BIOLOCH

(BIO-mimetic structures for LOComotion in the Human body)

June 22, 2004

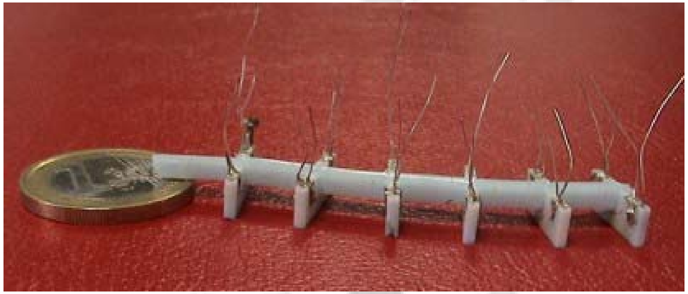
NEURO–IT.net Workshop

Bonn, Germany

BIOLOCH: BIO-mimetic structures for LOComotion in the Human body

Objective

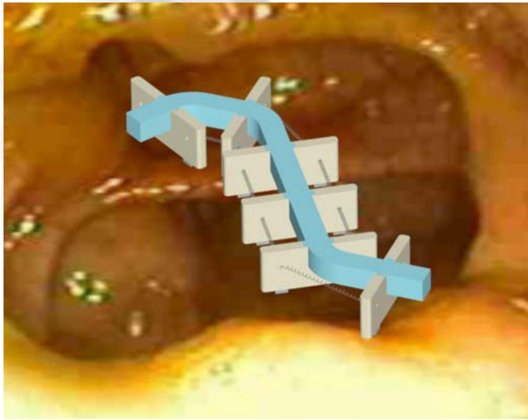
- To understand motion and perception systems of lower animal forms
- To design and fabricate mini- and micro-machines inspired by such biological systems.



Long term goal

A new generation of autonomous smart machines with:

- life-like interaction with the environment
- performance comparable to the animals by which they are inspired.



Envisaged application

The "inspection" problem in medicine (microendoscopy)

The BIOLOCH Partnership

- SSSA – Scuola Superiore Sant’Anna, Pisa, Italy
- UoB – University of Bath, United Kingdom
- UoP – University of Pisa, Italy
- FORTH – Foundation for Research and Technology, Heraklion, Greece
- UoT – University of Tubingen, Germany
- IHCI – Steinbeis Institute of Healthcare Industries, Germany

BIOLOCH: summary of results

Two undulatory motion systems:

-Undulatory motion based on waves longitudinal as regards the advancement direction (olygochaeta motion)

-Undulatory motion based on waves transversal as regards the advancement direction (polychaeta motion)

First te

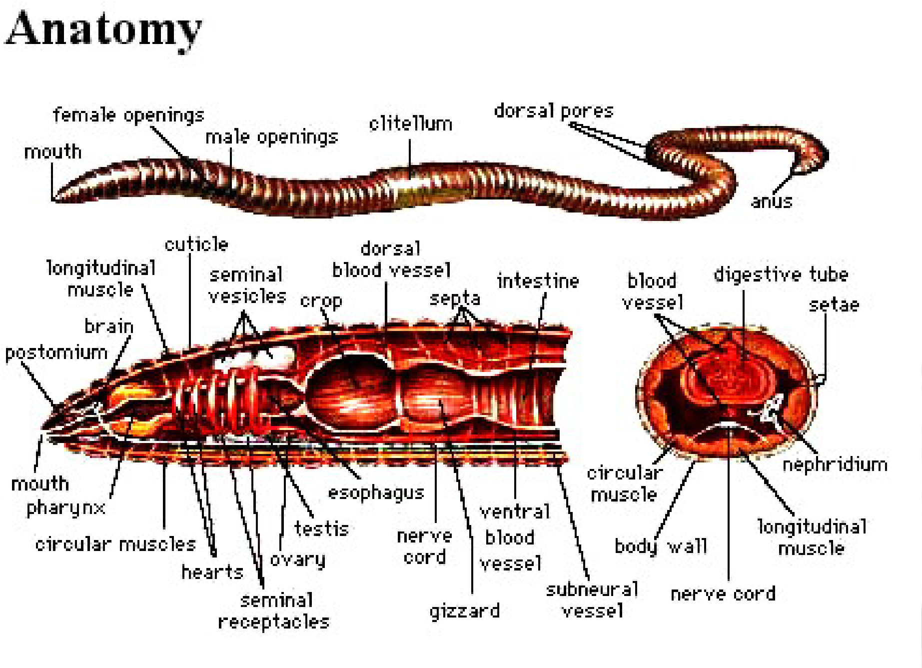
Set up
biolog
model
could
for the

Second term objective:

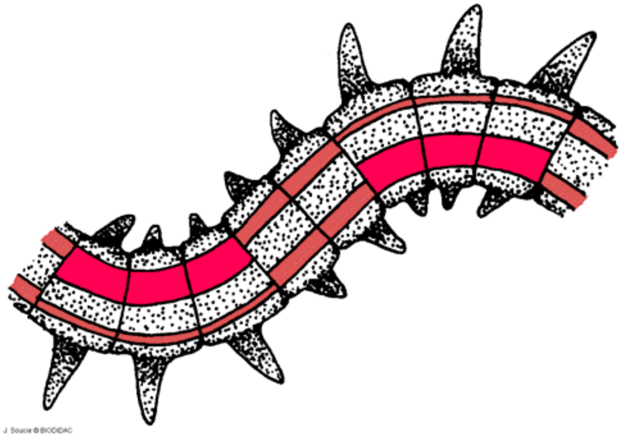
Design and preliminary fabrication of biomimetic locomotion units (BLUs) mimicking *some* selected biological models

Undulatory locomotion of living earthworms

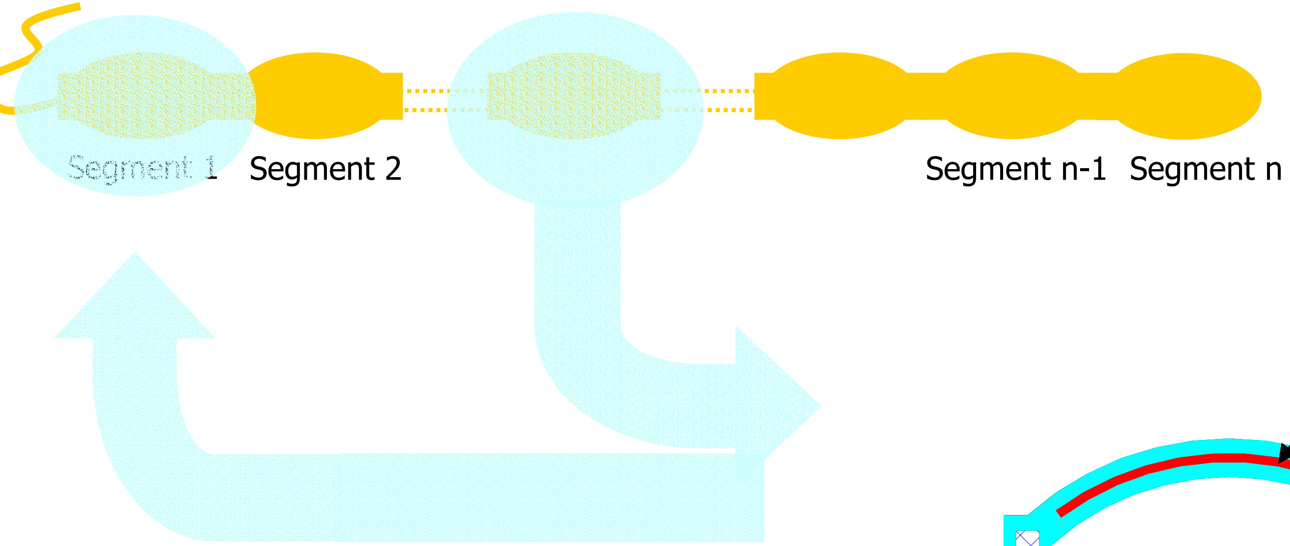
Hydrostatic skeleton with longitudinal and circular muscles, producing peristaltic changes in body shape and resulting in undulatory motion



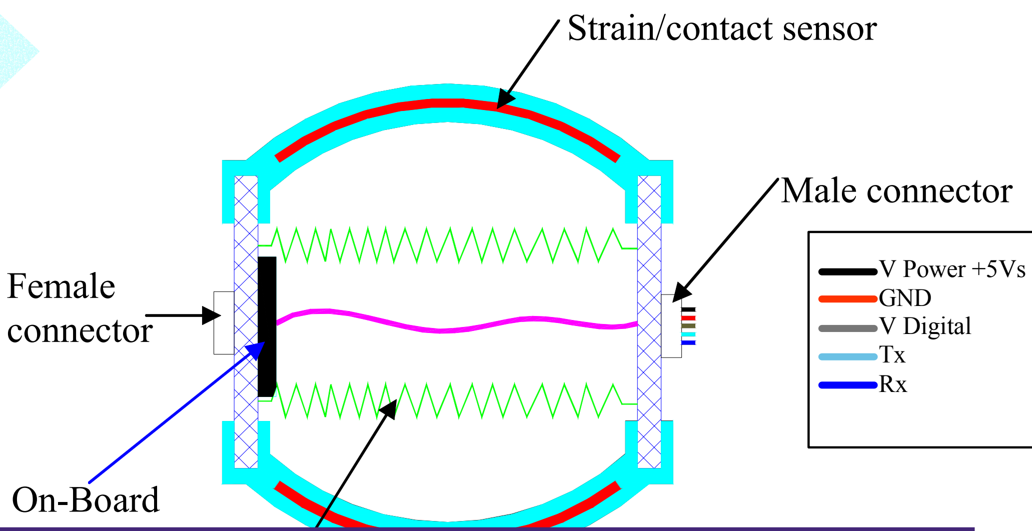
lternate contractions
f the longitudinal
nuscles form the
vedge shape resulting
n the zig zag
ocomotion



Artificial worm concept



The hardware is the same for each segment. The controller of the tail (or of the head) module is different because it drives the entire robot

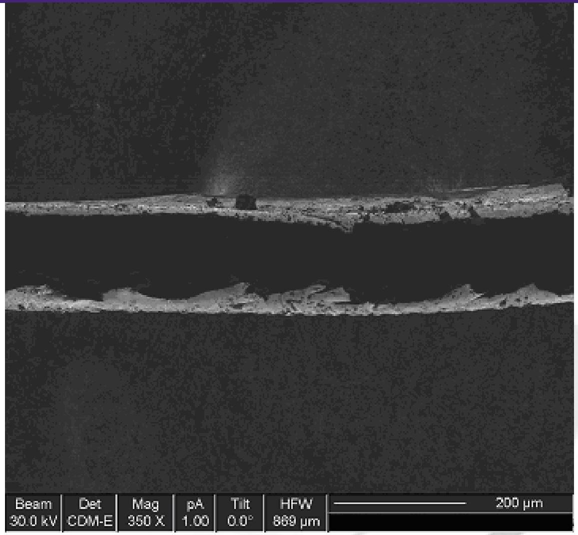


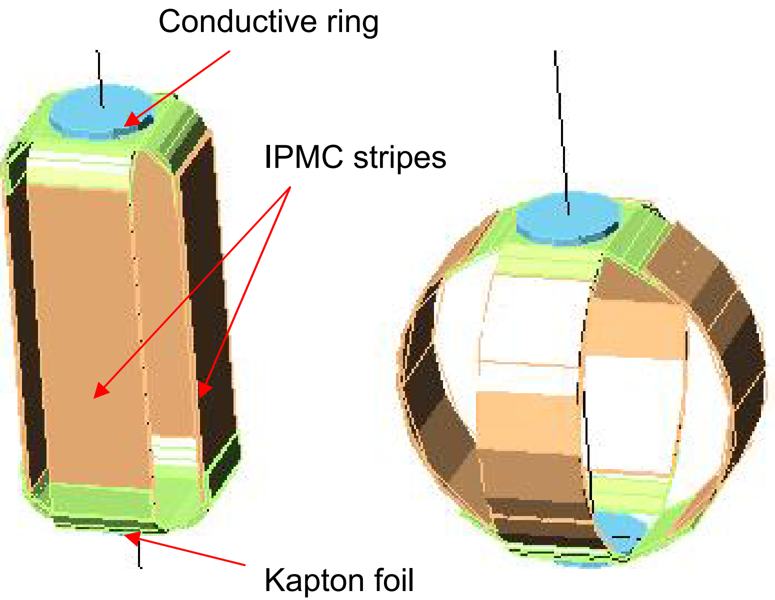
Selected maximum dimensions of the BLU:

- external diameter = 1 cm
- length = 1 - 2 cm

BLU – Ionic Polymer Metal Composite (IPMC) Module

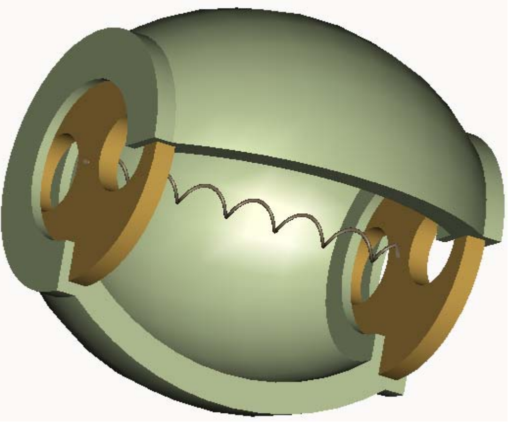
- high strains (up to 0.03)
- low driving voltages (< 3 V)
- low stresses (< 7 MPa)
- low frequency (< 10 Hz)
- low efficiency (< 3%)
- low reliability and durability
- wet environment needed





undeformed (d = 10 mm) and deformed configuration of the IPMC module design

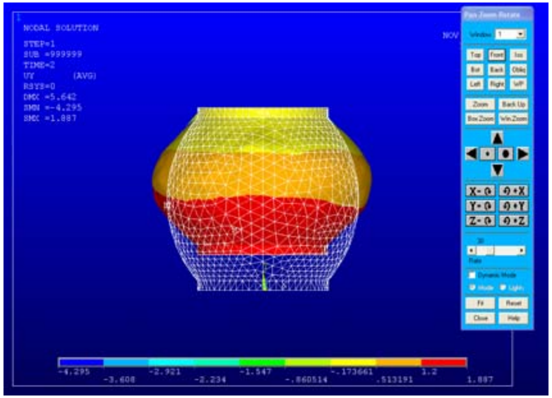
BLU – SMA Module



Spring made of SMA hape memory alloy) ire;

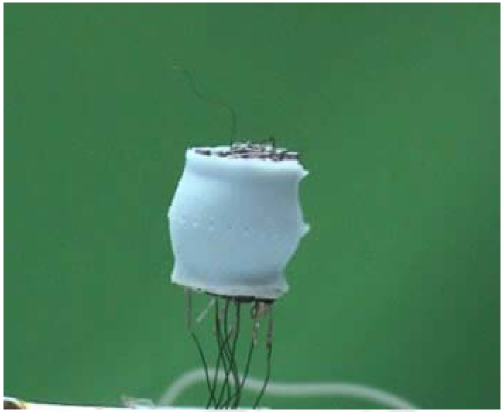
one or three springs per odule;

spring diameter pproximately 600 µm or 00 µm



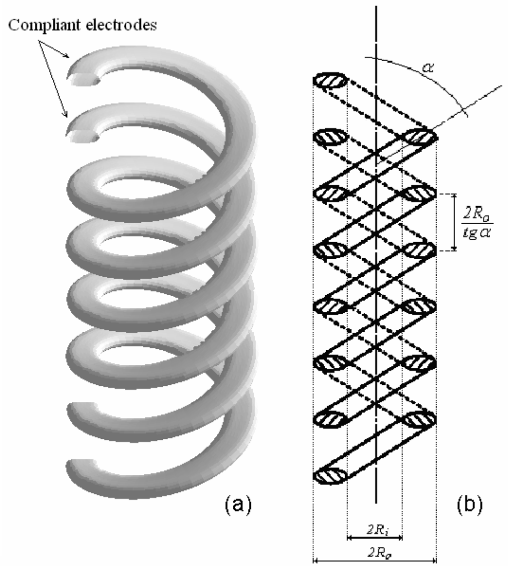
```
NODAL SOLUTION
STEP=1
SUB =999999
TIME=2
UY          (AVG)
RSYS=0
DMX =5.642
SMN =-4.295
SMX =1.887
```

- finite element analysis of the module carried out by ANSYS 6.0;
- optimal thickness for the silicone shell calculated as 0.8 mm.



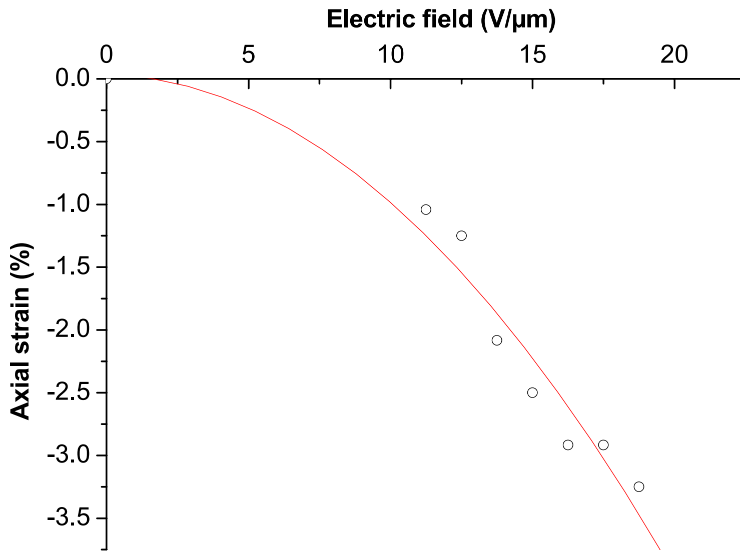
- silicone shell obtained by moulding;
- moulding technique allows testing of different silicones for the shell fabrication;
- polyurethane disks obtained by moulding;
- modules pneumatically sealed

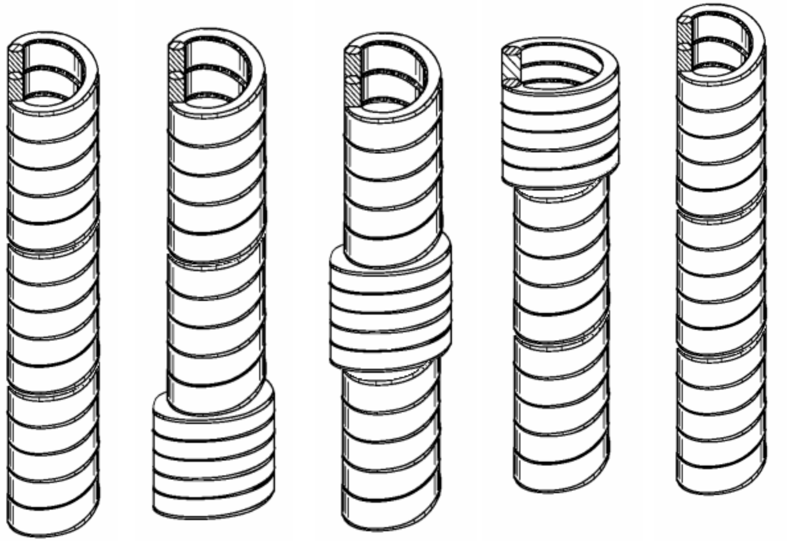
BLU - Dielectric elastomer modules



- Axial active contractions

- Radial active expansions





BLU design: adhesion

Adhesion module

- structure providing a fix point for generating a net advancement during propulsion;
- extremely important for locomoting in non structured environment;
- different mechanisms have been studied.

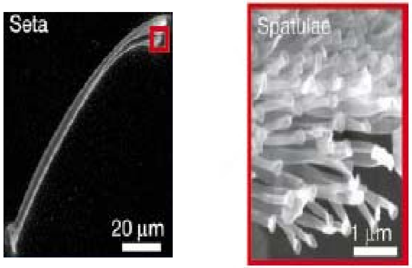
Differential friction module

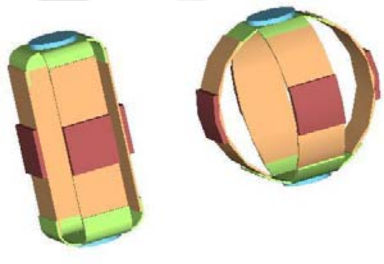
- no net displacement on flat surface
- net displacement on the velvet like surface

ifferential friction can be obtained by endowing the “skin” of the mini-robot ith directional setae

Van der Waals based adhesion module

- structured polymeric surfaces that mimic gecko toe



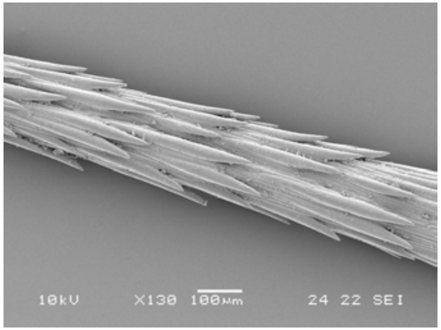


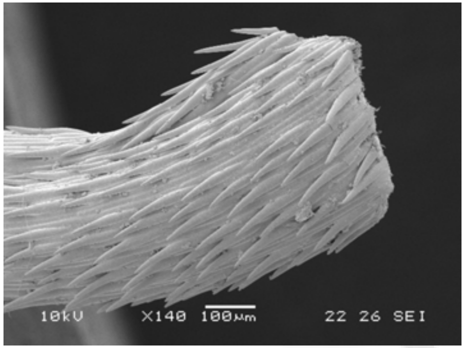
Fabrication

- ➢ **electrical induced structure formation**
- ➢ **nanomolding fabrication technique using nano-pore membranes as a template**

Microfabrication of a biomimetic skin

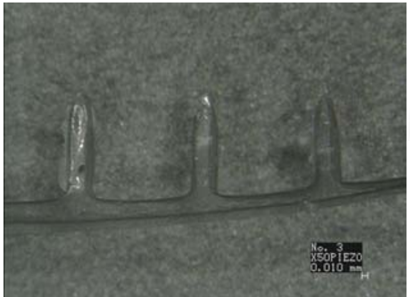
Avena Sativa

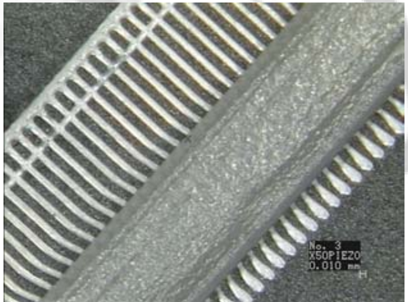




Soft-lithography

Pressure Activated Microsyringe

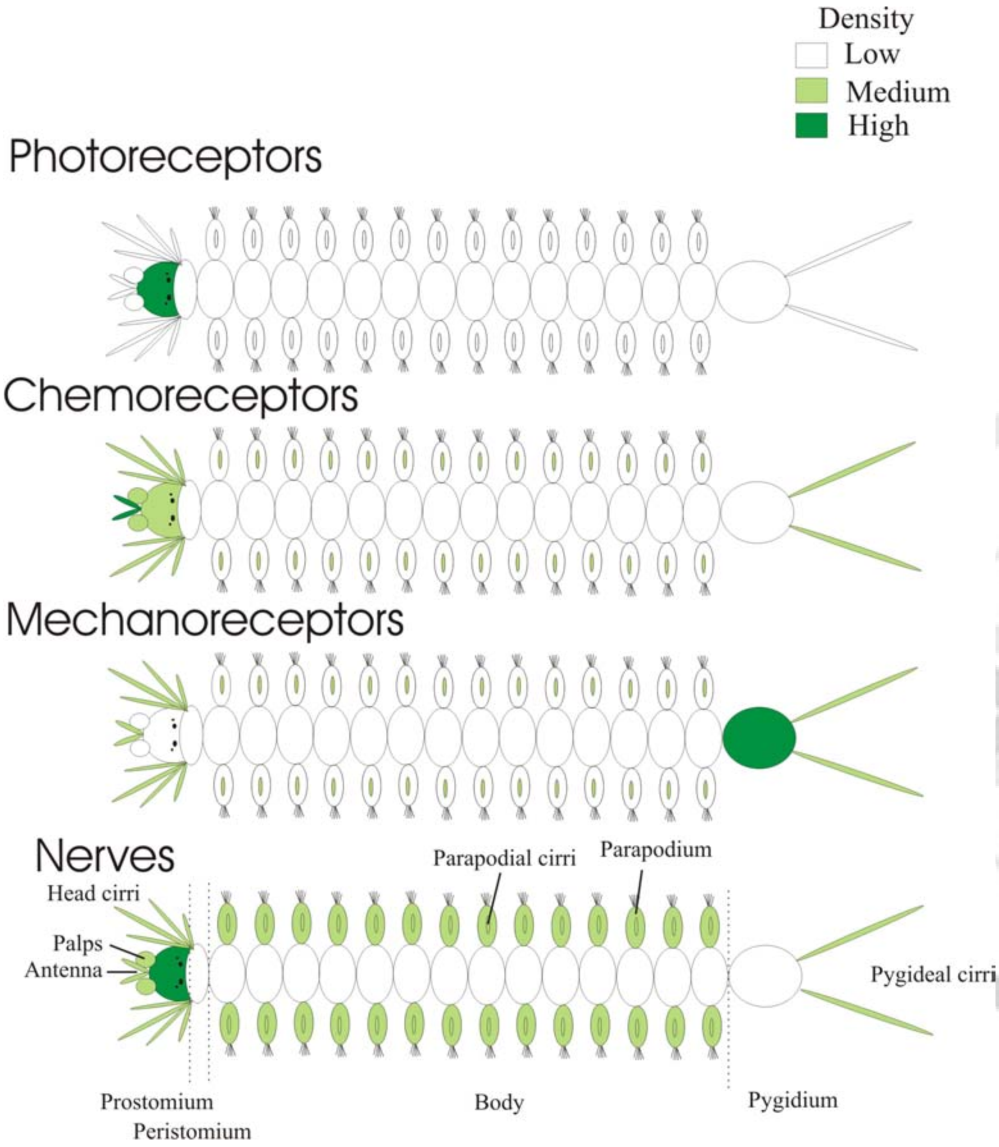




The Sensory System

	Polychaeta	Oligochaeta
Photoreceptors	Eyes, single cells distributed throughout the body	Single cells distributed throughout the body
Chemoreceptors	Palps, nuchal organ, cirri, antenna, sensory structures all over body	Prostomium, simple sensory structures and sensory cells all over body
Mechanoreceptors	Cirri, sensory structures all over body, setae?	Simple sensory structures all over body, setae?
Georeceptors	?	Statocysts
Proprioreceptors	? Associated with longitudinal and circular muscles, in parapodia, where segments join together	? Associated with longitudinal and circular muscles, where segments join together

The Sensory System

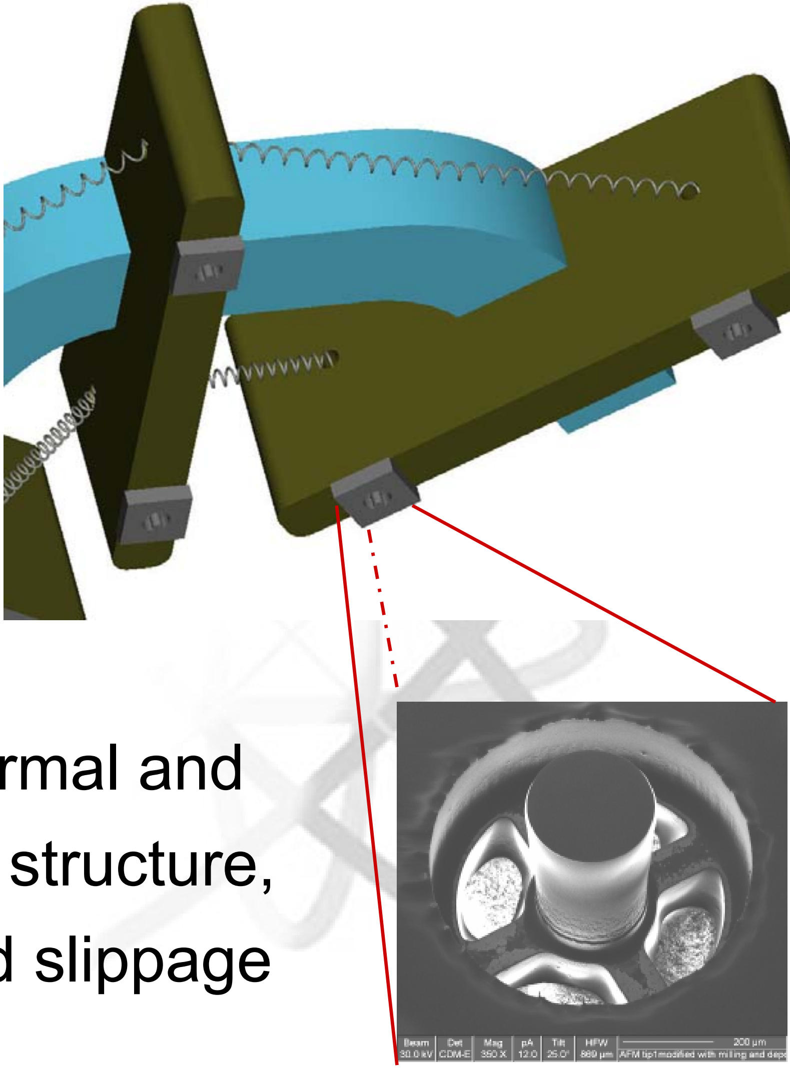


Behavioural Sequences

Behaviour	Initiation	Modulates	Termination	Sensory receptor	Poly	Oligo
Crawling	Attractant	Gradient	Arrival	Chemo	X	X
	Repellent	Intensity	Threshold	Chemo	X	X
Swimming	Threat	Intensity	Threshold	Mechano/ chemo	X	
	Reproduction urge	Phero/ lunar light	Gamete release	Chemo/photo	X	
Burrowing	Exposure to sunlight	Intensity	Completion of burrow	Photo	X	X
Irrigation	Low oxygen	Gradient	Adequate oxygen	Proprio	X	
Searching	Hunger	Intensity	Food encounter	Proprio/chemo	X	X
Withdrawal	Threat	Intensity	In burrow	Photo/mechano	X	X
Threatening	Antagonist	Distance	Retreat of opponent	Chemo/mechano	X	
Fighting	Intrusion	Intensity	Retreat of opponent	Chemo/mechano	X	

Sensing Element for Polychaeta

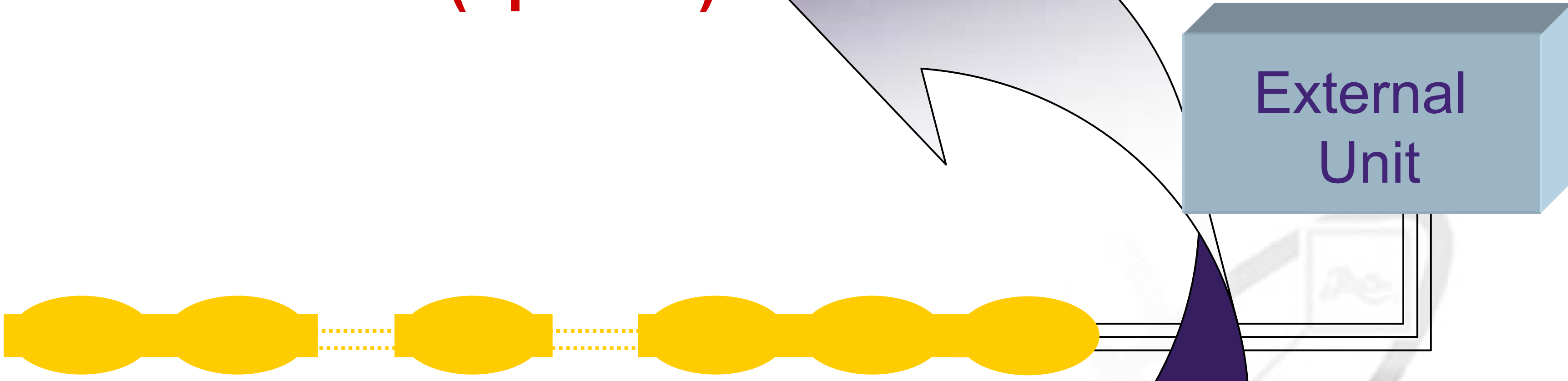
Integration of miniaturized hybrid silicon three axial force sensors in the bottom part of the transversal links is conceived:



- introducing a friction enhancement mechanism gives a specific directionality to locomotion;
- the three components of force (normal and shear) with a fully integrated silicon structure, in order to detect contact forces and slippage during movement, are measured.

Multi-segment robot control

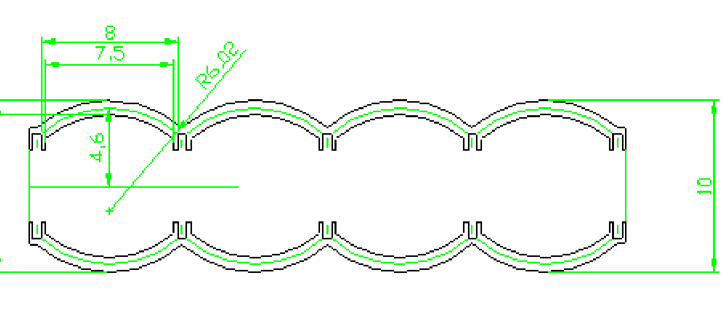
Control for multi **(up to 2^6)** s bot



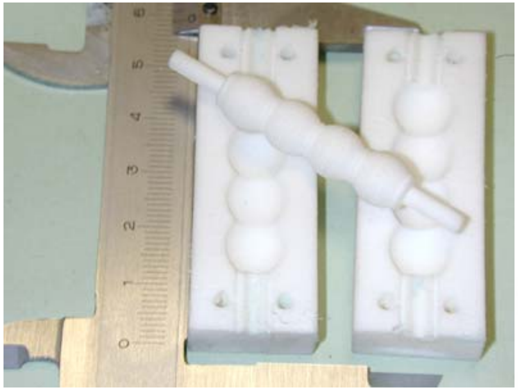
- Each segment equipped with actuator **and** **oard low-level control and gait generator**
- The whole robot delivers **3 wires** (pov d ground).
- The tail segment is the mast
- External unit provides:
  - power,

This architecture will not require additional wires for sensors for closed-loop feedback

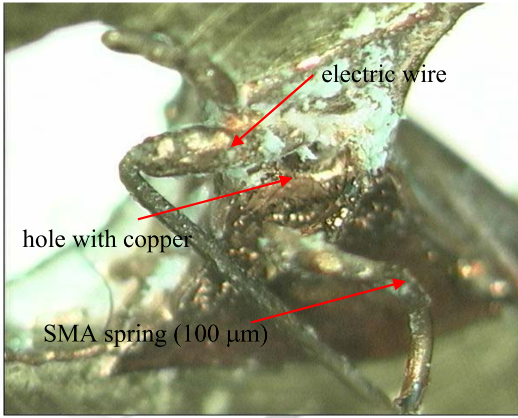
The 4-module SMA artificial oligocheata



Silicone mould design with 4 segments and 5 disks



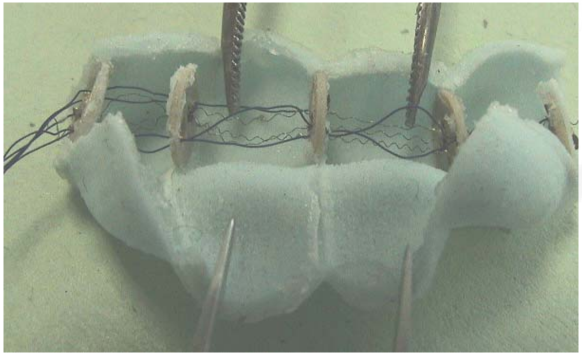
Mould for the silicone shell



Electrical connection betw

brass disk and SMA spring by copper electrodeposition

Earthworm skeleton

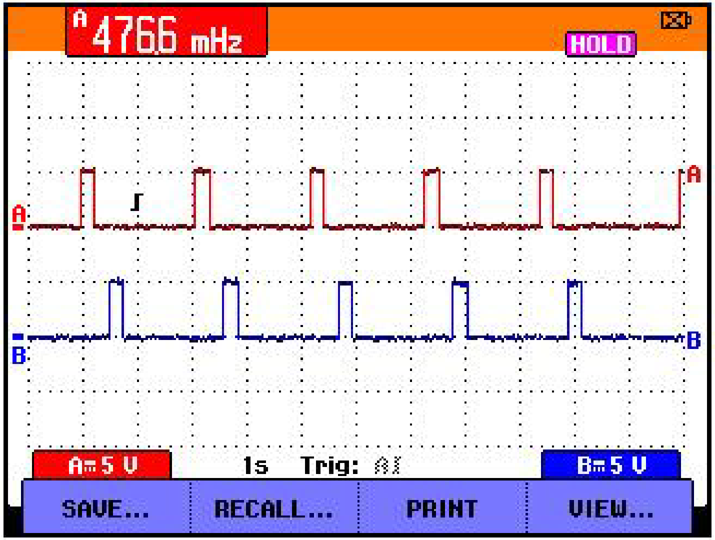


Covering by silicone shell

Final earthworm

Locomotion performance without anchoring legs

he driver produces a sequential
ontraction of the 4 modules. When 1
nodule is active the other 3 are in rest.

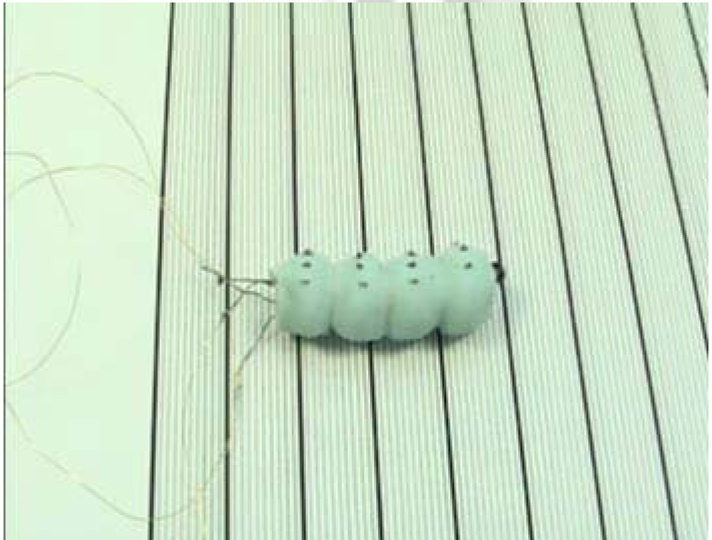


Activation sequence of two
contiguous modules

Typical period of one cycle: 2 s (0.5 Hz)

Typical current peak duration: 200 ms

Typical activation delay between contiguous modules: 300 ms

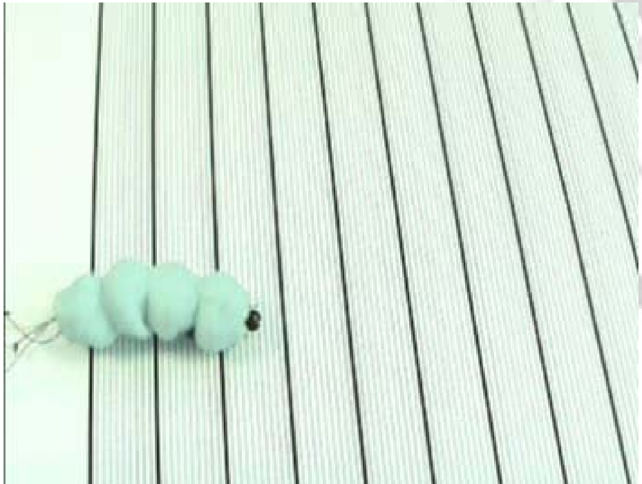


Locomotion performance with anchoring legs on paper substrate (1/2)

Frequency (mHz)	Current peak duration (ms)	Current (mA)	Energy for module (J)	Velocity on flat surface (mm/s)	Velocity on sloped surface (40°) (mm/s)
330	320	400	0.15	0.7	0.45
530	260	350	0.096	2	1.43
600	130	350	0.05	2.5	1.25

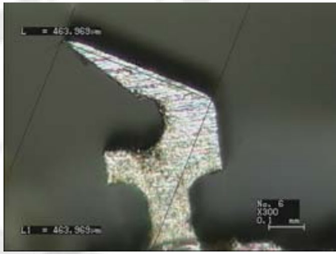
Earthworm with 4 segments and spring for segment (75 μm in diameter wire rather than 100 μm. This increases the robot speed)

For one complete cycle



Locomotion performance with anchoring legs on paper substrate (2/2)

Frequency (mHz)	Current peak duration (ms)	Current (mA)	Energy for module (J)	Velocity on flat surface (mm/s)	Velocity on sloped surface (40°) (mm/s)
330	320	400	0.15	0.7	0.45
530	260	350	0.096	2	1.43
600	130	350	0.05	2.5	1.25

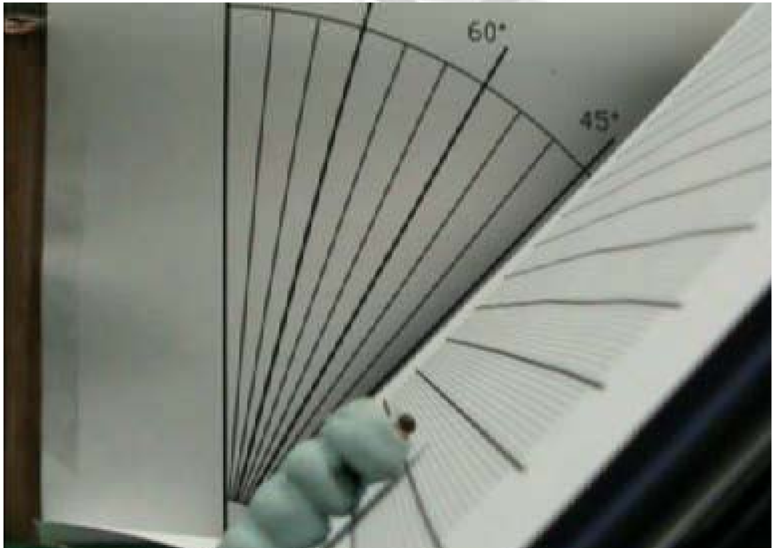


For one
complete
cycle

Setting the locomotion parameters as in the last line of the table, the earthworm can climb a sloped substrate up to the maximum angle of 45°.

Robot mass = 1.2 g

Max propulsion force = 8.3 mN



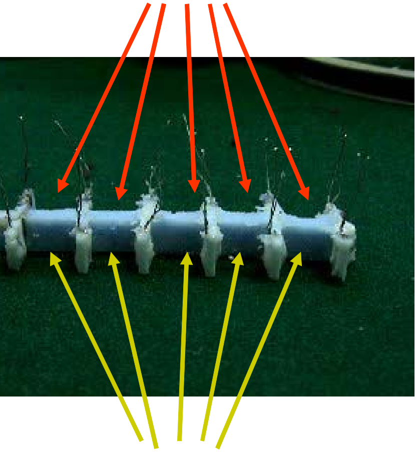
The 5-module SMA artificial polycheata

Main features:

By exploiting the same design rules and fabrication technologies used for th olygochaeta prototype, a 5-module artificial polychaeta controlled by SMA springs has been developed.

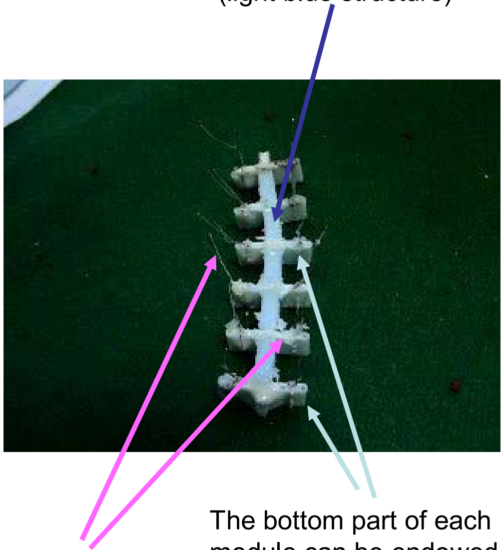
- A flexible skeleton divided into 5 segments by rigid transversal structures
- Both sides of each segment are connected by independent SMA springs which can be alternatively activated in order to obtain a bending behaviour.

5 SMA springs which can be actuated independently (left side)



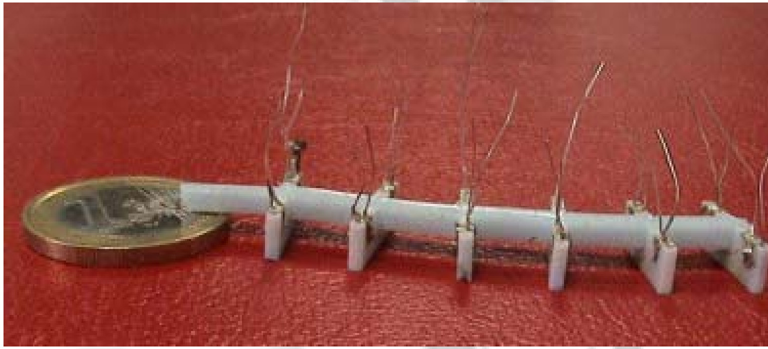
5 SMA springs which can be actuated independently (right side)

Flexible silicone core (light blue structure)

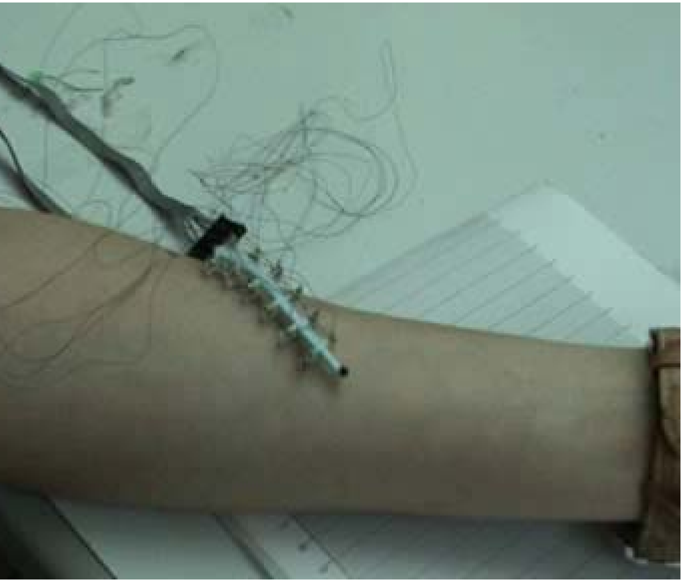


Contact exiting from the top part

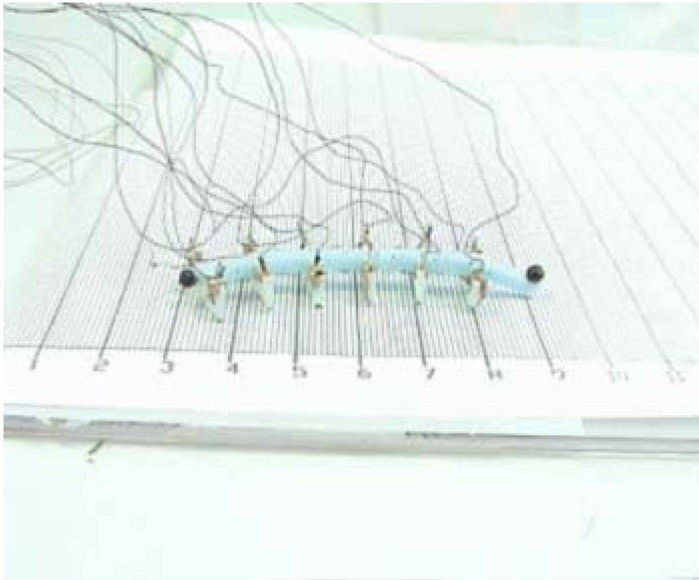
The bottom part of each module can be endowed with small leg/pins (passive) to enhance friction, if necessary



The 5-module SMA artificial polycheata: performance



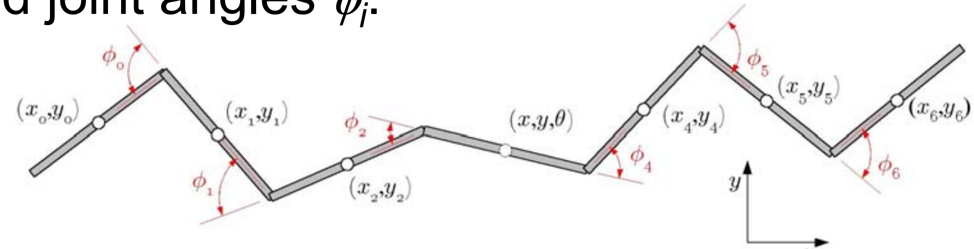
Polycheata with friction enhancement structures (small hooks, as in the earthworm prototype).



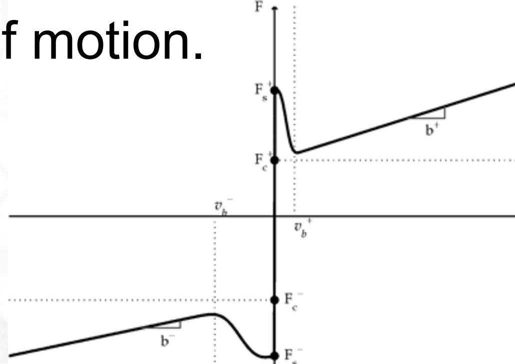
Frequency (Hz)	Current peak duration (s)	Current (mA)	Energy for module (J) - (R = 10 ohm)	Velocity on flat surface (mm/s)
0.5	0.2	170	0.06	1.3

Polychaete computational models

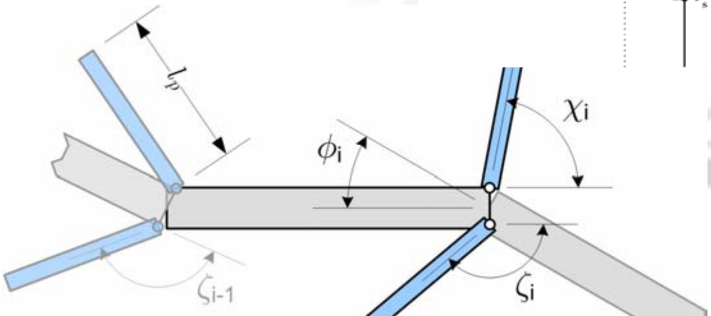
- Computational model for a polychaete-like undulatory mechanism:
  - Planar serial kinematic chain of N identical links.
  - Independently actuated joint angles ϕ_i.



- Lagrange equations of motion on the group *SE(2)xS*^{N}.
- SimMechanics: *Automatic generation* of equs. of motion.
- Interaction with the environment
  is described by appropriate *force terms,*
  depending on the substrate
  and on the contact elements
  of the mechanism.



- Parapodial appendages
  can be included in the models.



Artificial Polychaeta: first prototype

- 7 rotary d.o.f. are actuated by micro-servo motors with both encoder and gear reduction system embedded
- 8 DELRIN segments (7 d.o.f.) interconnected by aluminum links;
- total weight of prototype is 336 g;
- link dimension is 47 mm
- the bottom part of each segment (SCM) is used to impose different friction conditions, 2 types of SCM have been tested on this prototype:

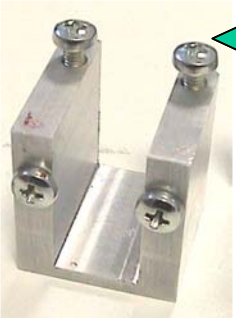
- single blocks of polyurethane with a jagged edge;

- couples of flexible plastic PET blades

The grooves on the sand, traced by the moving segments of the mechanism, are very similar to the link trajectories of simulation

Artificial Polychaeta: second prototype

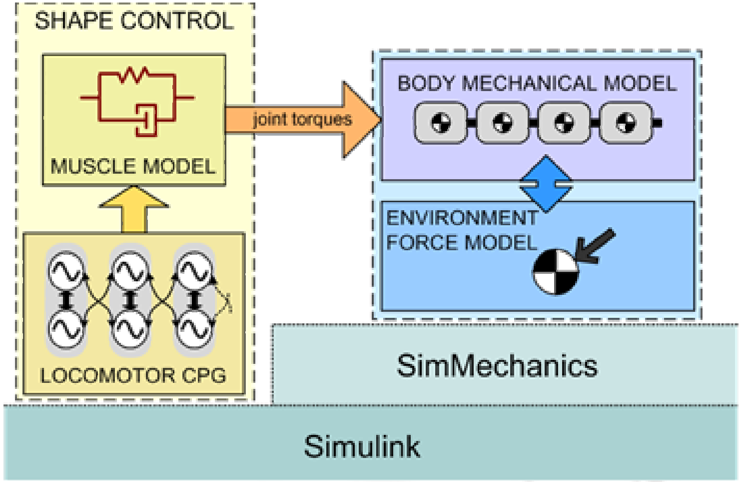
- 10 rotary d.o.f. are actuated by HYPE MINI 11S mini-servo motors with both encoder and gear reduction system embedded.
- 11 aluminum segments interconnected by aluminum links;
- total weight of prototype is 360 g;
- the link dimension is 35 mm
- bottom side is able to hold friction pads
- to control the servos, “Pololu Serial 16-Servo” electronic board has been used



Servo’s case

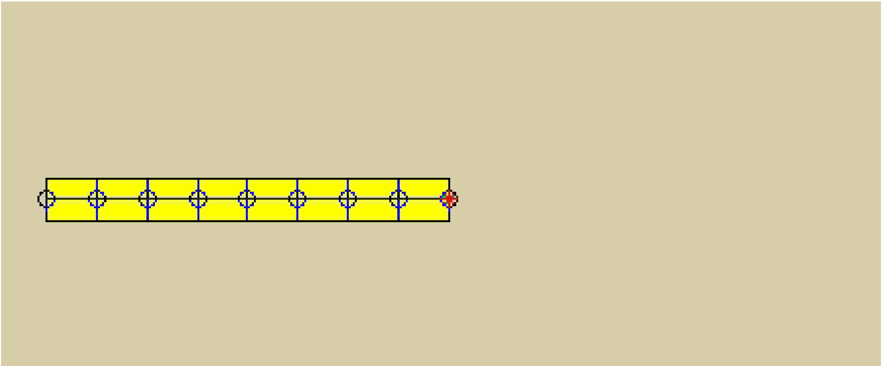
Link - Bridge

Polychaete computational models



The computational models:

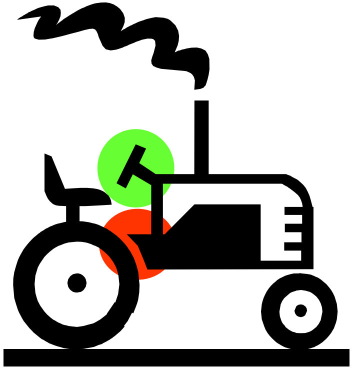
- Provide guidelines for the design of robotic undulatory prototypes.
- Can be used for testing sensing, actuation and control strategies.
- Predict accurately the trajectory characteristics of robotic prototypes of various sizes moving on a variety of environments (e.g. on sand).



"Driving" a polychaete-like mechanism

Locomotion principle:

Body undulations
+
Interaction w/ environment
= Propulsion



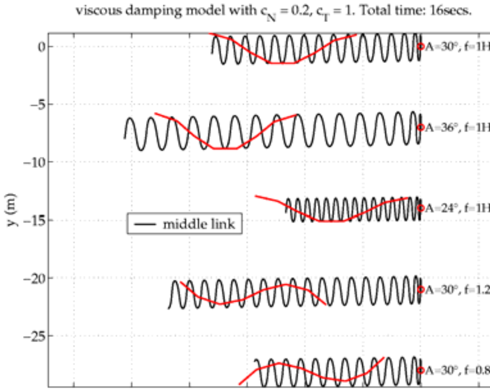
Joint angle control (one simple possibility):

$$\phi_m(t) = \boxed{A(t)}\sin\left(2\pi \boxed{f}\, t + m\frac{2\pi}{N}\right) + \boxed{\psi(t)}, \quad m = 1, \ldots, N.$$

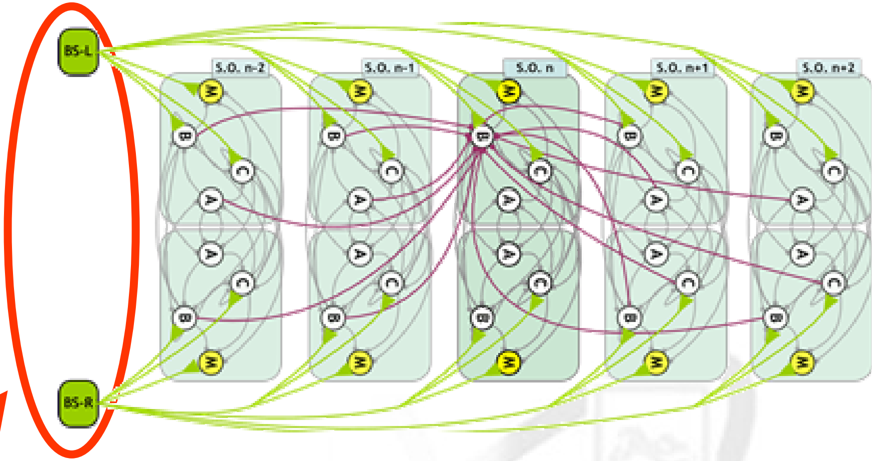
"Gas pedal"

Steering

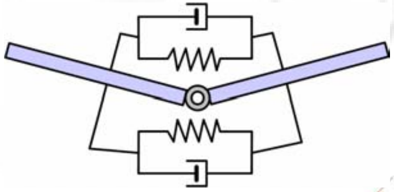
This joint angle control law propagates a travelling wave along the mechanism.

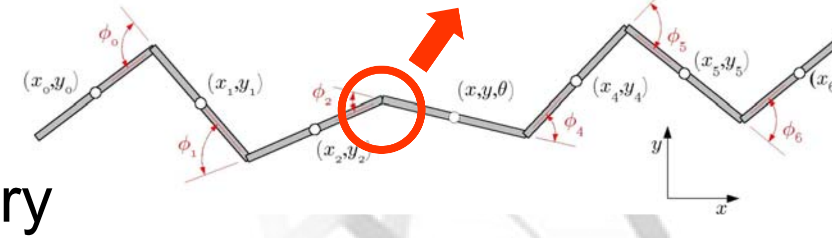


Neural Control

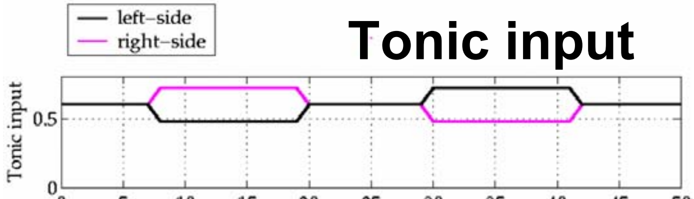


- **Segmental oscillators**
- Intersegmental connectivity
- **Antagonistic muscles** at the joints (spring-and-damper model)



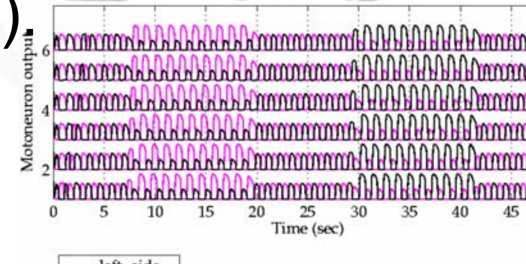


Steering: via **tonic input** asymmetry (if symmetric, polychaete robot moves straight).



Tonic input

Motoneuron output

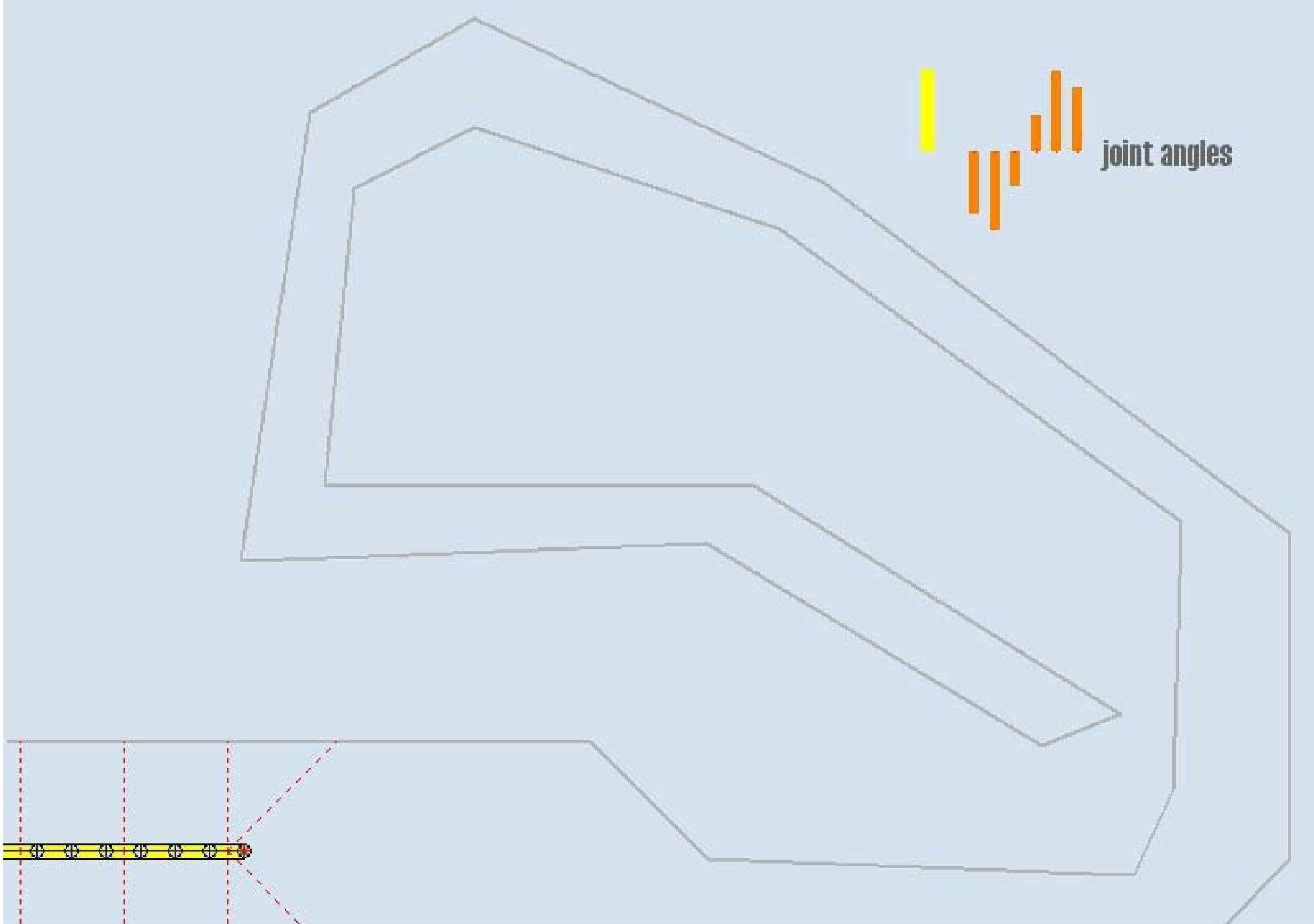


Reactive undulatory behaviors via neural control

- Bee-inspired sensor-based undulatory centering behavior (movement in the middle of free space) is generated by the CPG-based neural control.
- **Sensory data:** are obtained from multiple pairs of **distance** sensors.
- **Tonic input steering:**
  Sensor-guided adjustment of the tonic input which is applied to the two sides of the body CPG (symmetric tonic input drives the robot straight).

Undulatory centering behavior with amplitude shaping

Body undulation amplitude A is globally modified based on the minimum of the measured distances.



Future plan

PART 1: better theory and technology

- Systematizing design rules for oligo- and polychaeta-like robots
- Comparison with biological models
- Assembling of BLUs for oligochaeta and polychaeta prototypes where implementing the high level neural control

PART 2: usable devices

- Finalising the BLU fabrication with sensor, actuators, adhesion module and low level control integration
- Medical assessment and testing
- Looking for new applications (e.g. rescue robotics)

Thank you for your attention!