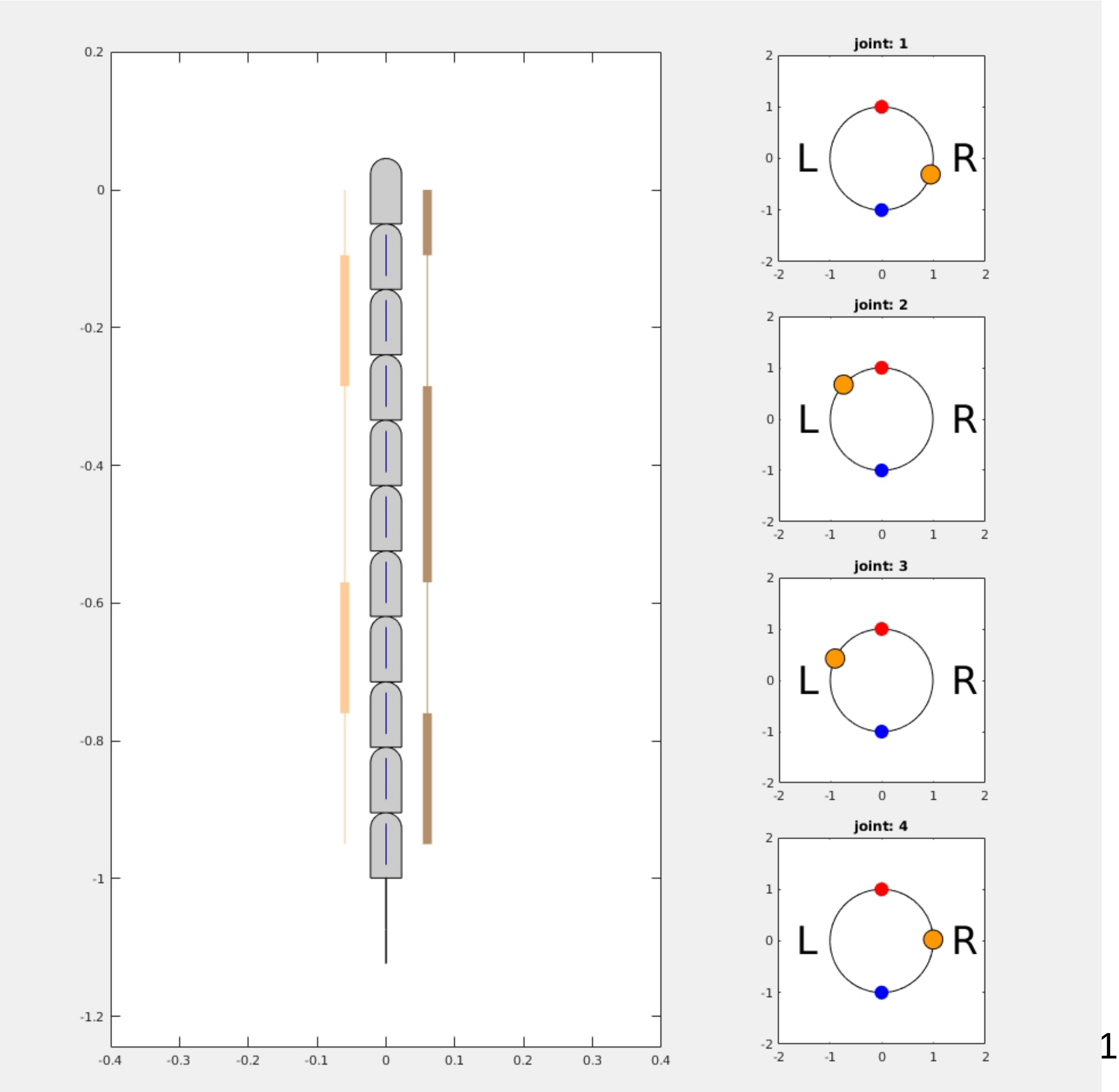
Sensory feedback helps handle perturbations

Decoupled oscillations coordinated by feedback

Decoupled

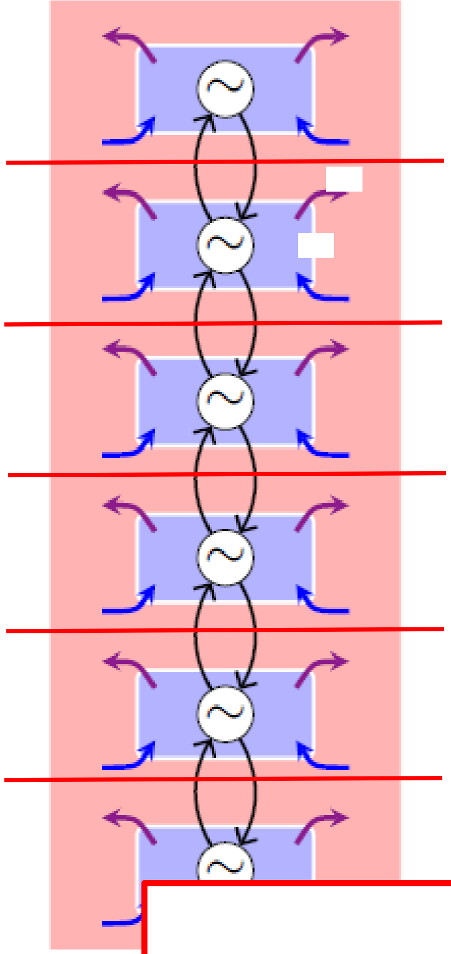


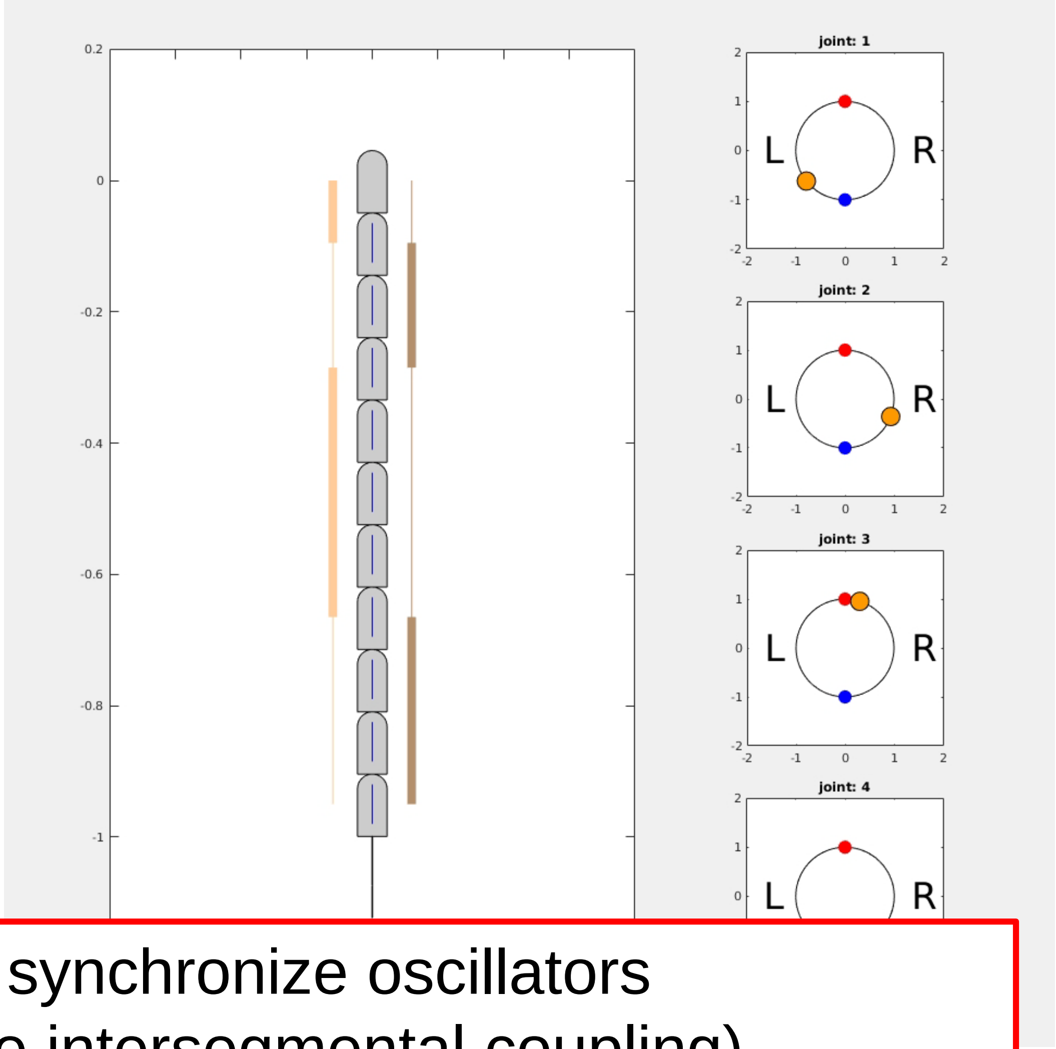
Open loop case



Decoupled oscillations coordinated by feedback

Decoupled





SF can synchronize oscillators
(i.e. replace intersegmental coupling)

Clo

Swimming summary

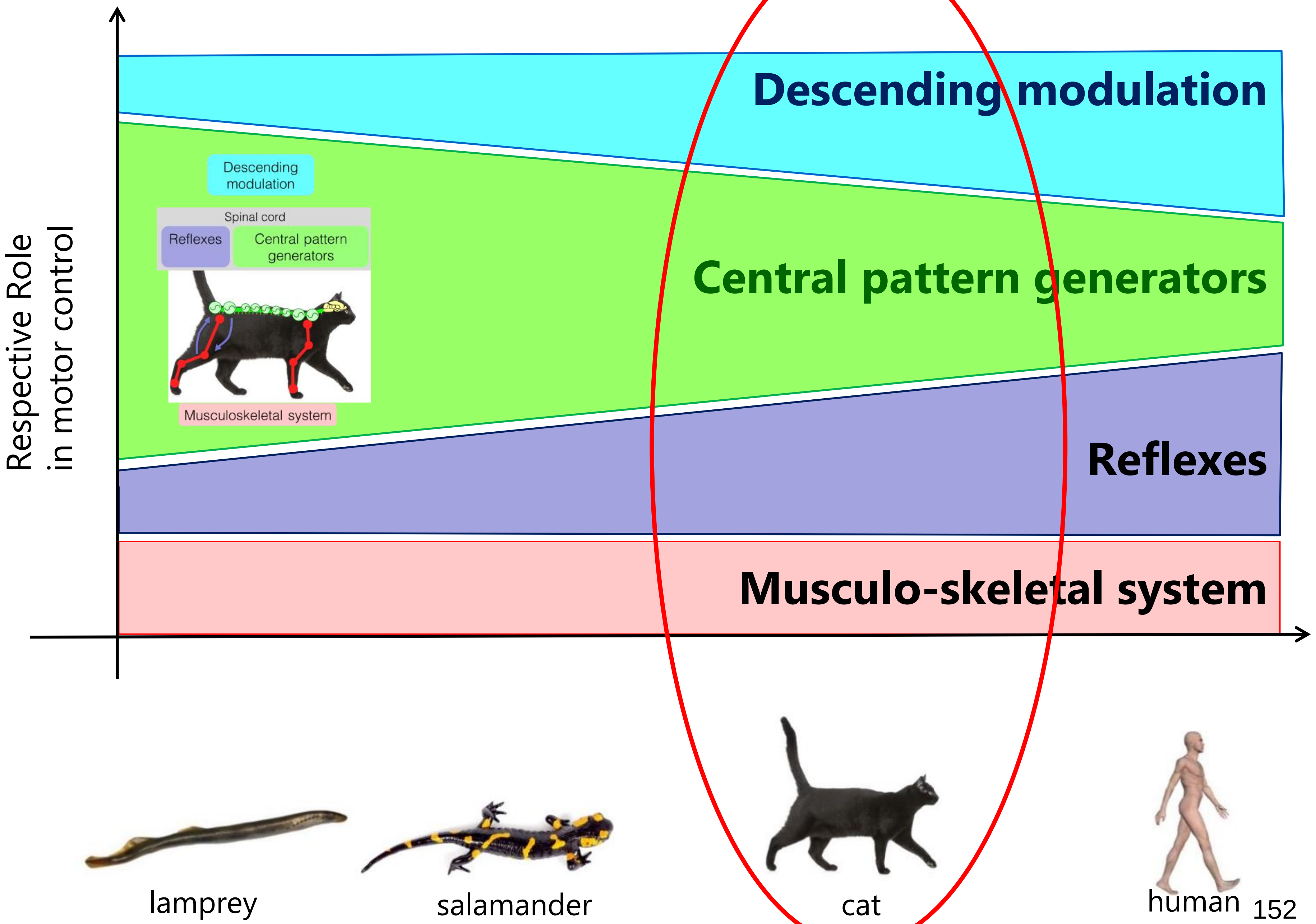
Local sensory feedback (together with distributed oscillators):

1. helps **handle perturbations**
2. can lead to **faster swimming**
3. leads to **higher frequencies**
4. can **correct wrong CPG patterns** (wrong phase lags)
5. can **synchronize oscillators** (i.e. replace intersegmental coupling)
6. can **generate rhythms** (i.e. replace oscillators)

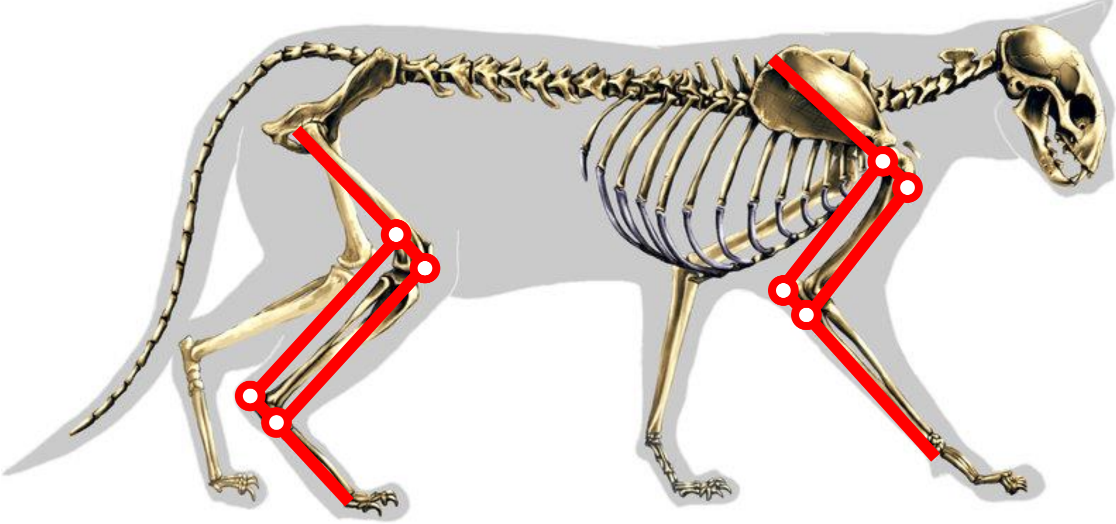
- **Self-organized locomotion**
- **Strong redundancy:** many aspects of swimming can be generated both by **central <u>and</u> peripheral mechanisms**

- Work in progress: still many things to explore such as other sensor modalities, implementation as a neural network, …

Modeling spinal cord circuits



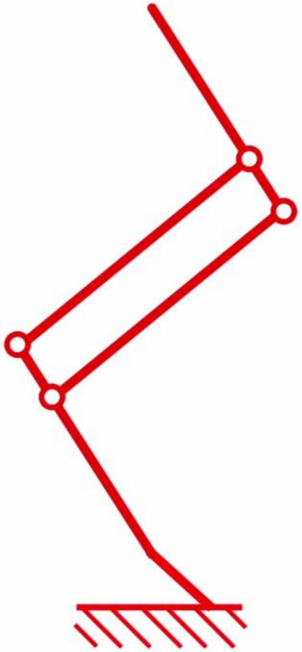
Cheetah-Cub: a compliant quadruped robot

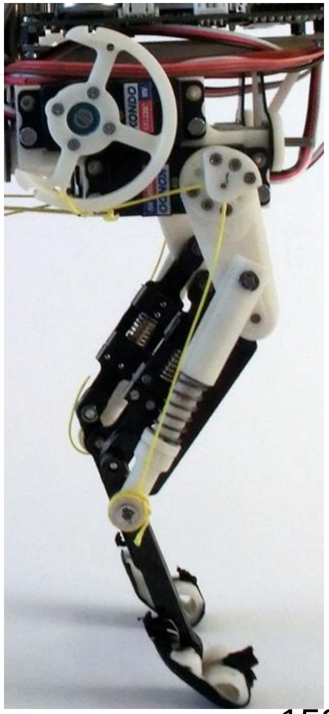


Scientific question:
What are the key principles underlying the agility of cats' locomotion?

Hypothesis:
self-stabilizing property of the musculoskeletal system

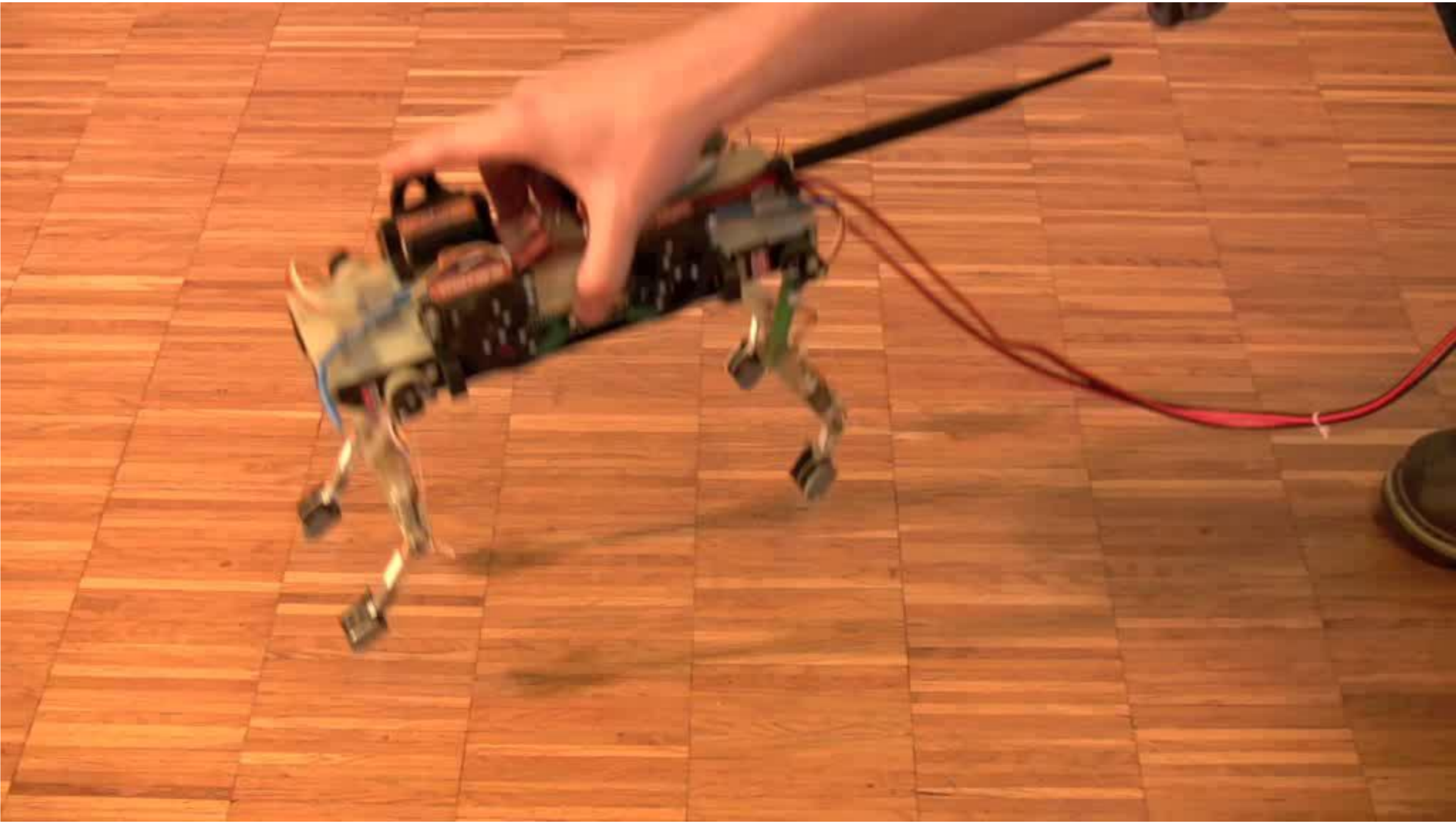
~ Pantograph structure



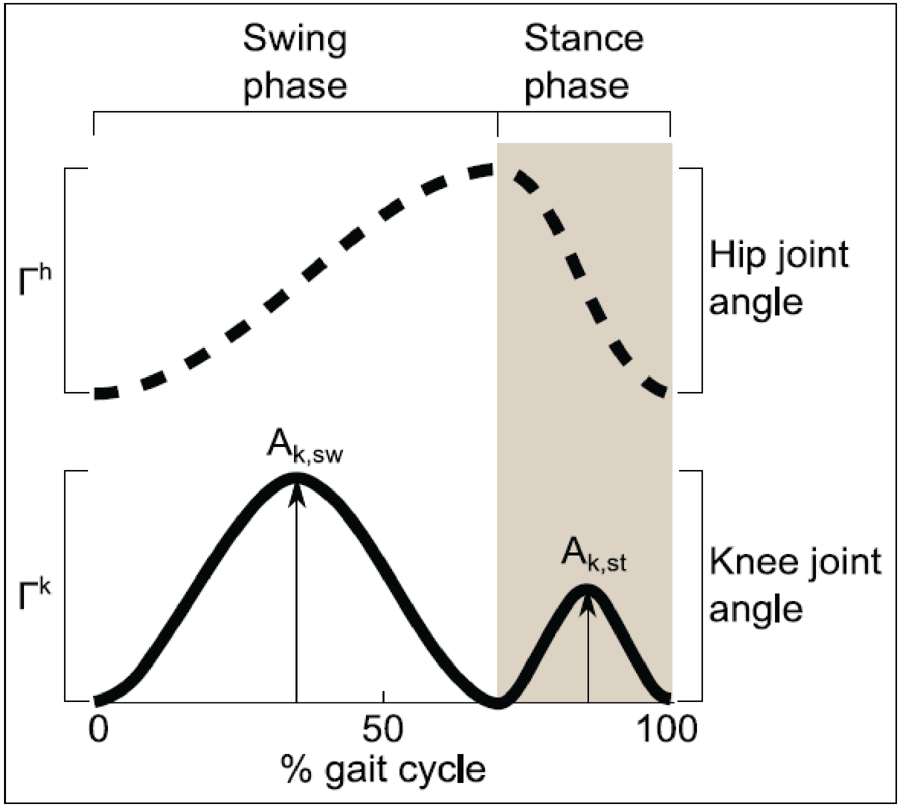


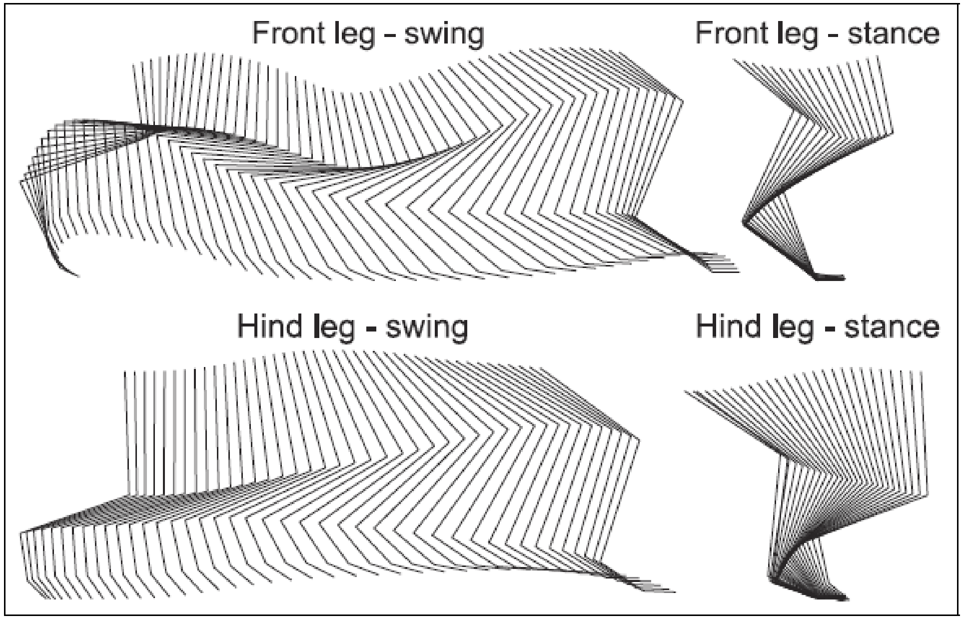
Key properties:
1) light-weight
2) Viscoelastic
3) segmented leg with a **pantograph structure**

Robustness and Self-stabilization



Open-loop control patterns





Well-tuned open loop control pattern
(joint angles for the servomotors)

→

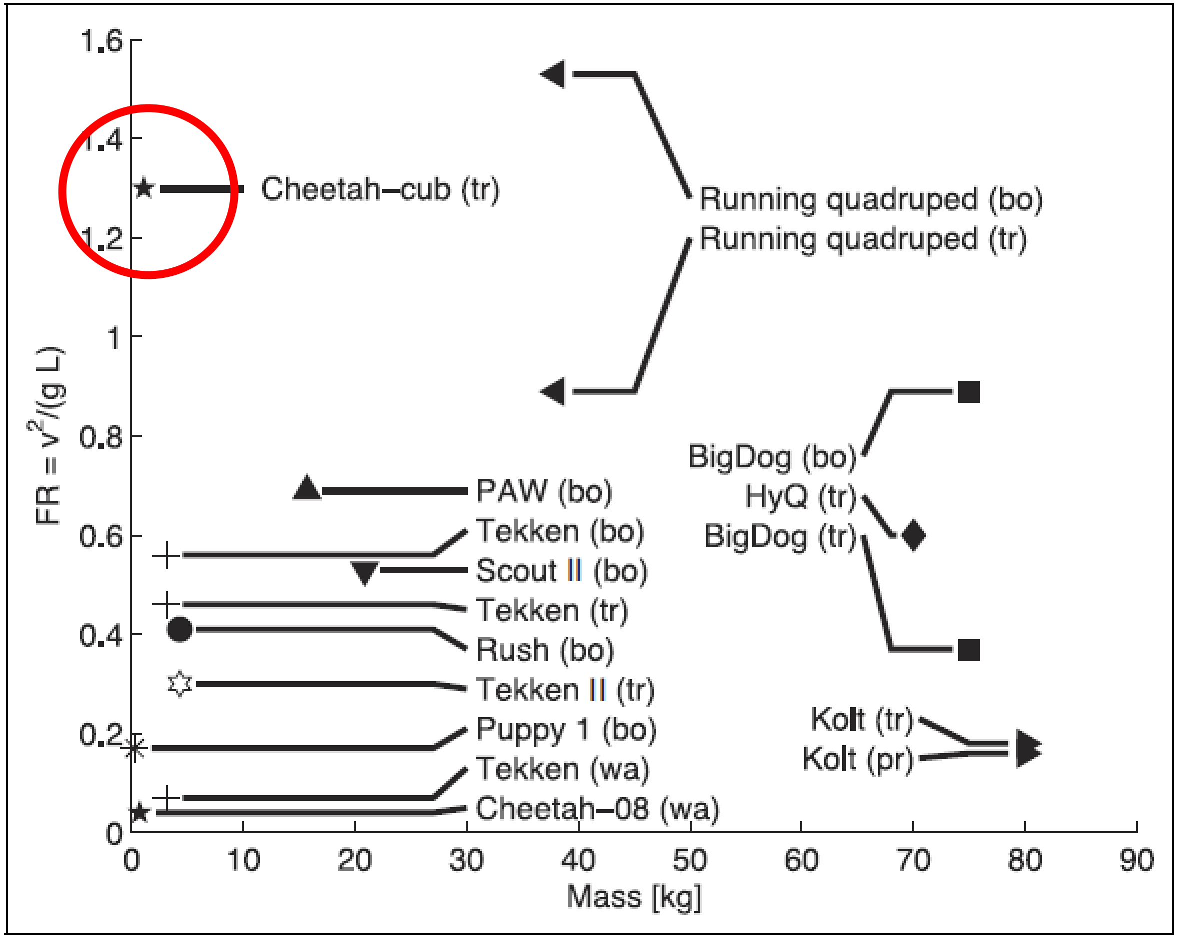
Stable animal-like gait

Robustness and Self-stabilization

Robust against perturbations (e.g. steps down)

A. Sproewitz, A. Tuleu, M. Vespignani, M. Ajallooeian and E. Badri et al. Towards Dynamic Trot Gait Locomotion---Design, Control and Experiments with Cheetah-cub, a Compliant Quadruped Robot, **International Journal of Robotics Research**,vol. 32 no. 8, pp 932-950 , 2013.

Froude number



The **fastest of all quadruped robots below 30kg and above 0.3Kg** in terms of body lengths per seconds (6.9 BL/s) and Froude number

The Froude number is a dimensionless number useful for size-independent comparison of speed:

$$\mathrm{FR} = \bar{v}^2/(g \cdot h)$$

v : mean forward velocity

g: earth gravity

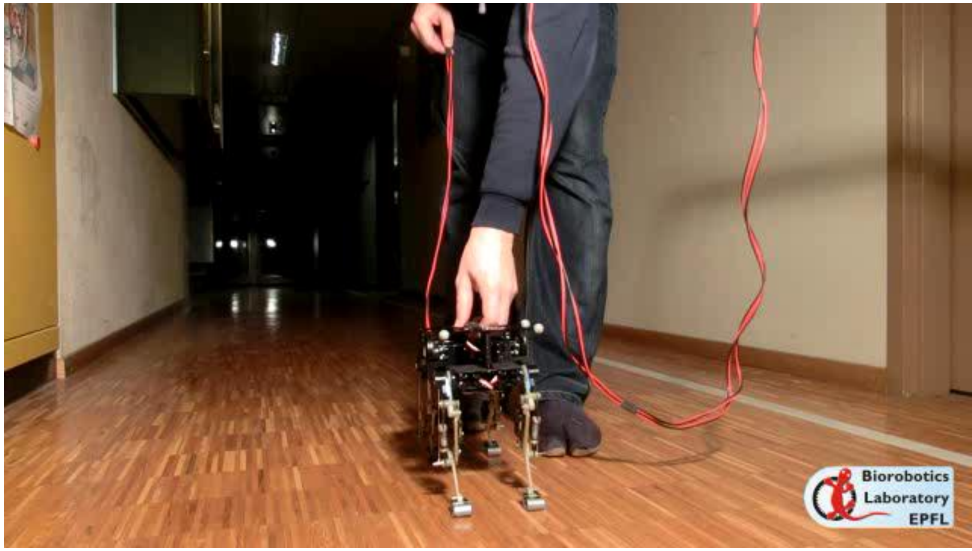
h : hip joint height

Cheetah-Cub take-home message

The vertebrate **musculoskeletal system** has very interesting **intrinsic properties to handle perturbations and simplify control**

Well-tuned open-loop patterns lead to quite robust locomotion

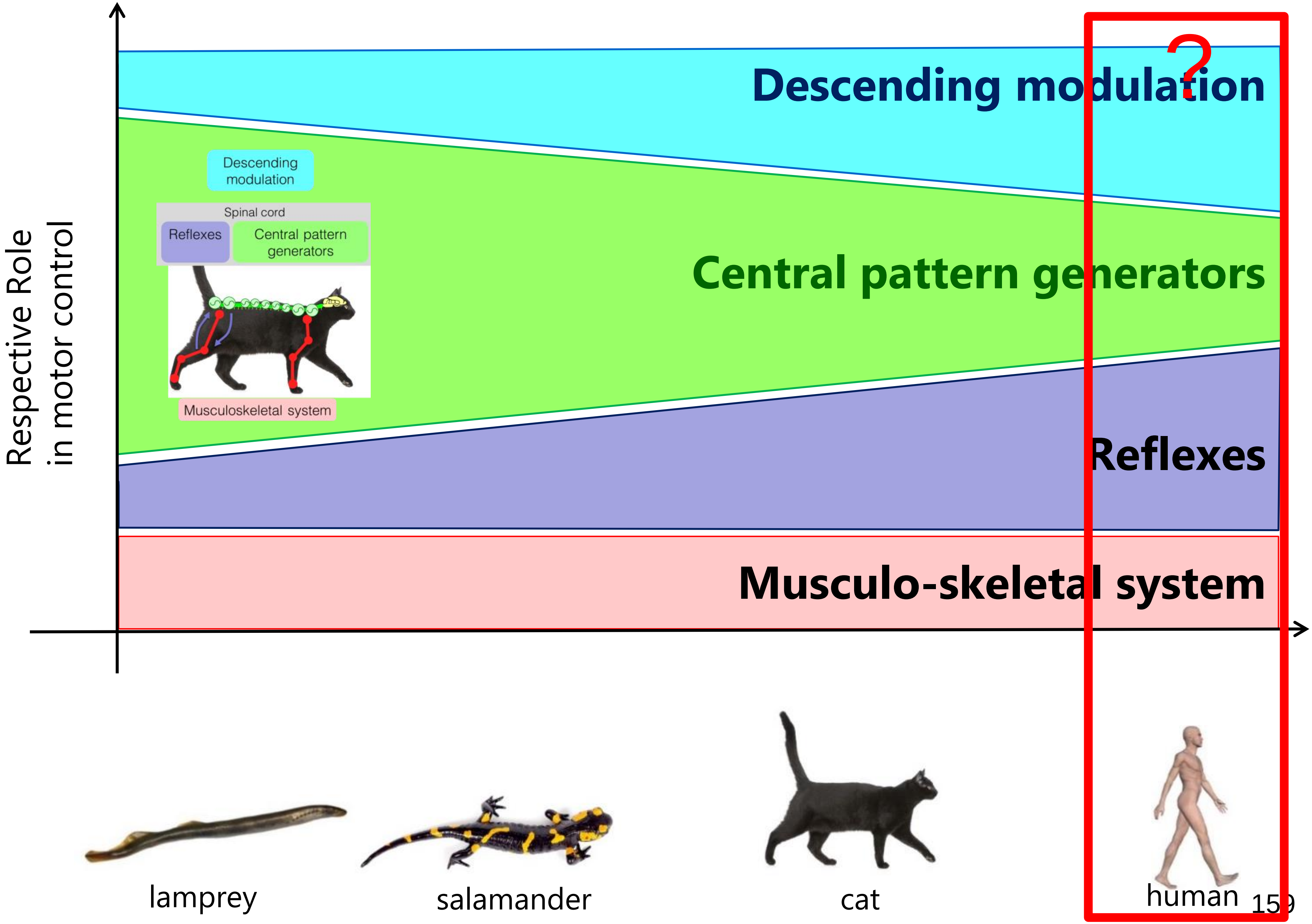
It offers an excellent source of inspiration for **fast and agile robots.**



Check out the
EPFL News Youtube channel:
Over 1.2 million hits

Reference:
A. Sproewitz, A. Tuleu, M. Vespignani, M. Ajallooeian and E. Badri et al. Towards Dynamic Trot Gait Locomotion---Design, Control and Experiments with Cheetah-cub, a Compliant Quadruped Robot, **International Journal of Robotics Research**,vol. 32 no. 8, pp 932-950 , 2013.

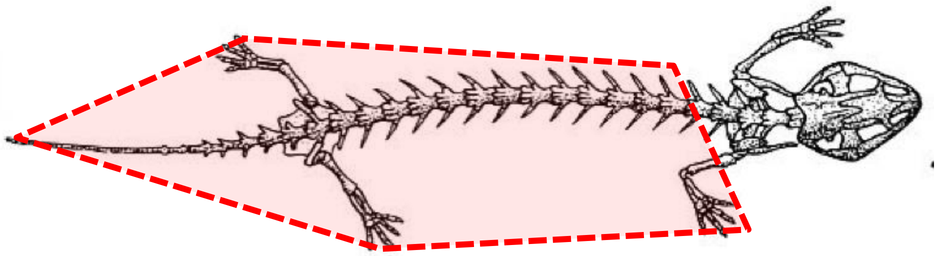
Modeling spinal cord circuits



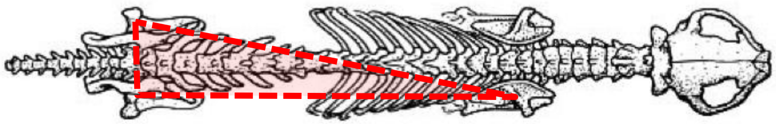
Key transition
from amphibians/reptiles to mammals

Sprawling posture

Upright posture

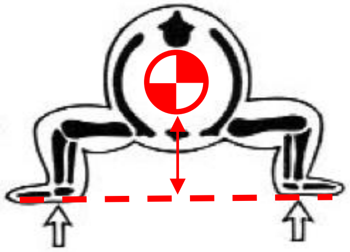


Salamander



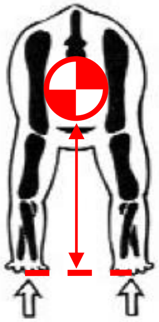
studyblue.com

Mammal



Low center of mass

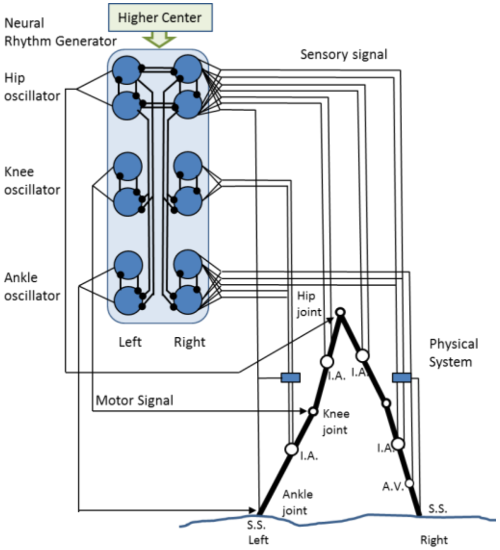
Large support polygon



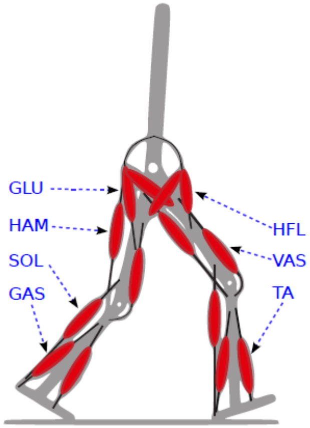
High center of mass

Small support polygon

Neuromechanical models of human locomotion

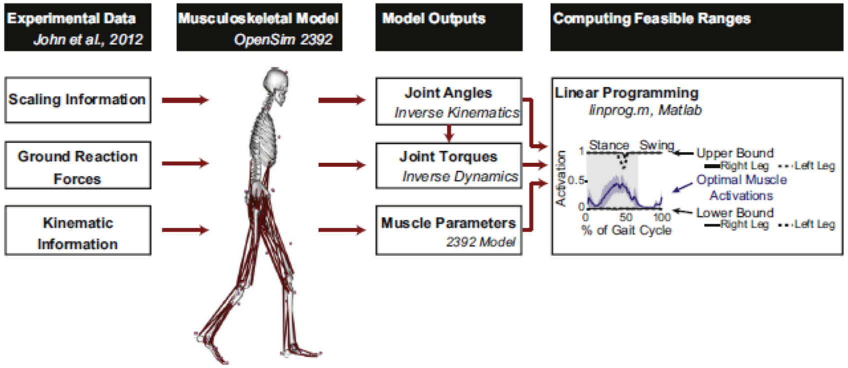


Taga 1995, 1998



Geyer and Herr, 2010.

Y.Nakamura lab (Sreenivasa et al 2012)



L. Ting lab (Simpson et al 2016)

Geyer and Herr’s sensory-driven model

Sensory-driven model

+

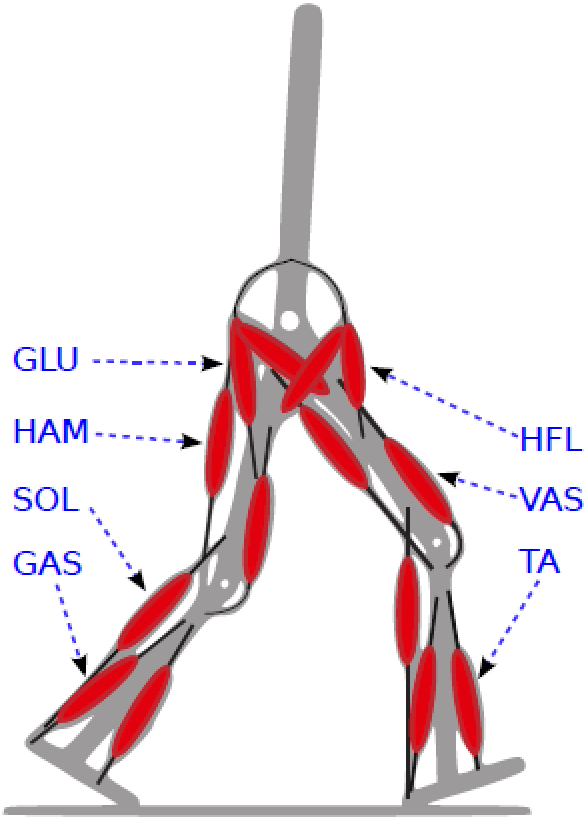
7 muscles per leg

+

Different reflexes

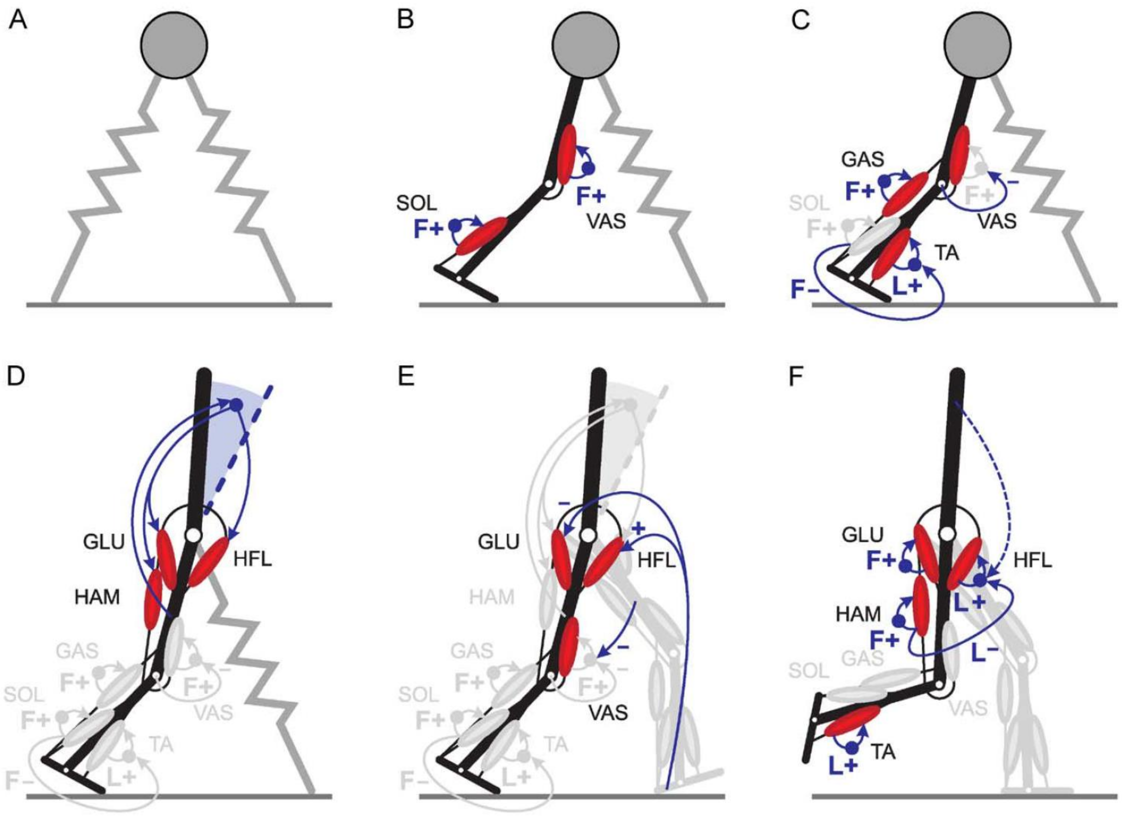
+

Posture control (torso angle)



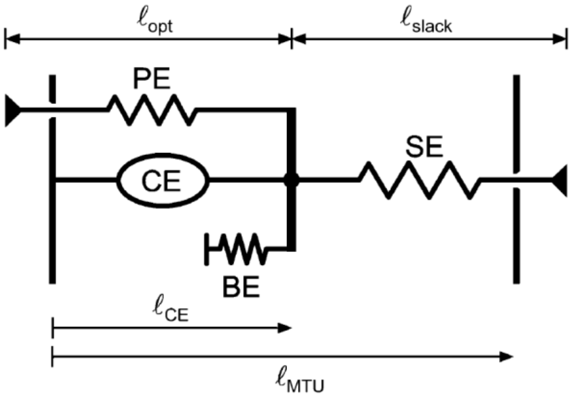
H Geyer, HM Herr. A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities. **IEEE Trans Neural Syst Rehabil Eng** 18(3): 263-273, 2010.

Geyer and Herr’s sensory-driven model



Different reflexes act on different muscle at particular moments of the cycle.

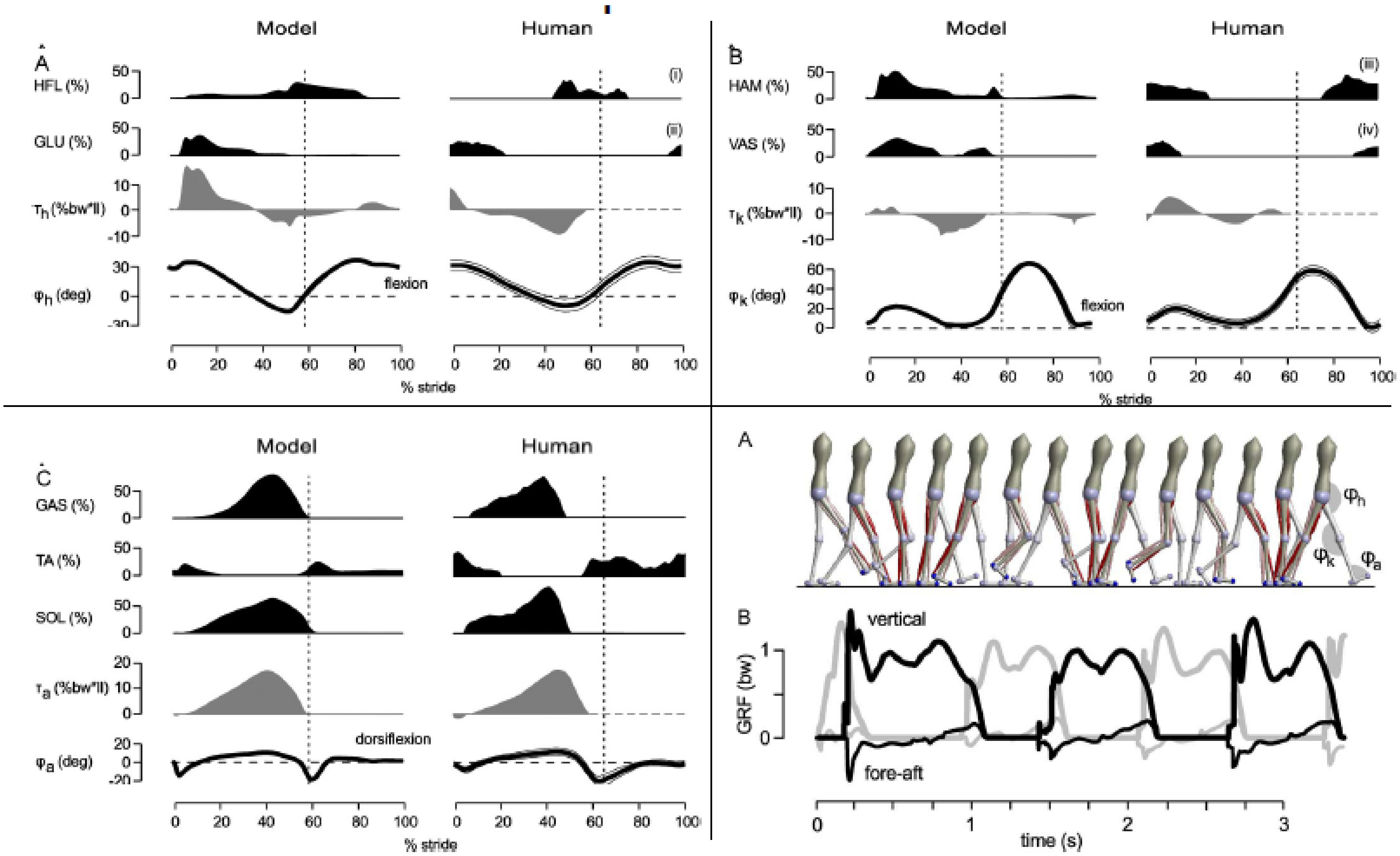
Muscles are simulated with Hill-like models:



Numerical optimization to find reflex gains

H Geyer, HM Herr. 2010.

Good match to human data



H Geyer, HM Herr. A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities. **IEEE Trans Neural Syst Rehabil Eng** 18(3): 263-273, 2010.

Adding CPGs

Florin Dzeladini

N. van der Noot

D. Renjewski

- Is it worth adding a CPG to the sensory-driven network?
- Yes, we think so!

Hypotheses: adding a CPG to the feedback-driven controller can

1) Improve the **control of speed**
2) Improve **robustness against sensory noise**
3) Improve **robustness against sensory failure**

This can be seen as adding a feedforward controller to a feedback controller


Florin Dzeladini


N. van der Noot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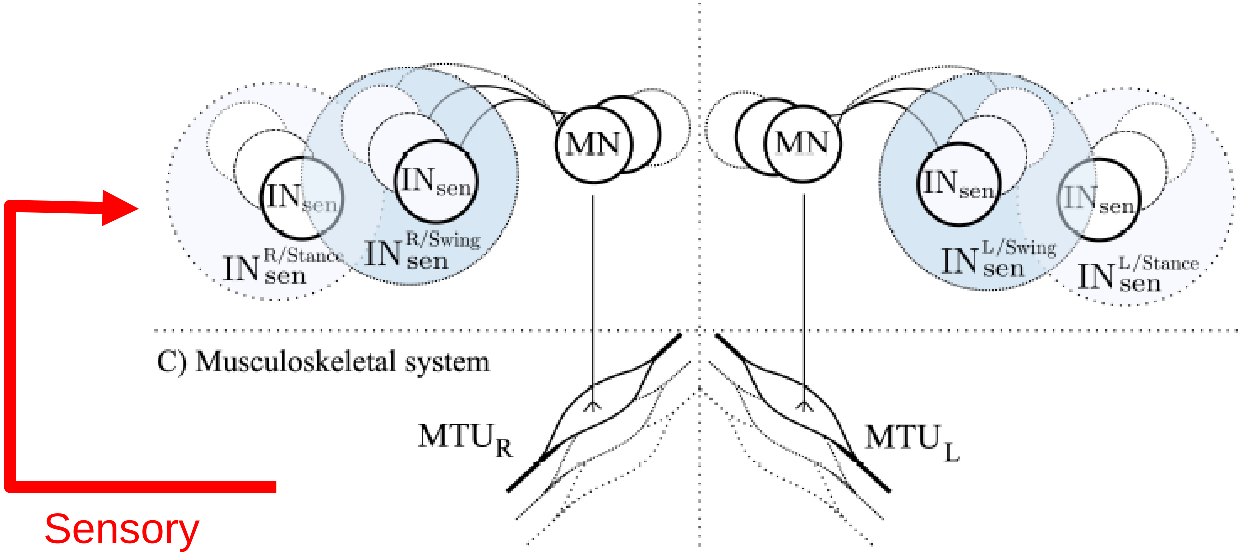
CPG construction

Art Kuo: the **CPG could act as an internal model** of limb motion that predicts the state of the limb.

We start with the sensory-driven model:

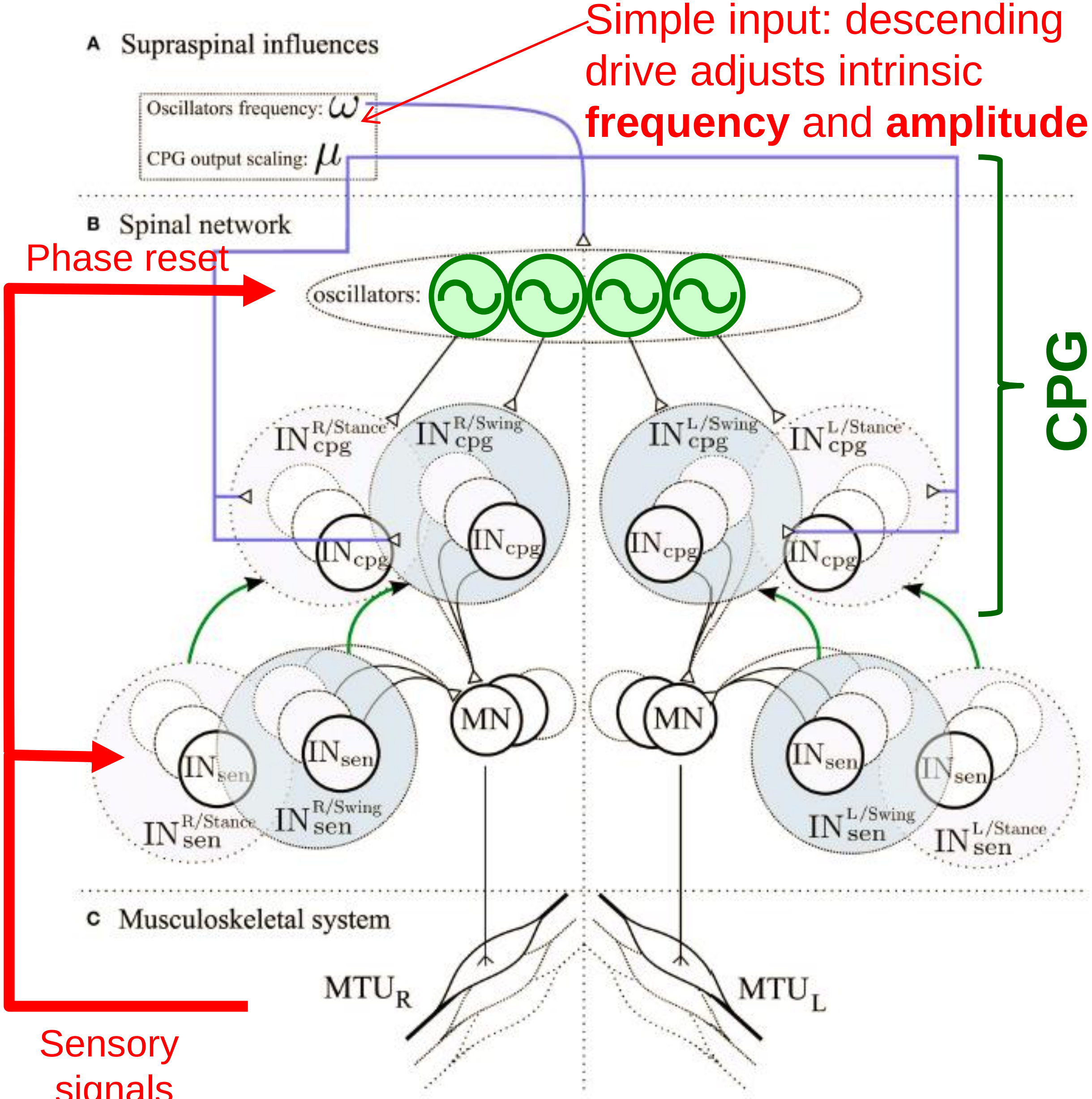


Sensory signals

Dzeladini et al 2014, Frontiers in Human Neuroscience

CPG construction

… and add a **CPG that replicates the control signals produced during steady-state**



Simple input: descending drive adjusts intrinsic **frequency** and **amplitude**

Phase reset

CPG

Sensory signals

Dzeladini et al 2014, Frontiers in Human Neuroscience

CPG construction

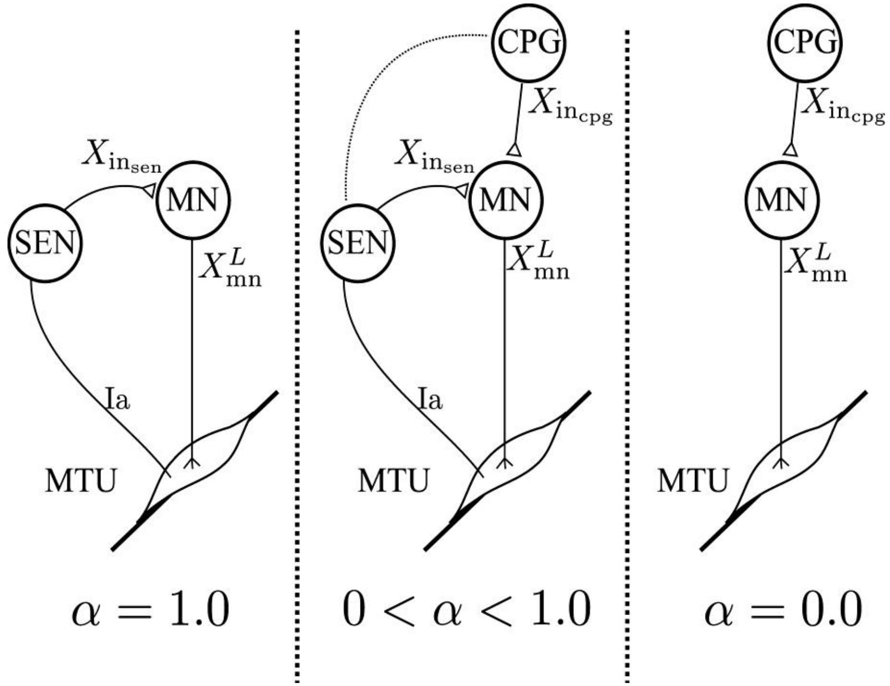
Feedback & CPG network

$$X_{\mathrm{mn}} = f\left(X_{\mathrm{in}_{\mathrm{sen}}}, X_{\mathrm{in}_{\mathrm{cpg}}}\right) + X^0_{\mathrm{mn}}$$

$$f(x_{\mathrm{fb}}, x_{\mathrm{ff}}) = G^s\Big(x_{\mathrm{ff}} + \alpha\big(x_{\mathrm{fb}} - x_{\mathrm{ff}}\big)\Big)$$

$\alpha = 0$ → pure feedforward

$\alpha = 1$ → pure feedback



pure feedback

pure feedforward

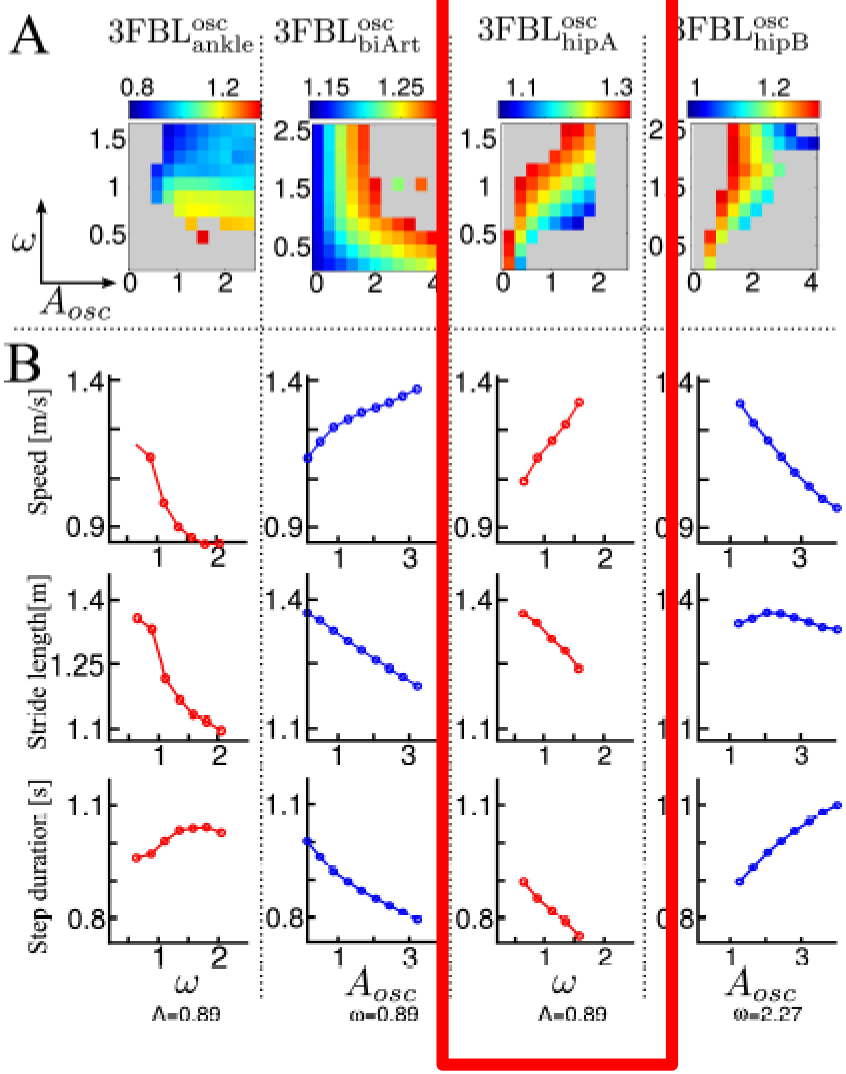
Dzeladini et al 2014, The contribution of a central pattern generator in a reflex-based neuromuscular model, Frontiers in Human Neuroscience

Results: speed modulation

- Simple model of supraspinal influences
  Feedforward frequency and amplitude modulation

- *Tested on different models*
  - *Feedforward added on ankle pathways*
  - *Feedfoward added on biArt pathways*
  - *Feedforward on pathways acting on all hip muscles*
  - *Feedforward on pathways acting on two over four hip muscles*

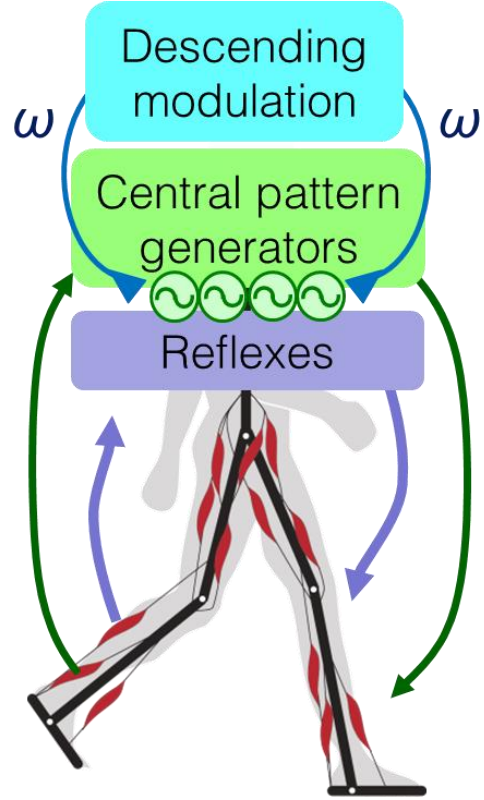
Nice control of speed by adding oscillators to the hips



Dzeladini et al 2014, Frontiers in Human Neuroscience

Neuromechanical model of human locomotion

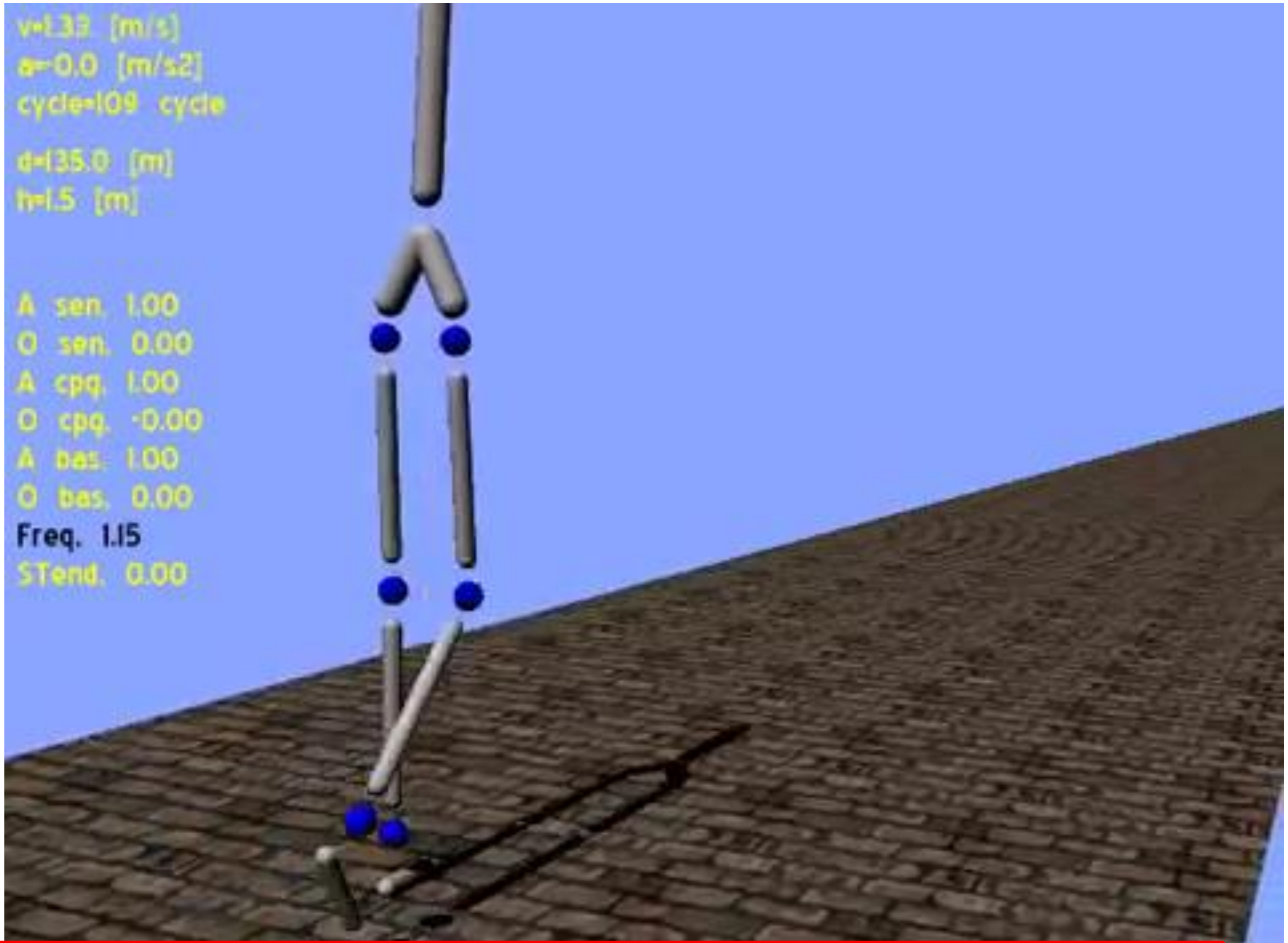
F. Dzeladini



Descending modulation

Central pattern generators

Reflexes

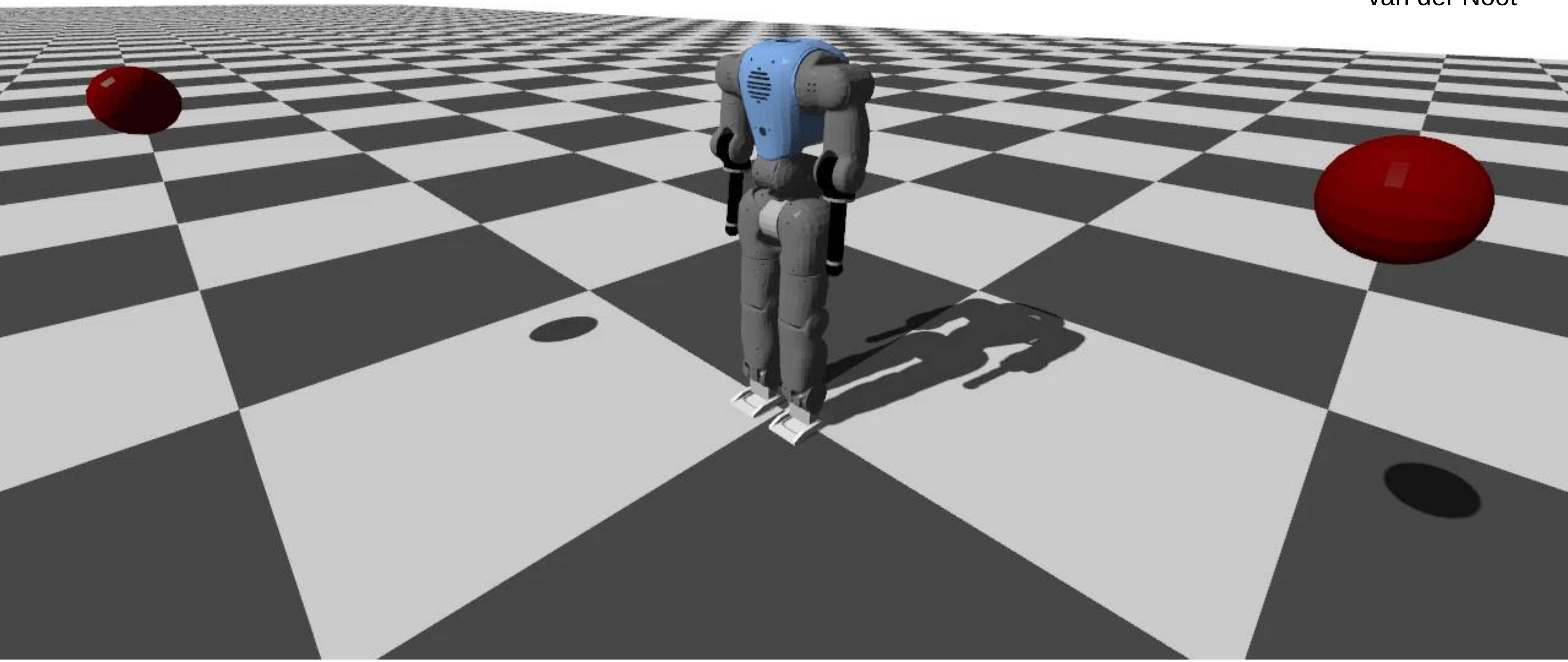


```
v=1.33 [m/s]
a=-0.0 [m/s2]
cycle=109 cycle

d=135.0 [m]
h=1.5 [m]


A sen. 1.00
O sen. 0.00
A cpg. 1.00
O cpg. -0.00
A bas. 1.00
O bas. 0.00
Freq. 1.15
STend. 0.00
```

Proximo-distal gradient? **Proximal joints** driven by **CPGs,**
Distal joints driven by **sensory feedback**

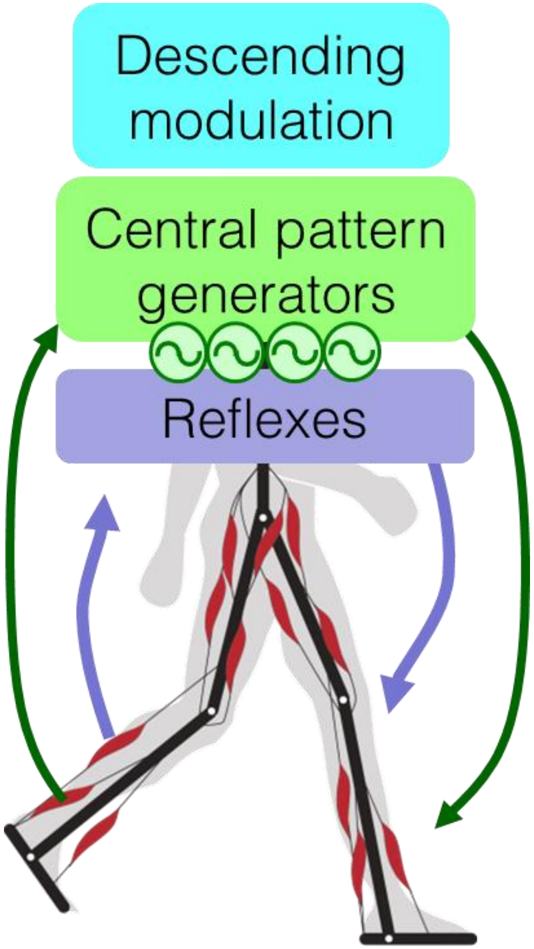
3D CPG-based controller

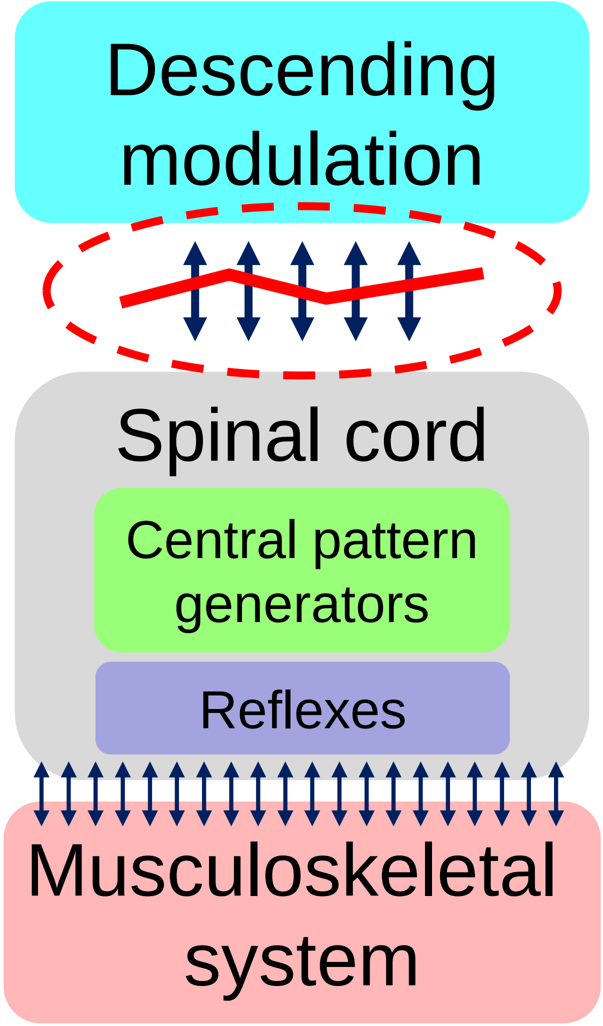
Nicolas
van der Noot



N Van der Noot, AJ Ijspeert, R Ronsse
The International Journal of Robotics Research 37 (1), 168-196, 2018.

Link to neuroprosthetics





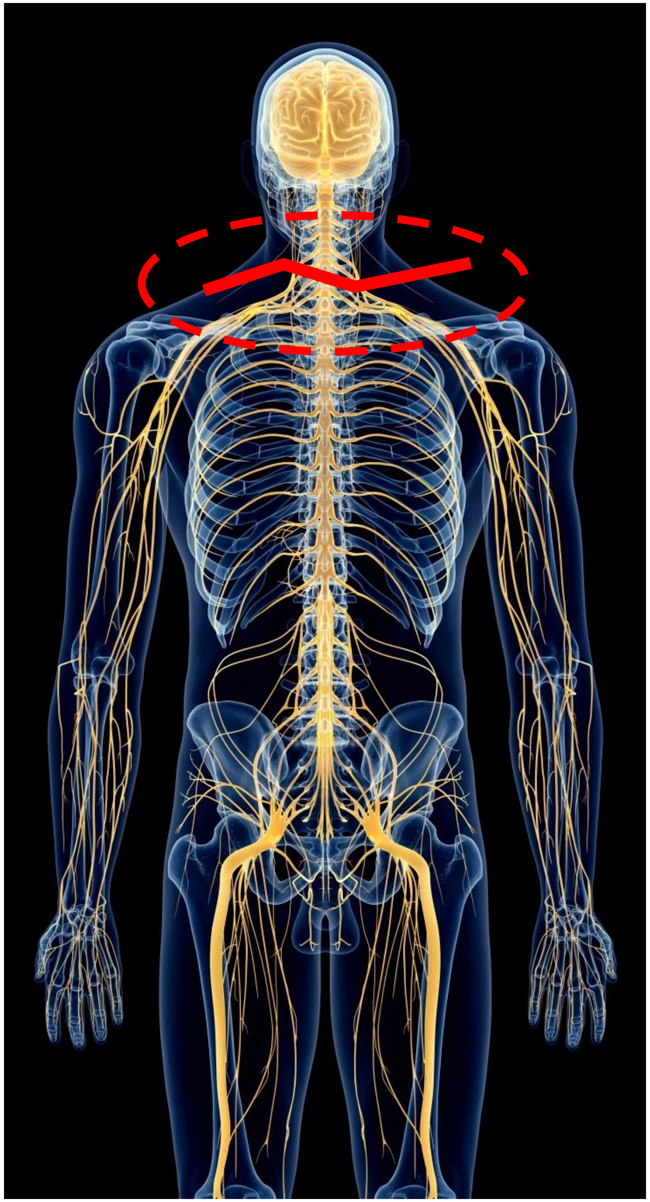
Descending modulation

Spinal cord

Central pattern generators

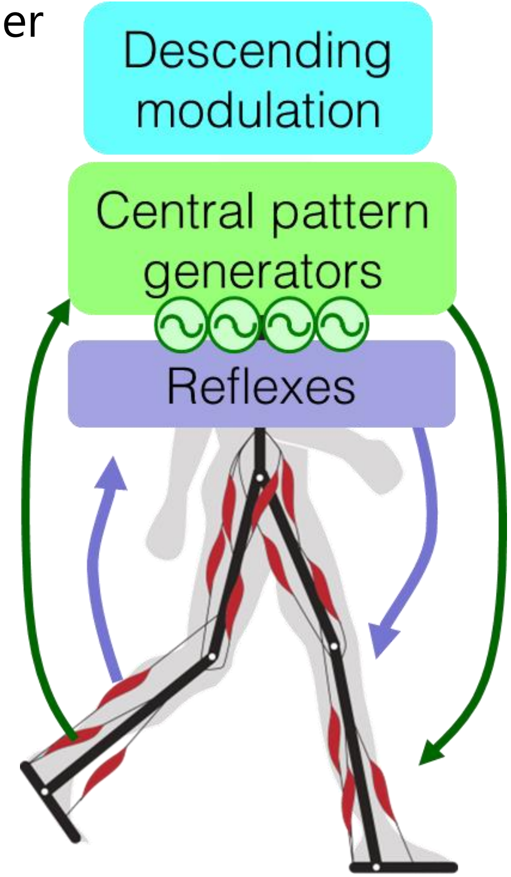
Reflexes

Musculoskeletal system



Controllers for exoskeletons

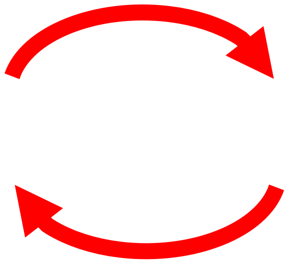
Simulated neuro-mechanical controller



Descending modulation

Central pattern generators

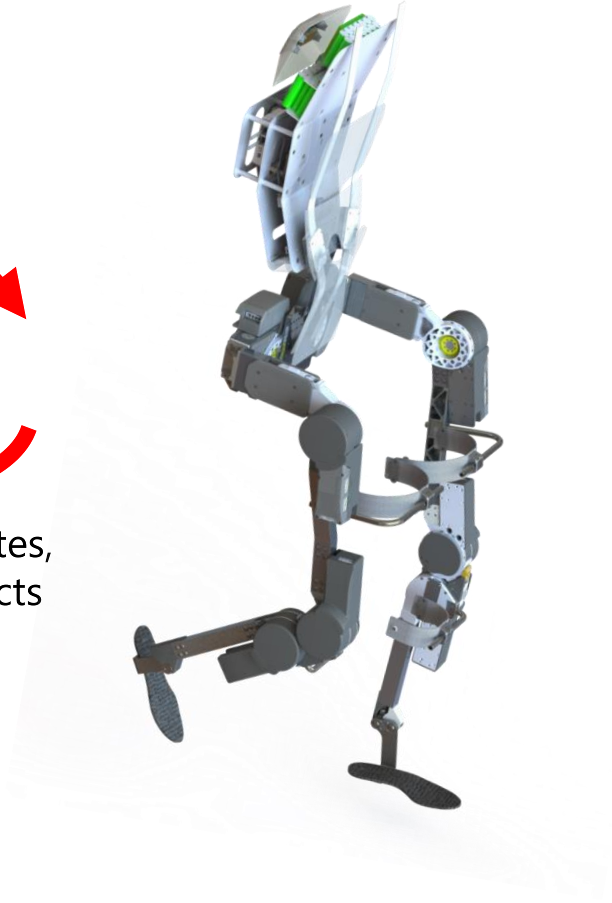
Reflexes



Torques

Joint angle states, Ground contacts

Wearable exoskeleton



Symbitron project:
U. Twente, TU Delft, Imperial College, Santa Lucia Fondation, Össur, EPFL

Surprisingly fast gaits:

Speed modulation 0.8 m/s to 1.1 m/s

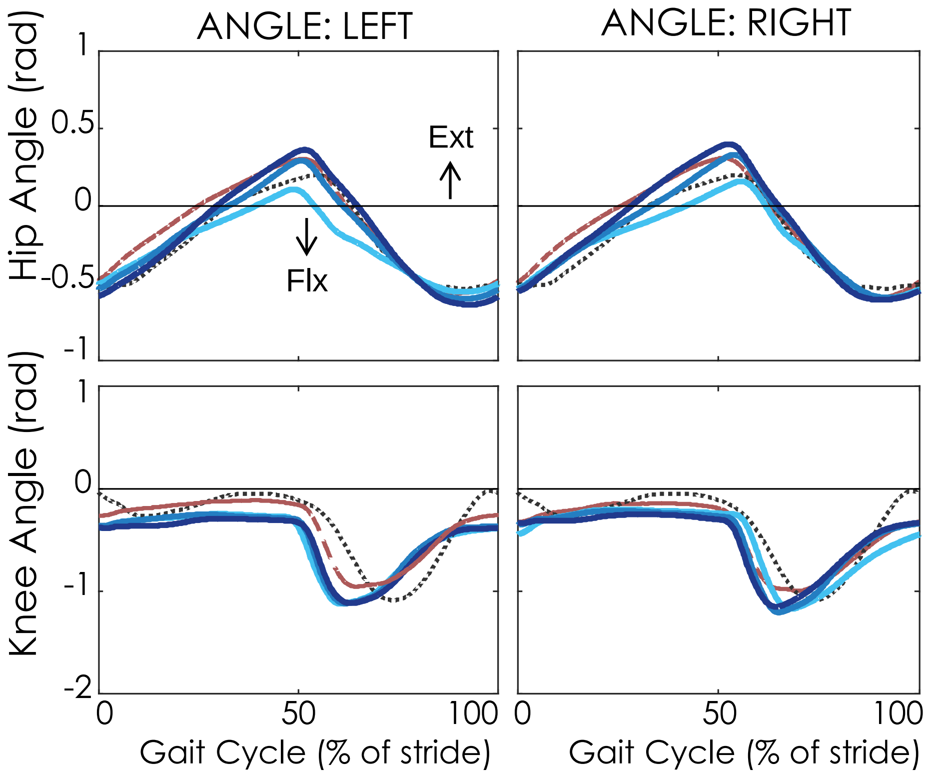
Spinal-cord injured (SCI) subjects with complete lesion and no motor function of legs

A. Wu

F. Dzeladini

Wu et al, WeRob 2016

Similar joint angles as healthy locomotion (but without a reference trajectory!)



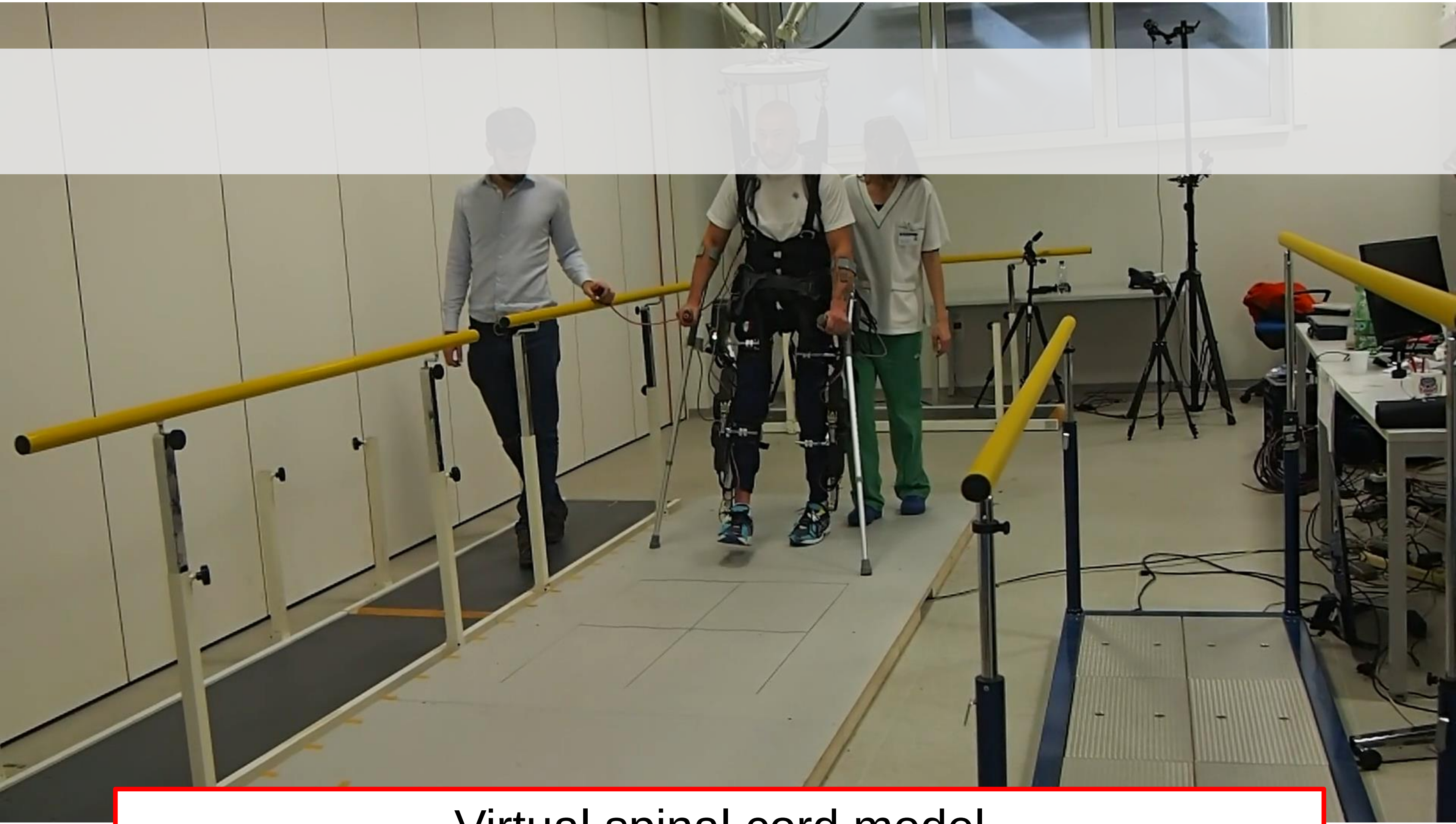
Subject	Group	Speed (m/s)	NMC level	Mean BWS (% BW)
Healthy	Healthy	1.0	100%	---
S09	I	0.5	80/90	35%

········ Healthy Shod (1.0 m/s)
-·-·- Healthy LNMC (1.0 m/s)
━━ SCI LNMC S08 (0.7 m/s)
━━ SCI LNMC S08 (0.9 m/s)
━━ SCI LNMC S08 (1.0 m/s)

Robustness against swing foot perturbations

Wu et al, WeRob 2016

Tests with the wearable exoskeleton

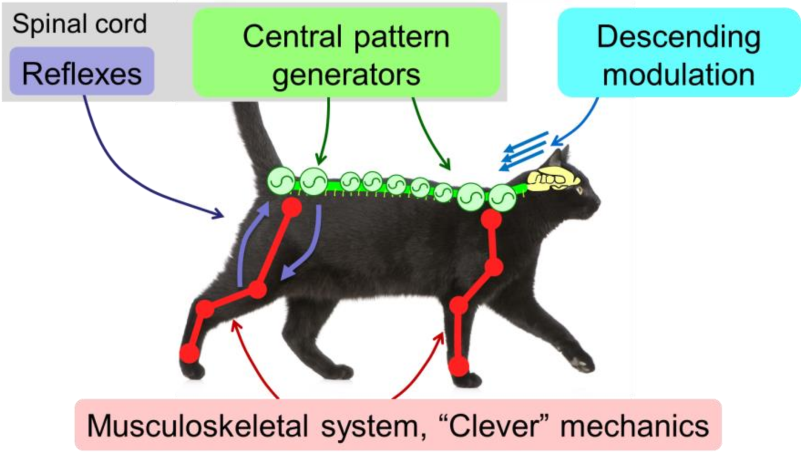


Virtual spinal cord model
can serve as exoskeleton controller

Neuroscience, take-home messages

CPGs and sensory feedback are good friends!
They provide **redundant control mechanisms**

There respective roles **have probably changed during evolution**



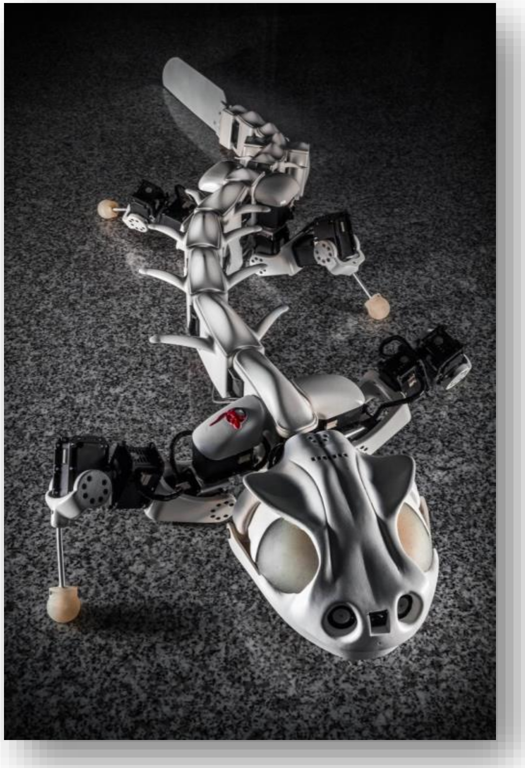
Good compromise: **distributed oscillators that are synchronized by sensory feedback** (in addition to <u>weak</u> central coupling)

(Much) more to be done on decoding the **interactions between all components.**

Biorobotics

Robotics applications

Inspection
Monitoring
Search and rescue
Transport
Pollution monitoring
Agriculture
Service robotics



Scientific applications

Neuroscience
Biomechanics
Sport science
Ethology
Prosthetics
Neuroprosthetics
Paleontology

Edutainment applications

Toys
Animatronics
Artificial pets

Filming wild life
Museums
Recreating extinct animals

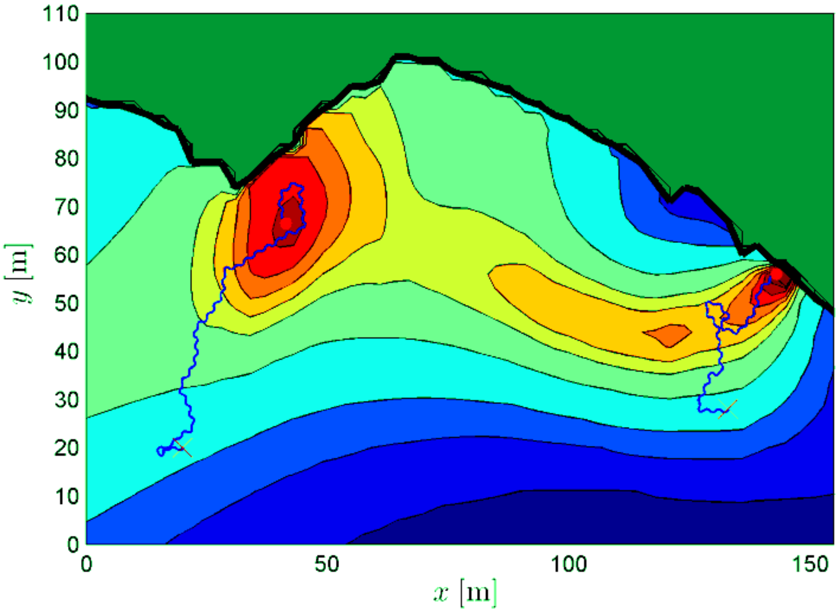
Pollution monitoring, Envirobot

A. Crespi

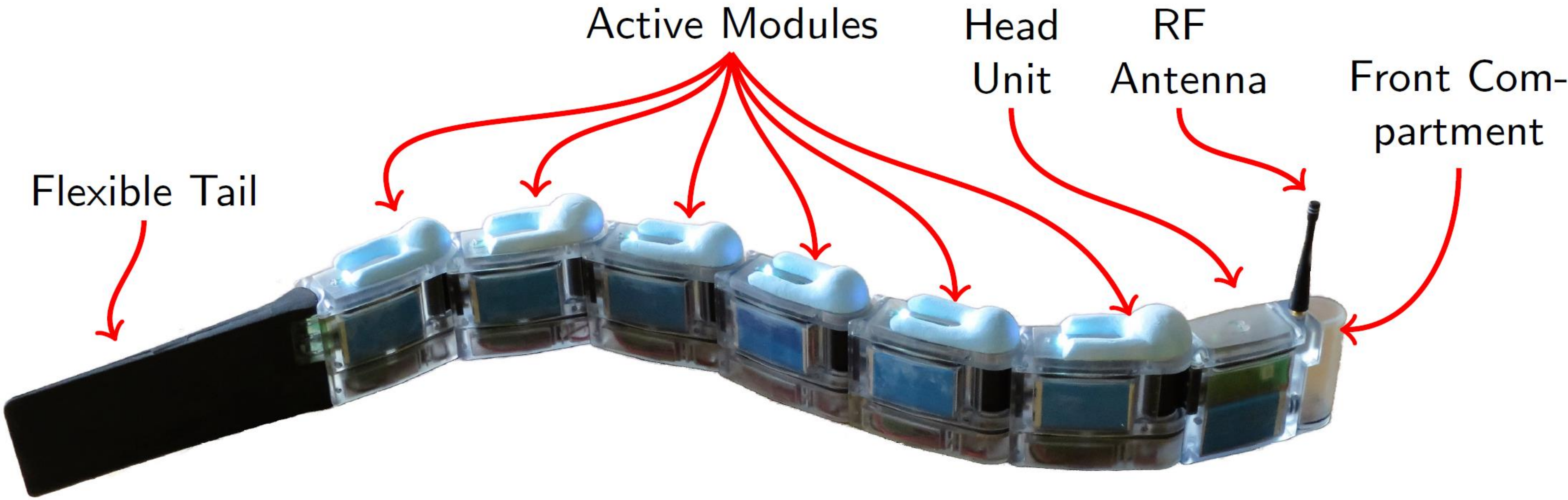
B. Bayat

Modular robot for **pollution monitoring**:

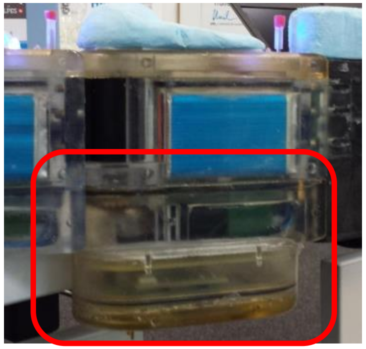
- Dynamic mapping of pollutants
- Gradient-climbing



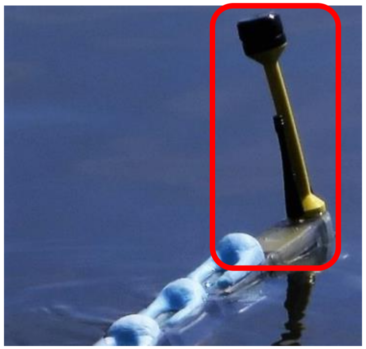
Pollution monitoring, Envirobot



Sensor compartment and water sampling mechanism.
Sensors:
- temperature,
- conductivity,
- turbidity,
- mercury-responsive bioluminescence …

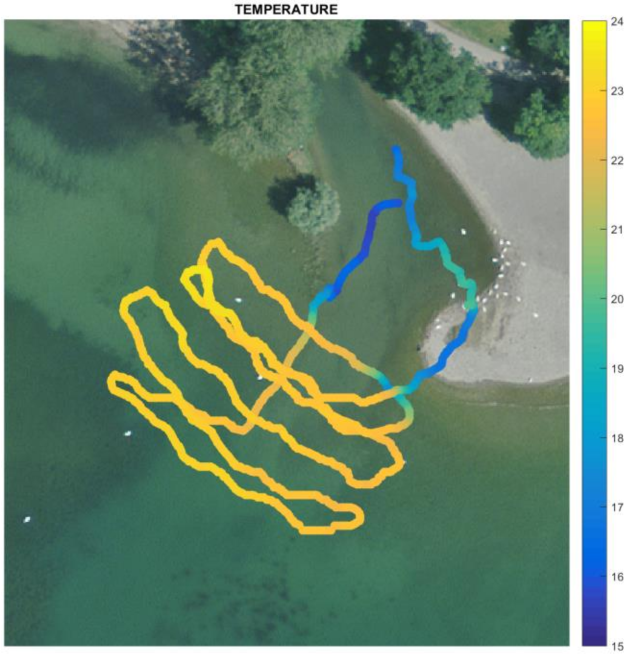


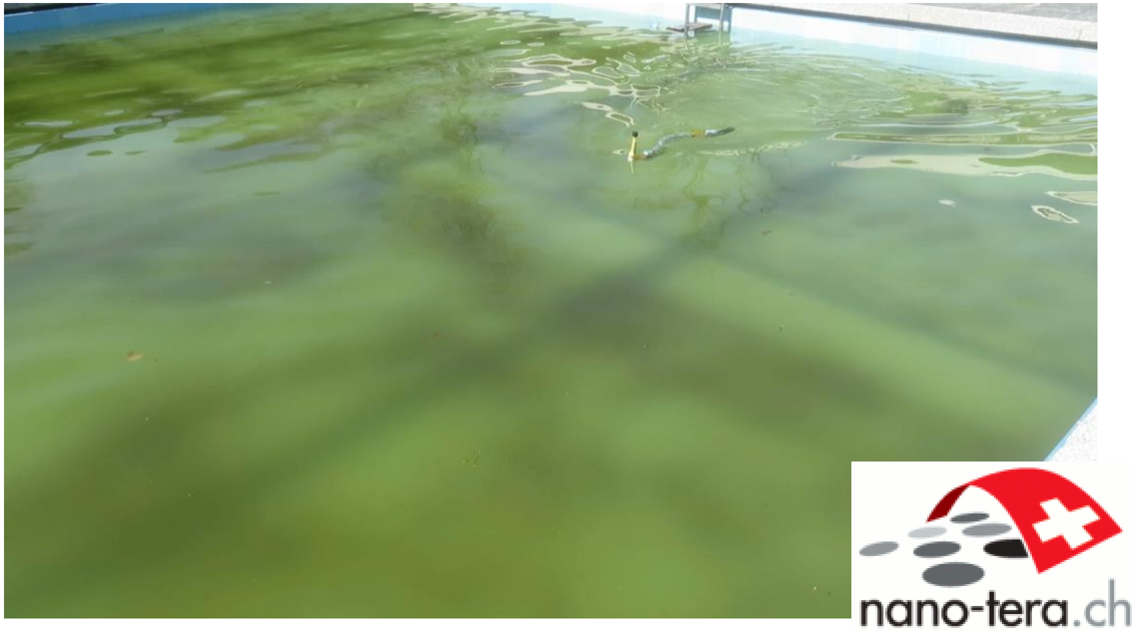
GPS/WiFi Antenna



Pollution monitoring, Envirobot

Interesting properties:
- Portable
- Reconfigurable
- Low drag swimming
- Not dangerous for swimmers
- Low risk of getting stuck



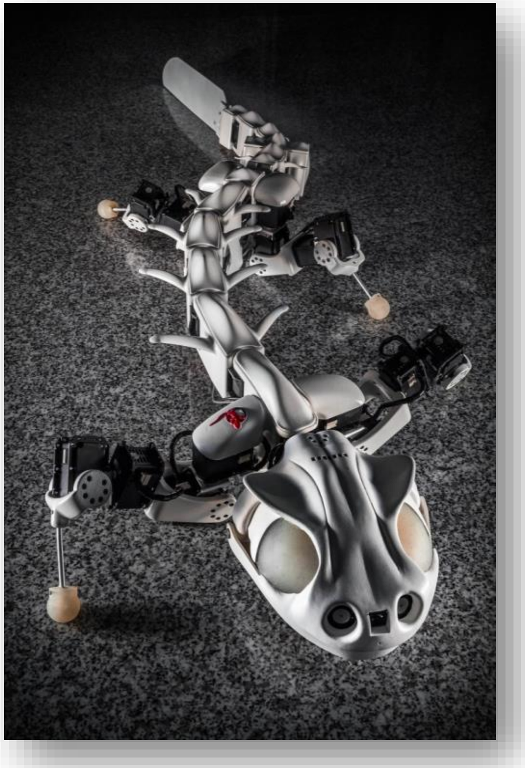


nano-tera.ch

Biorobotics

Robotics applications

- Inspection
- Monitoring
- Search and rescue
- Transport
- Pollution monitoring
- Agriculture
- Service Robotics



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- Neuroscience
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- Sport science
- Ethology
- Prosthetics
- Neuroprosthetics
- Paleontology

Edutainment applications

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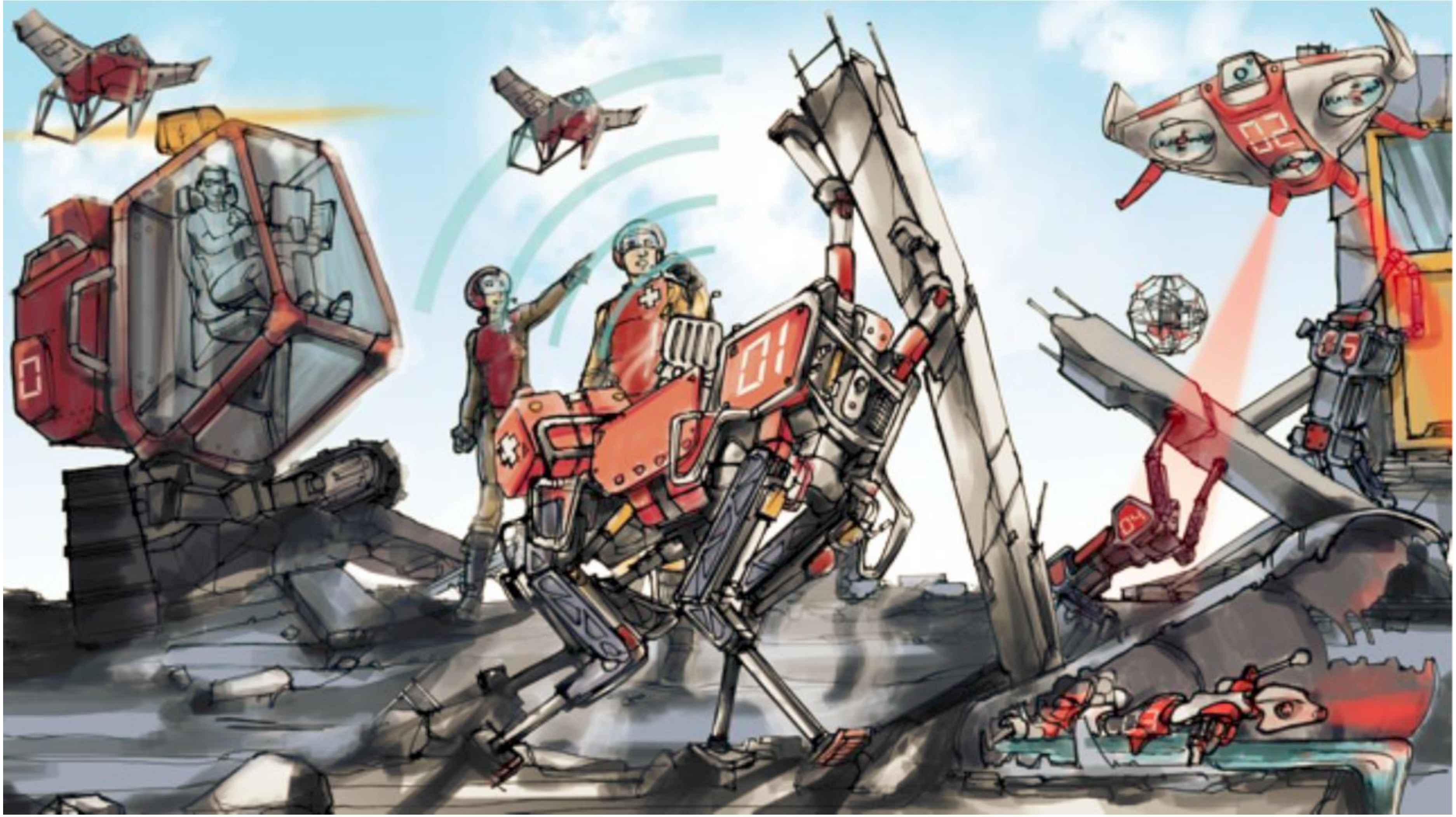
- Animatronics
- Artificial pets

- Filming wild life
- Museums
- Recreating extinct animals

Robots for search and rescue



robotics
Swiss National
Centre of Competence
in Research

Tohoku, Japan, March 2011

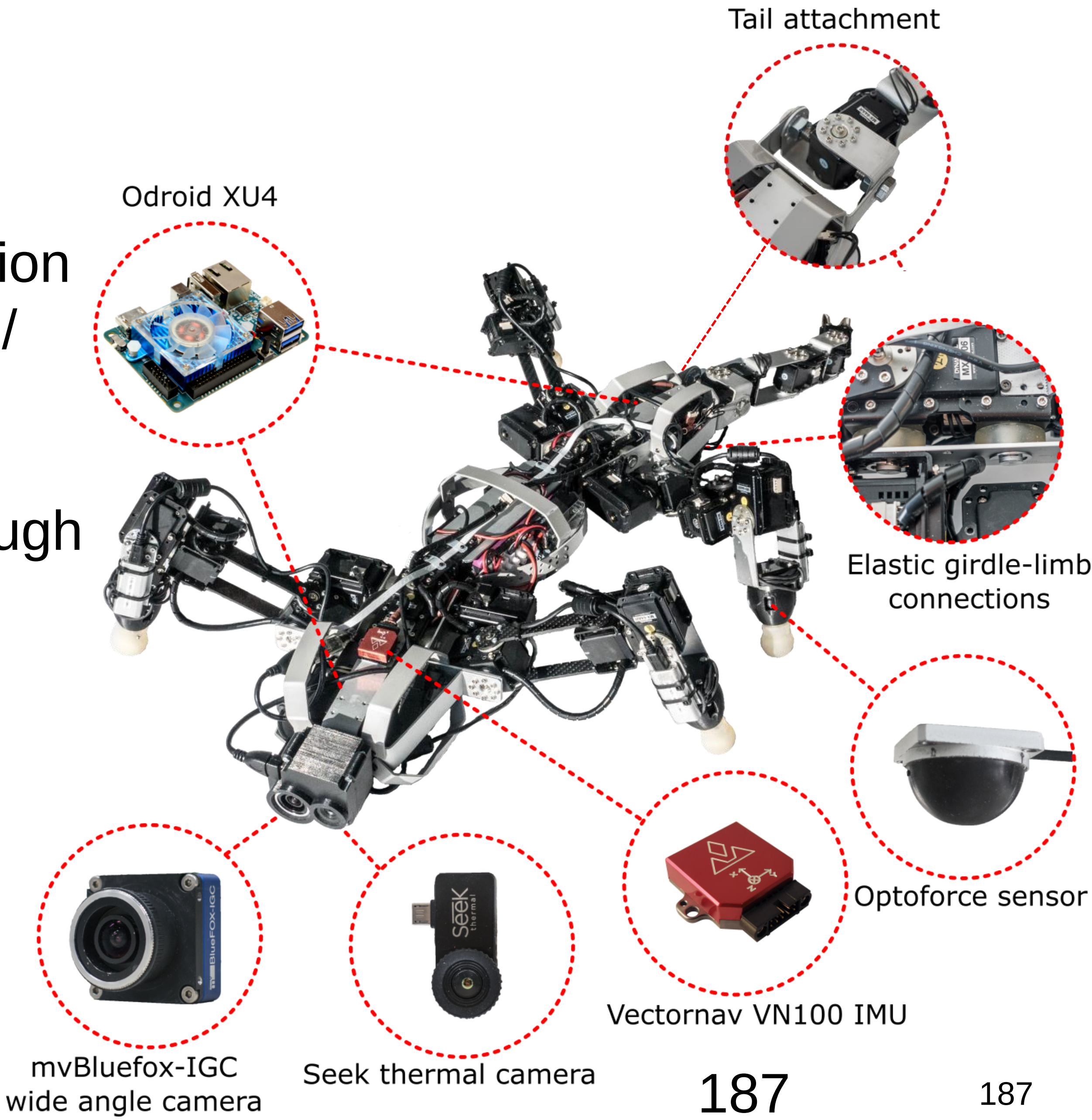
Swiss National
Centre of Competence
in Research

Amphibious robots for rescue

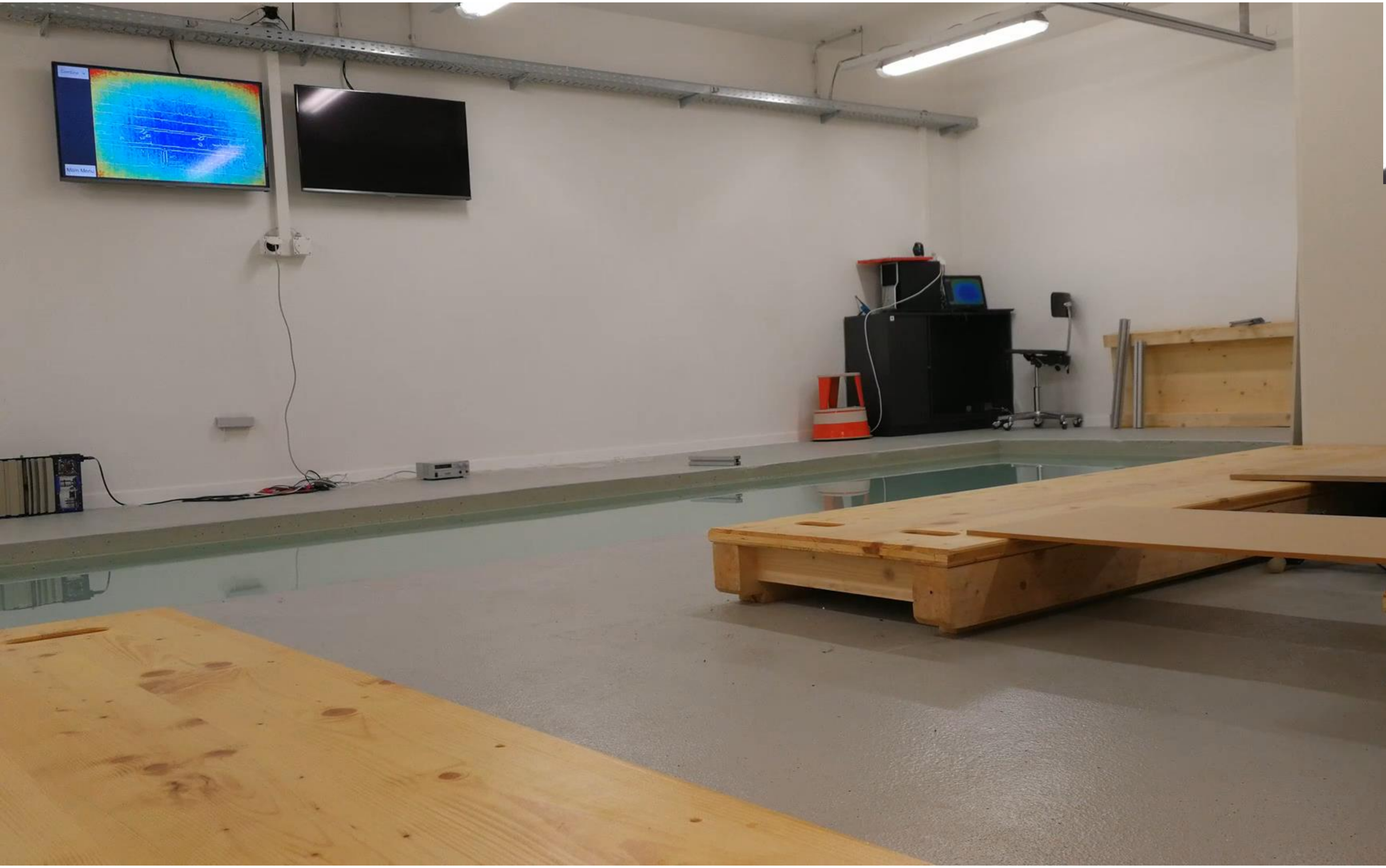

K. Melo


T. Horvat

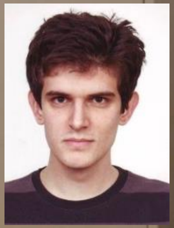
- Multimodal locomotion (swimming/crawling/ walking)
- Ability to move through small holes/pipes
- Stable crouched posture
- Portable
- Reconfigurable



K-Rock2



K. Melo



T. Horvat

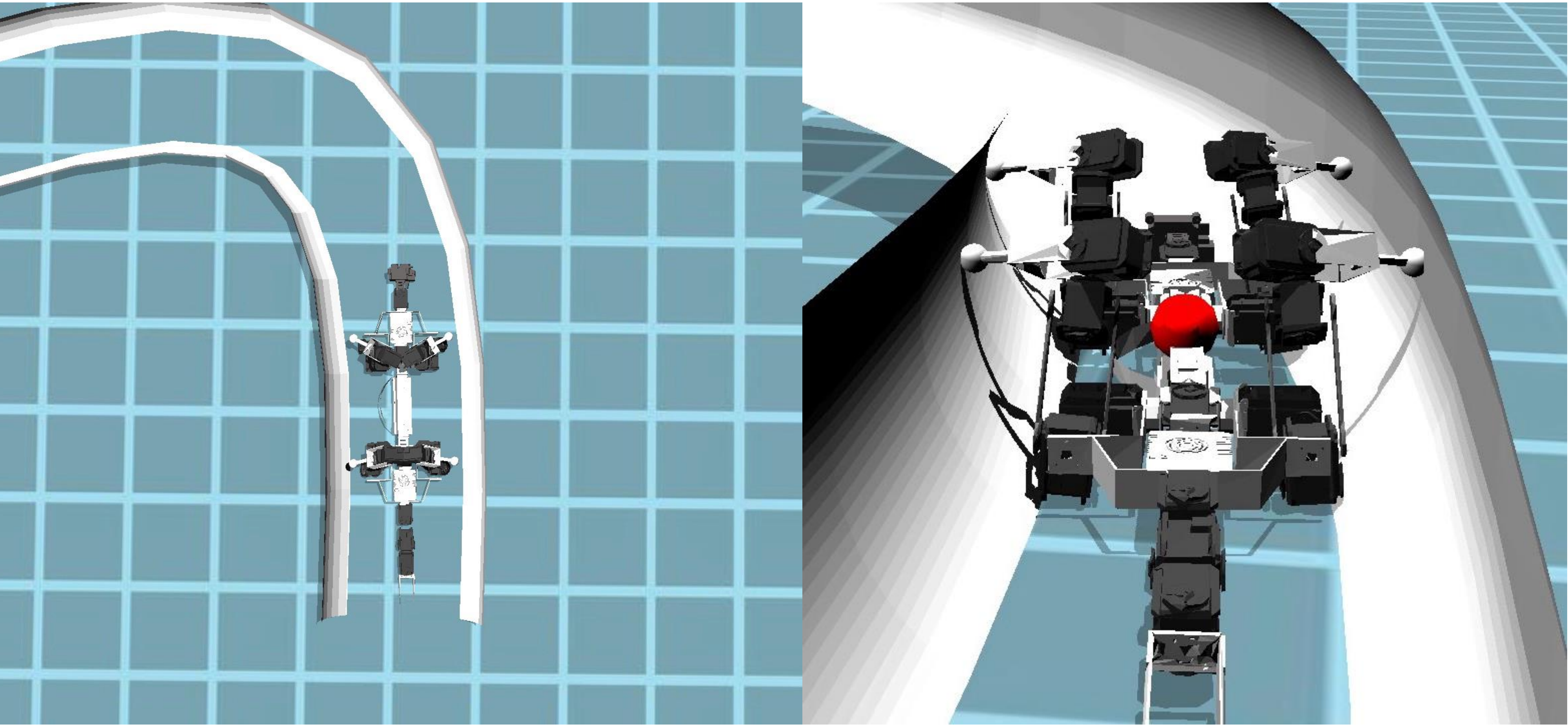
robotics
Swiss National
Centre of Competence
in Research


L. Paez


K. Melo

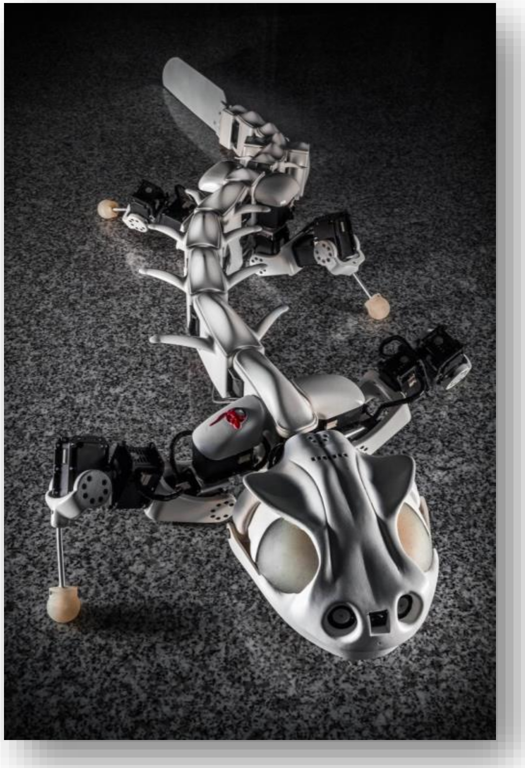

T. Horvat

Locomotion in pipes with K-Rock2



Horvat et al, IROS 2017

Biorobotics



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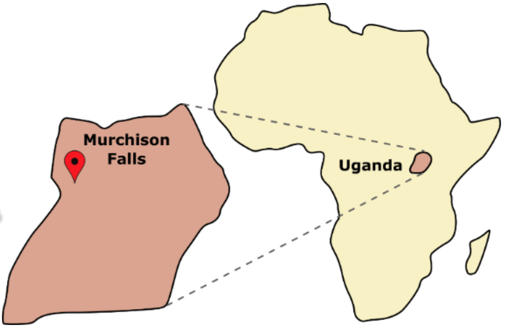
Filming wild life

Requirements

- Mimic real animals
- Robustness
- Power autonomy
- Remote control
- Waterproofed
- Equipped with cameras

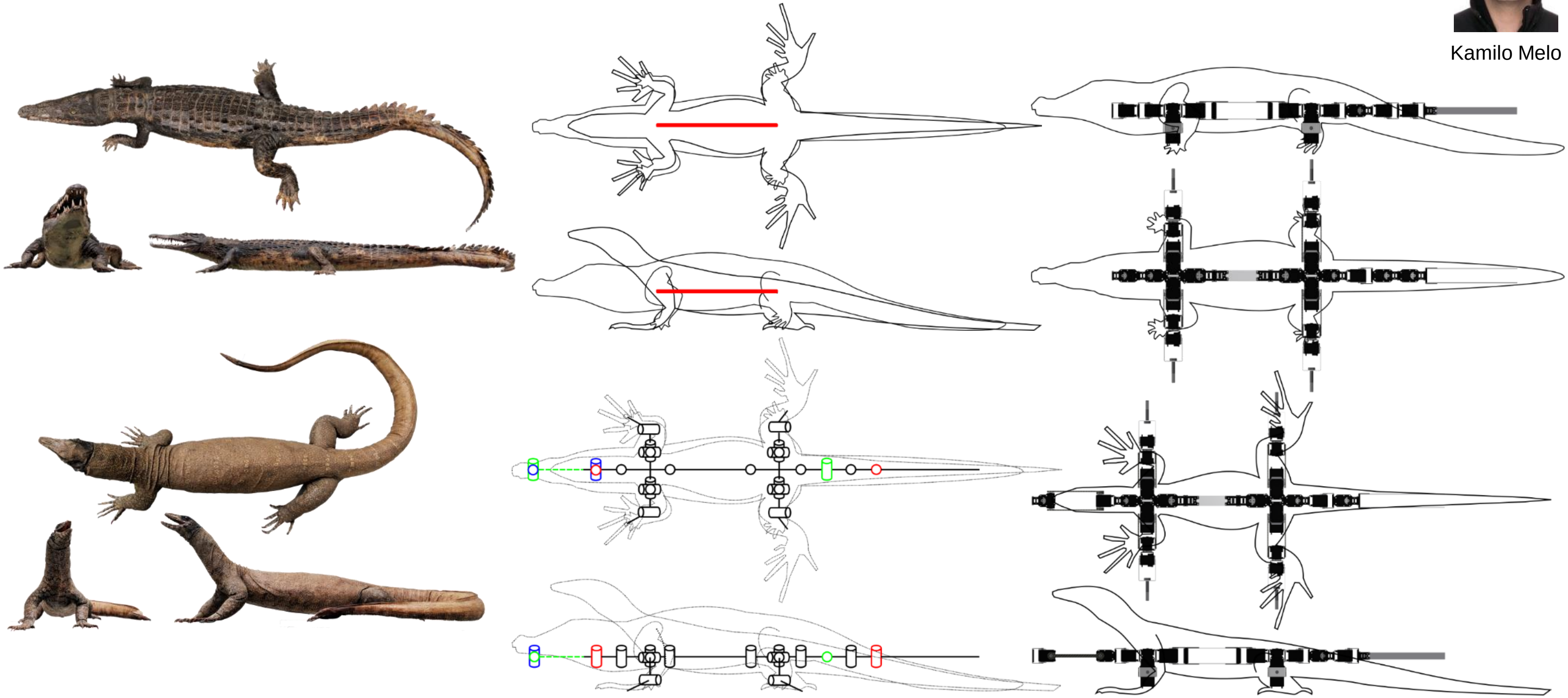
Our answer:

Krock-1



Design methodology of Krock-1

Kamilo Melo



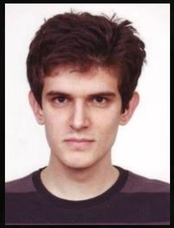
Technical specifications

- 23 actuated joints
- ~ 4.6 kg (without the skin)
- 5800 mAh battery
- Odroid-XU4 computer
- Bluetooth or RF (Xbee) communication

Robots for filming wild life

K-Rock Robot developed for «Spy in the Wild» BBC 2017

K. Melo



T. Horvat

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K. Melo

T. Horvat

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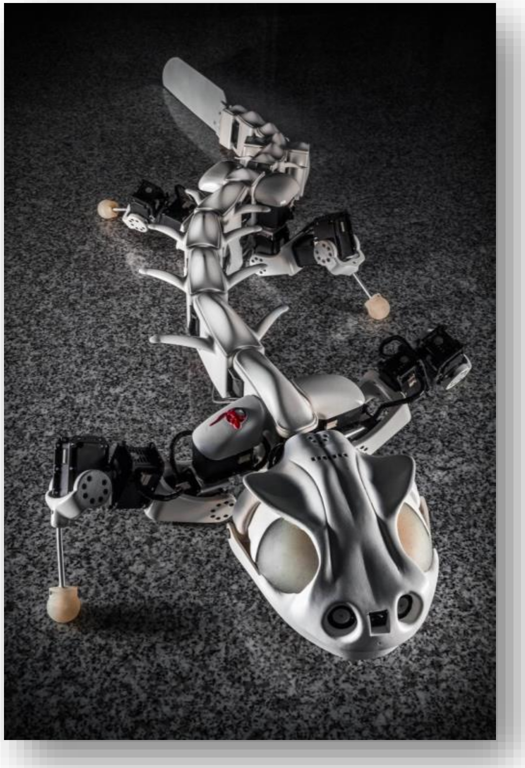

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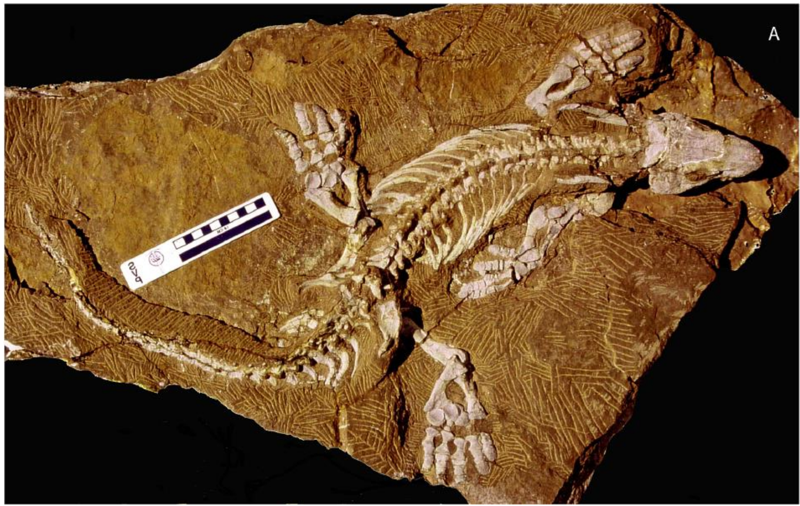
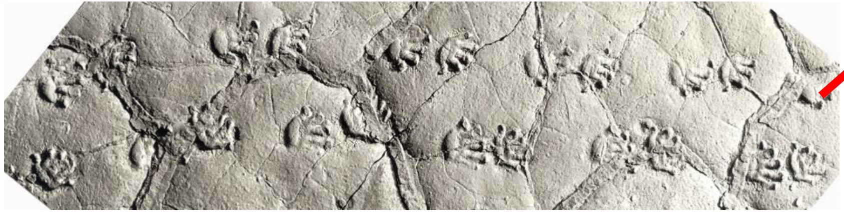
Robotic Paleontology: reverse engineering the locomotion of Orobates, an early tetrapod



Well-preserved fossil



Foot track for the same species

What was the most likely gait?

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Robot model of amniote fossil suggests how early tetrapods walked

PAGE 351

ROBOTIC PALAEONTOLOGY

BIOMEDICINE
THE PRIZE DIVIDE
Women who win get less than men
PAGE 287

MATERIALS SCIENCE
POLYCRYSTAL DESIGN
A boost to the strength of architected materials
PAGES 303 & 305

BIOTECHNOLOGY
LIGHT TOUCH
Optogenetic system helps regulate bladder control
PAGES 298 & 361

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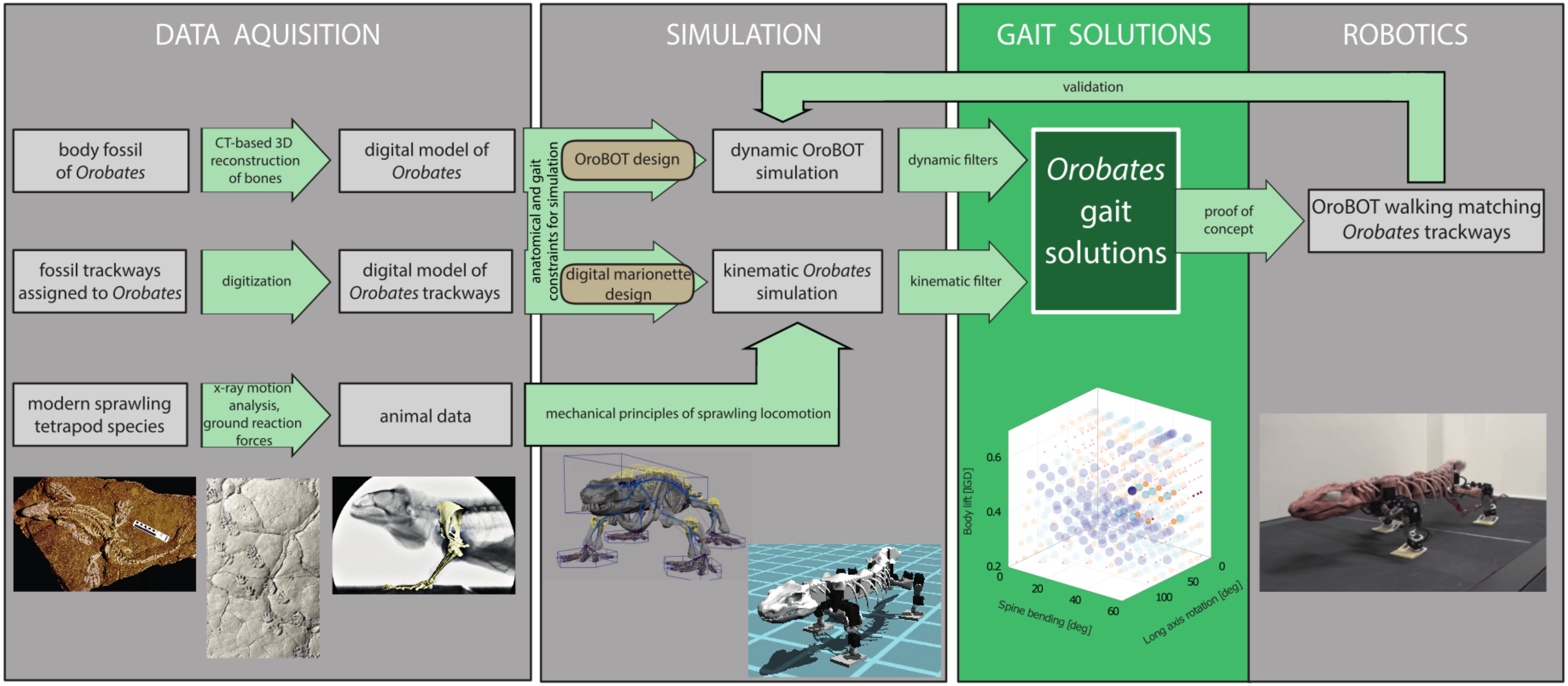
Vol. 565, No. 7739

Robotic Paleontology: reverse engineering the locomotion of Orobates, an early tetrapod



DATA AQUISITION

SIMULATION

GAIT SOLUTIONS

ROBOTICS

body fossil of *Orobates*

CT-based 3D reconstruction of bones

digital model of *Orobates*

fossil trackways assigned to *Orobates*

digitization

digital model of *Orobates* trackways

modern sprawling tetrapod species

x-ray motion analysis, ground reaction forces

animal data

anatomical and gait constraints for simulation

OroBOT design

digital marionette design

dynamic OroBOT simulation

kinematic *Orobates* simulation

mechanical principles of sprawling locomotion

dynamic filters

kinematic filter

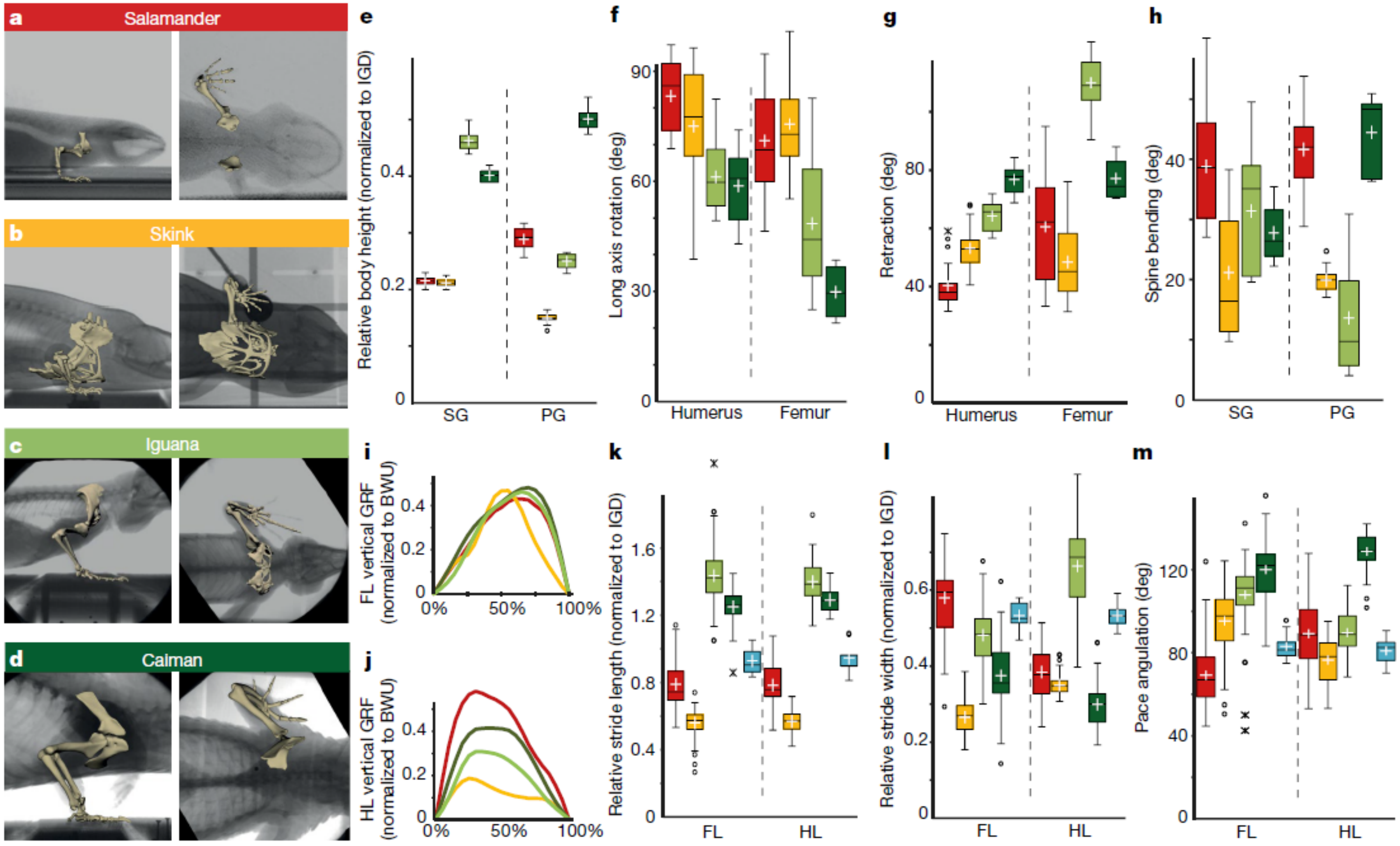
Orobates gait solutions

proof of concept

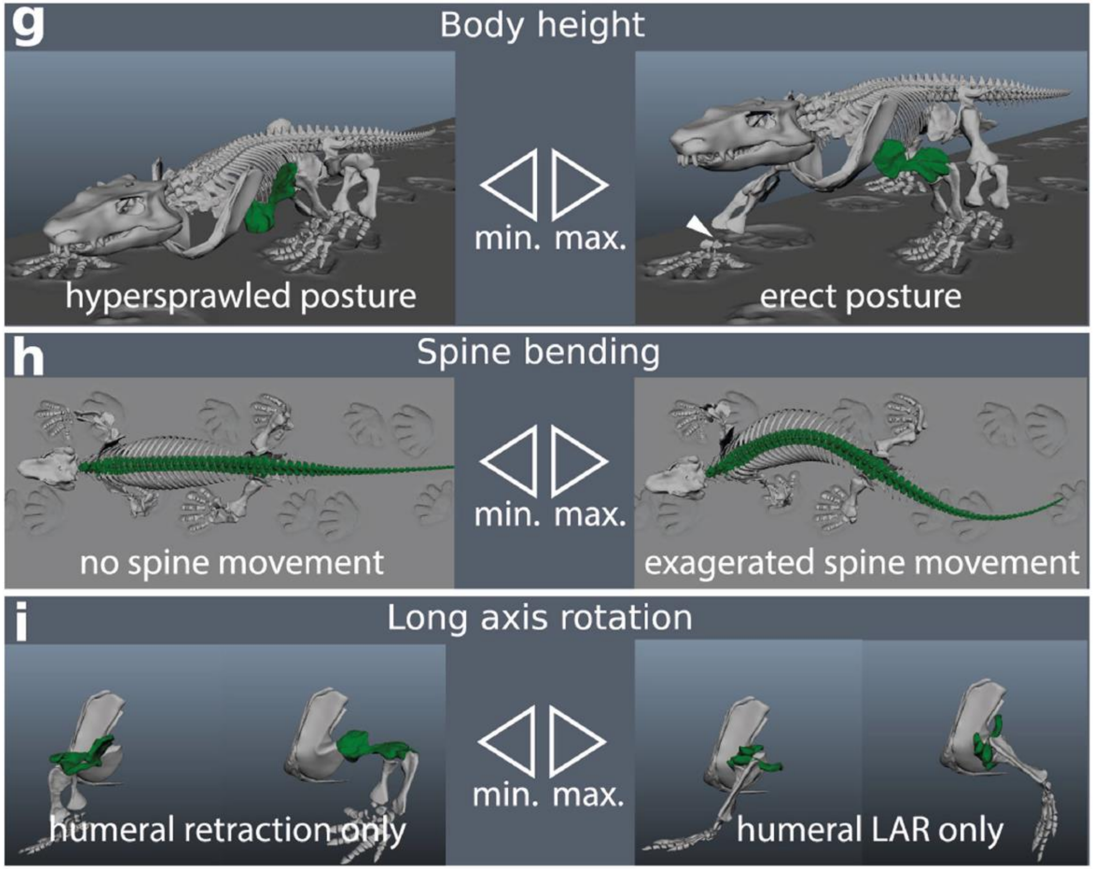
OroBOT walking matching *Orobates* trackways

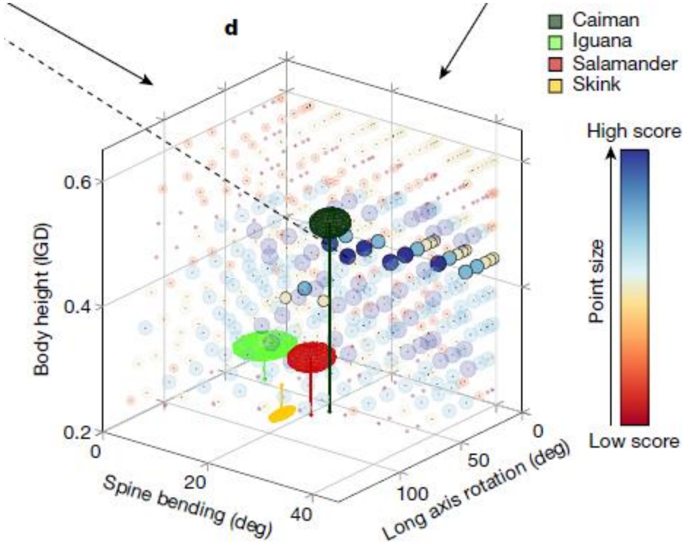
validation

Analysis of extant animal gaits

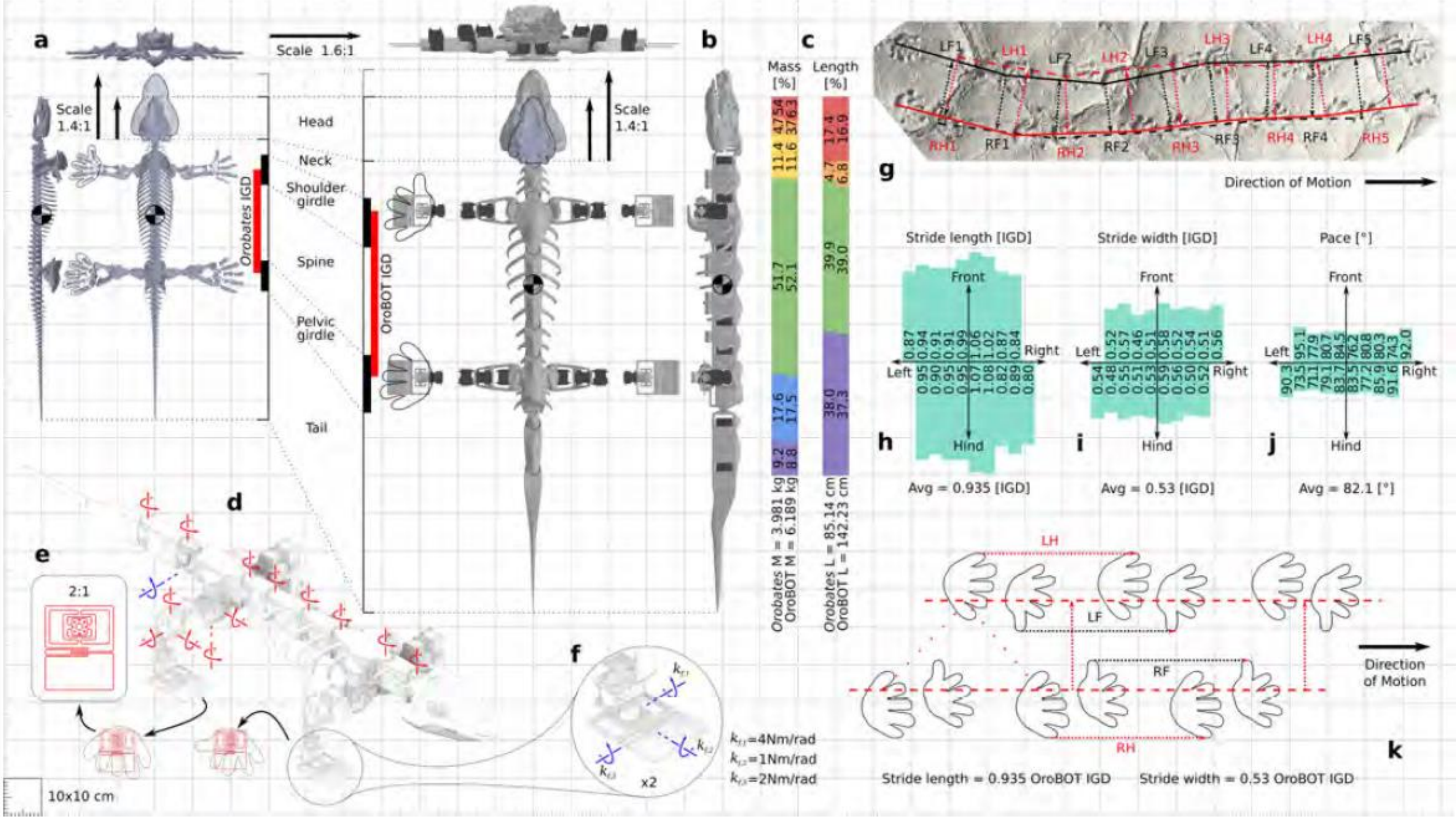


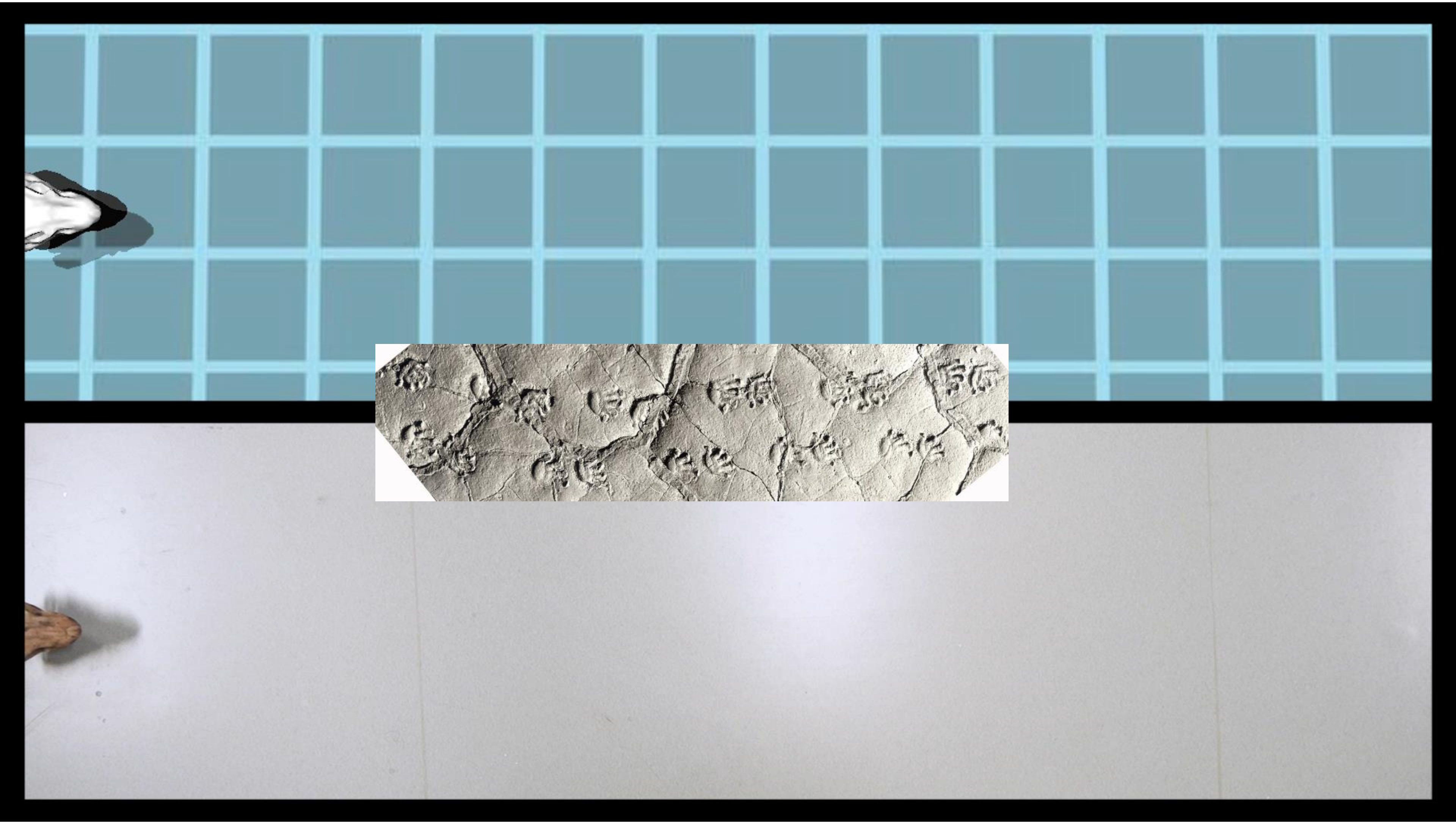
Sprawling gaits space





Robot construction





Interactive websites

Metrics for finding the most likely gaits:

- Bone collisions
- Power expenditure
- Balance
- Precision
- GRF Ground reaction forces

Interactive websites

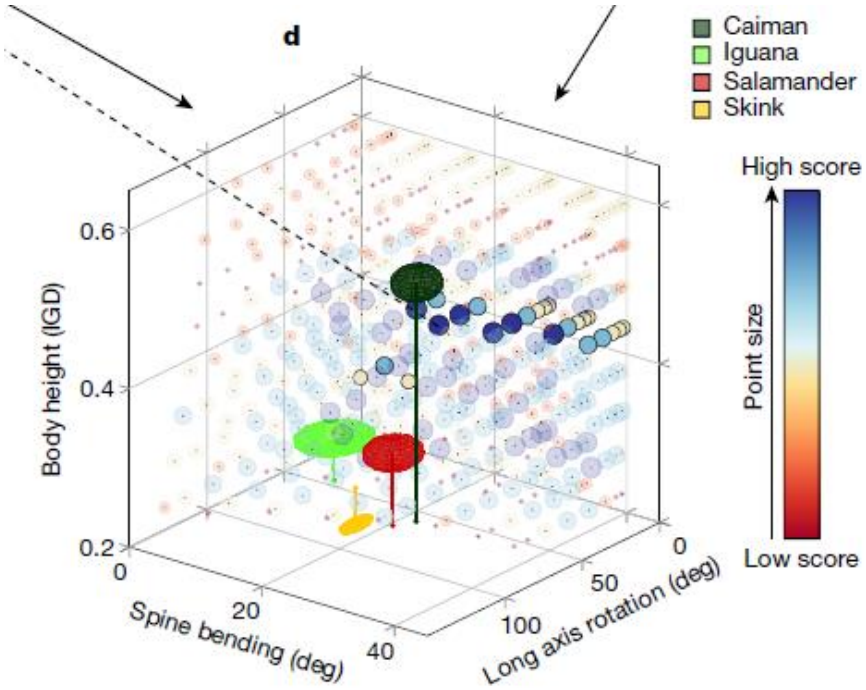
https://biorob2.epfl.ch/pages/Orobates_interactive/

https://cyberbotics2.cyberbotics.com/orobot/simulation.php

Conclusion

- Orobates had a **quite erect and athletic gait**
- More **similar to Caiman** than to salamander
- **More advanced than initially thought** for this stem amniote

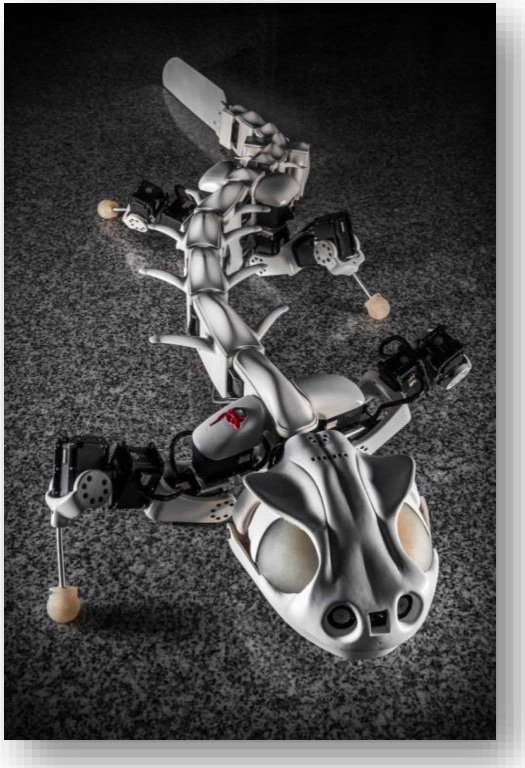
- New **quantitative methodology for paleontology**



Biorobotics

Robotics applications

Inspection
Monitoring
Search and rescue
Transport
Pollution monitoring
Agriculture
Service Robotics



Scientific applications

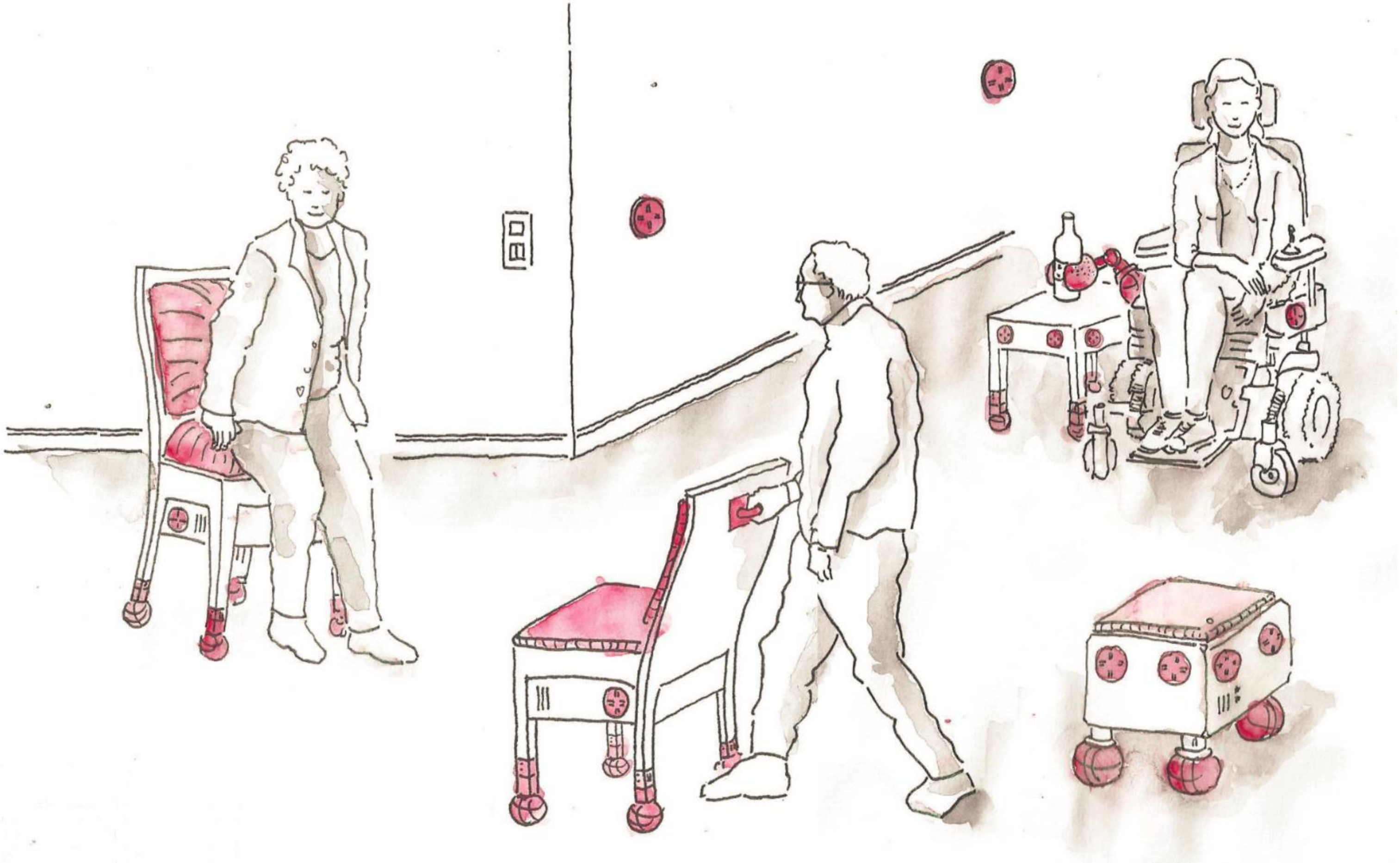
Neuroscience
Biomechanics
Sport science
Ethology
Prosthetics
Neuroprosthetics
Paleontology

Edutainment applications

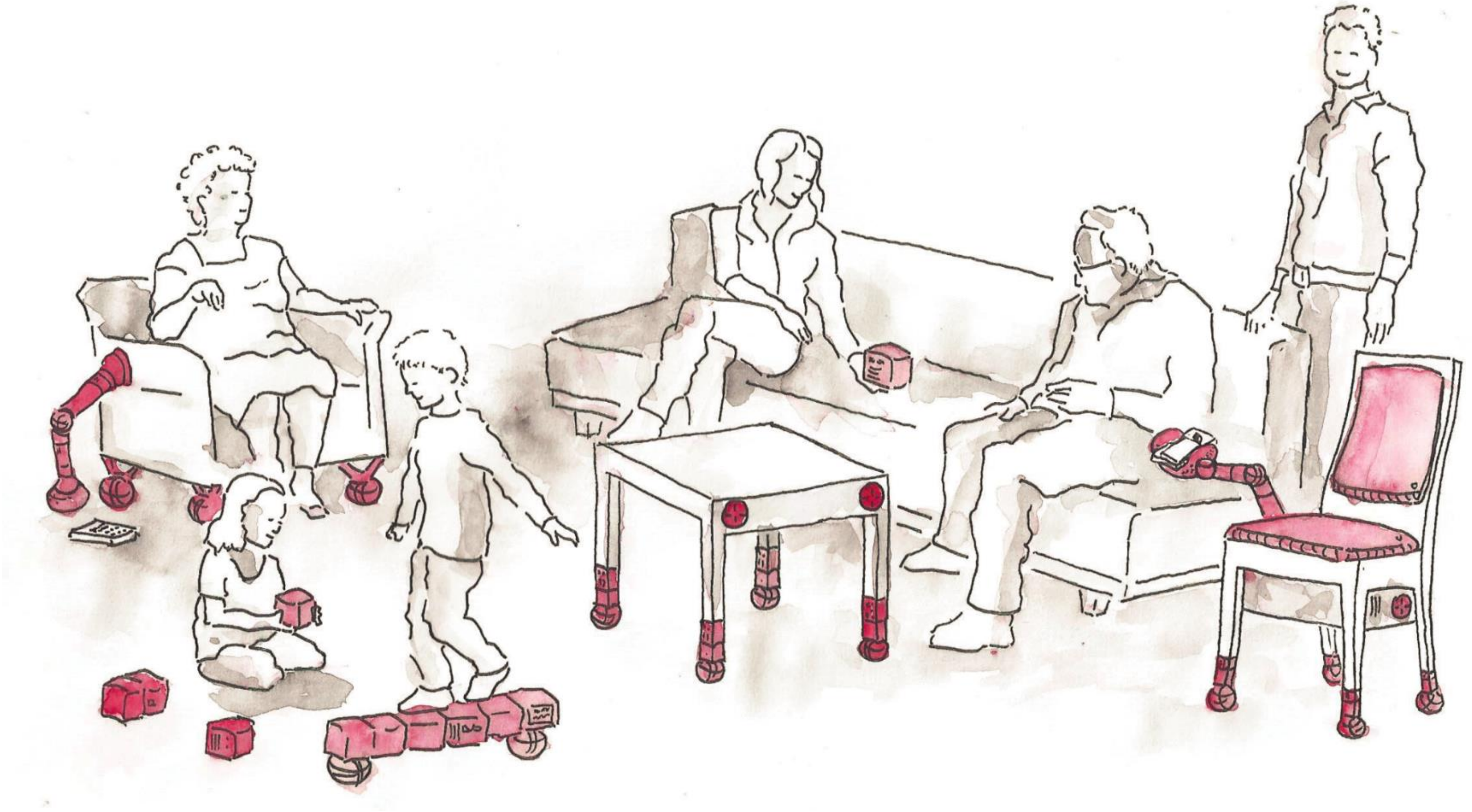
Toys
Animatronics
Artificial pets

Filming wild life
Museums
Recreating extinct animals

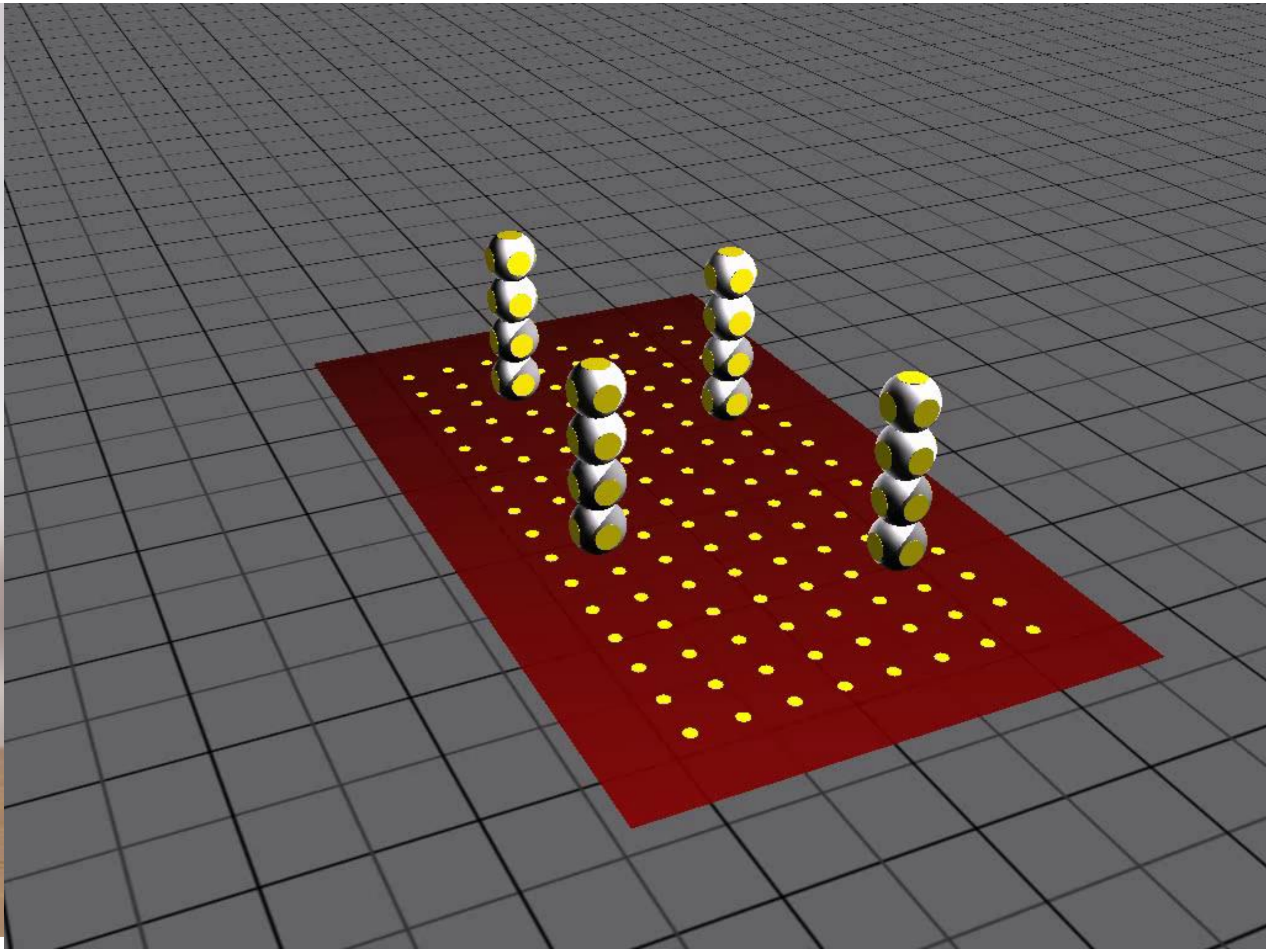
Roombots: Robots for assistive environments

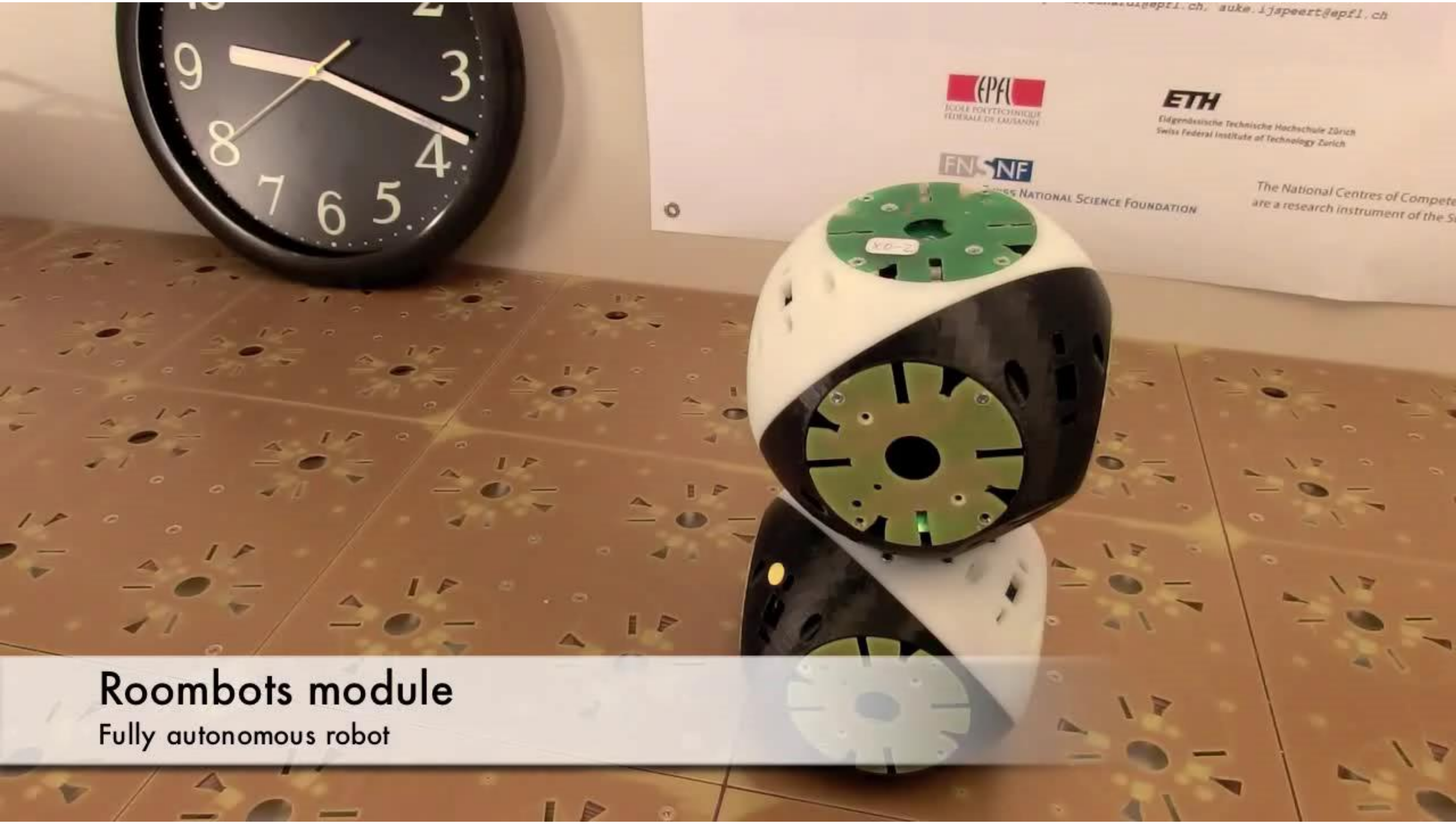


Roombots: Robots for assistive environments



Roombots: Robots for assistive environments

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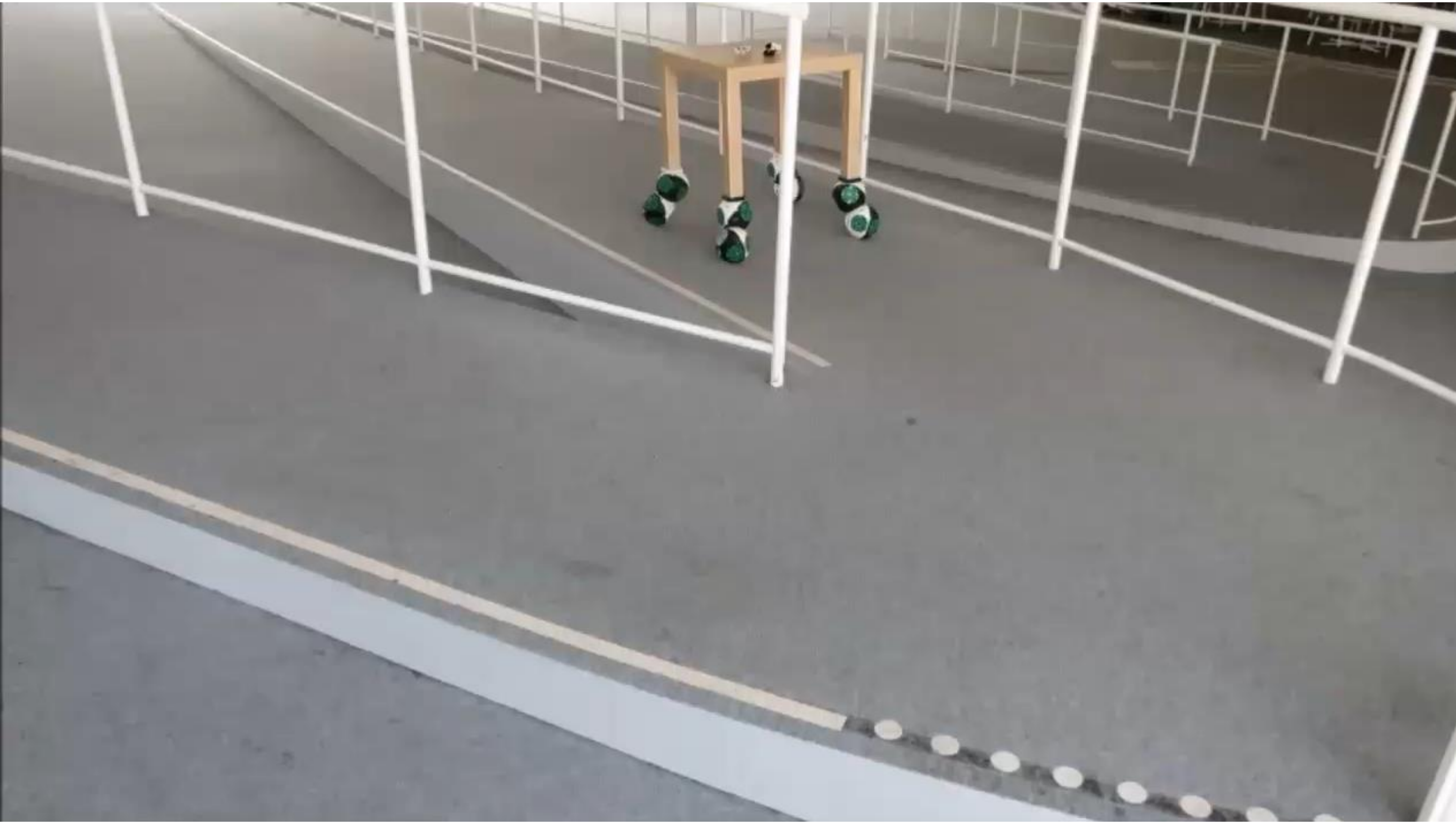
are a research instrument of the S
Roombots module
Fully autonomous robot



Roombots: Robots for assistive environments

People at BIOROB


A. Ijspeert


A. Crespi


B. Bayat


K. Melo


S. Lipfert


A. Wu


H. Razavi


R. Baud


T. Horvat


J. Lanini


F. Dzeladini


J. Arreguit O'Neil


P. Eckert


L. Paez


S. Ramalingasetty


S. Faraji


M. Caban


S. Hauser


M. Mutlu


F. Longchamp


A. Guignard


S. Fiaux

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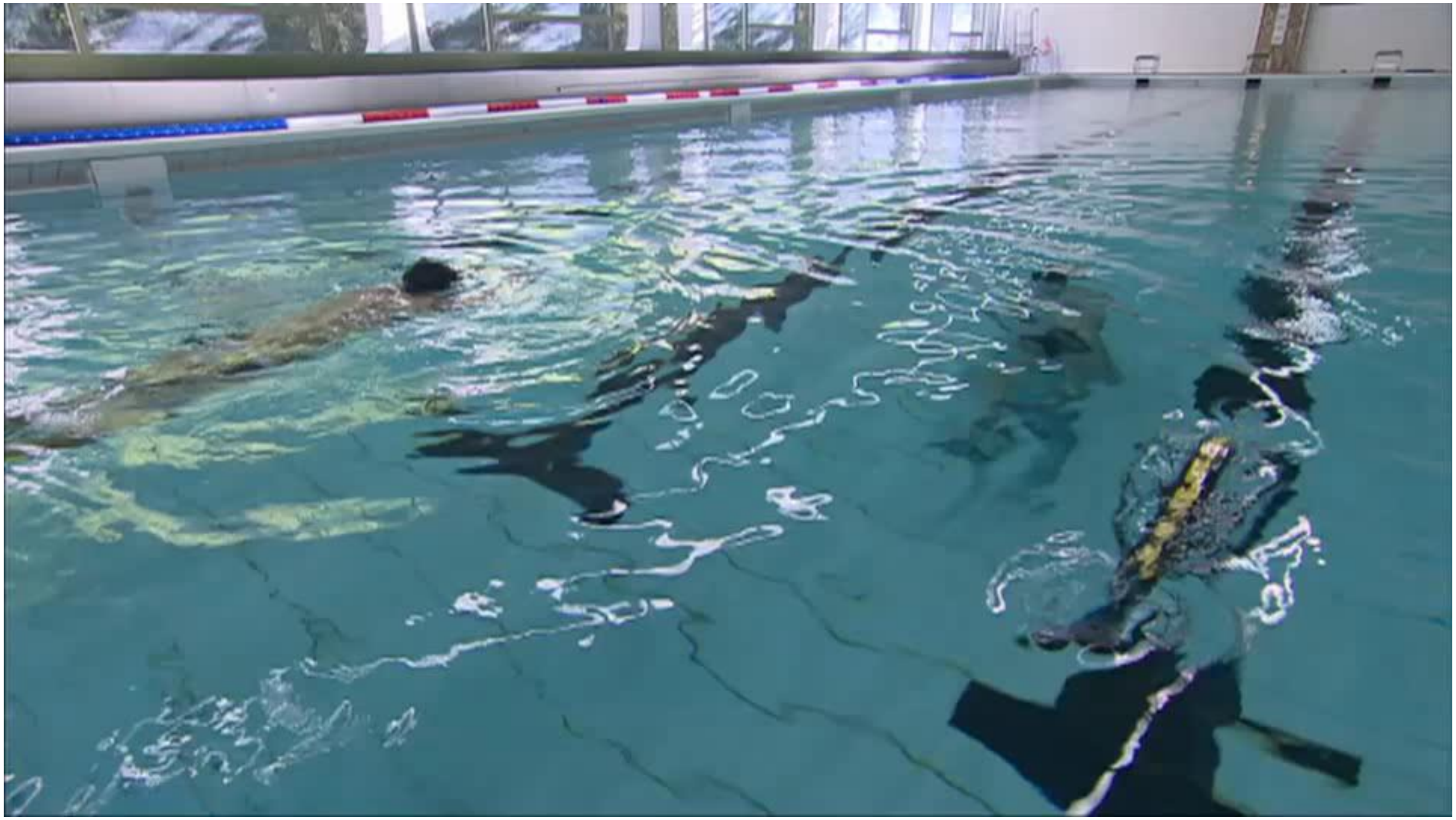
More info: http://biorob.epfl.ch

The human-robot race!!



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