Neuro-IT Workshop

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BIOLOCH

BIOmimetic structures for LOComotion in the Human body

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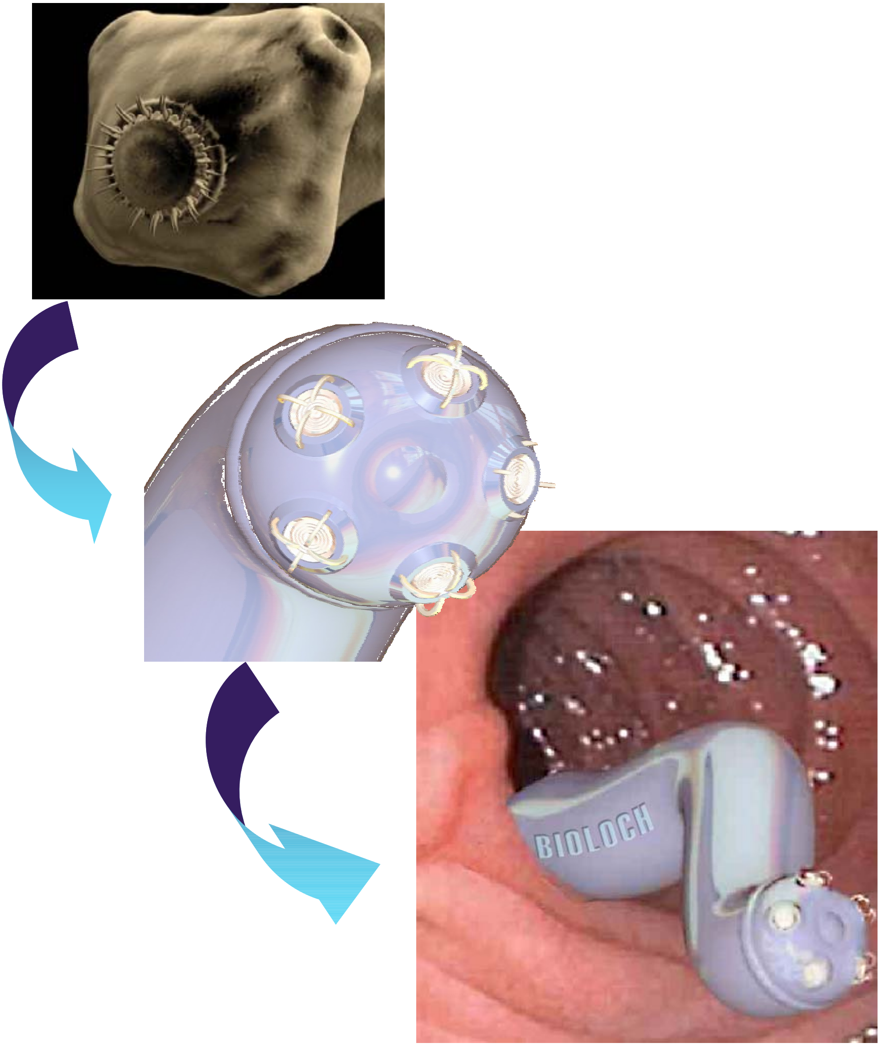
BIOLOCH: BIO-mimetic structures for LOComotion in the Human body

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.

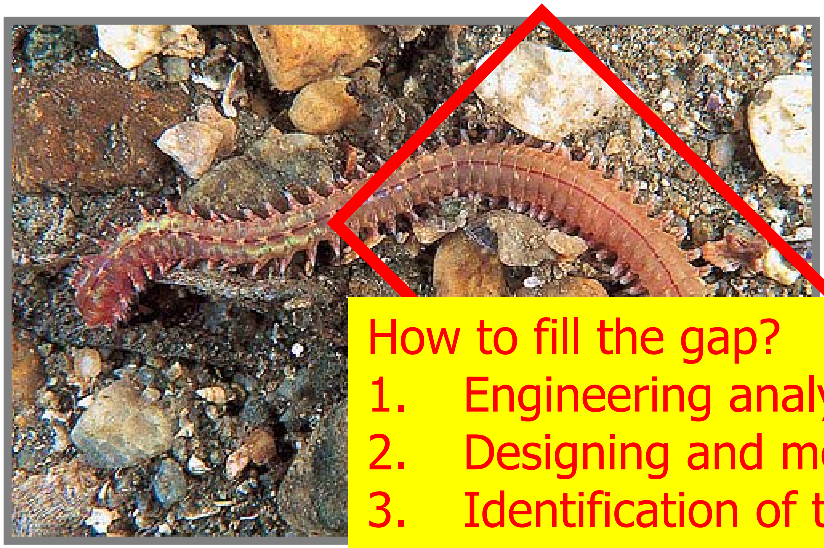
Envisaged application

The "inspection" problem in medicine (microendoscopy).

The BIOLOCH Consortium

- 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

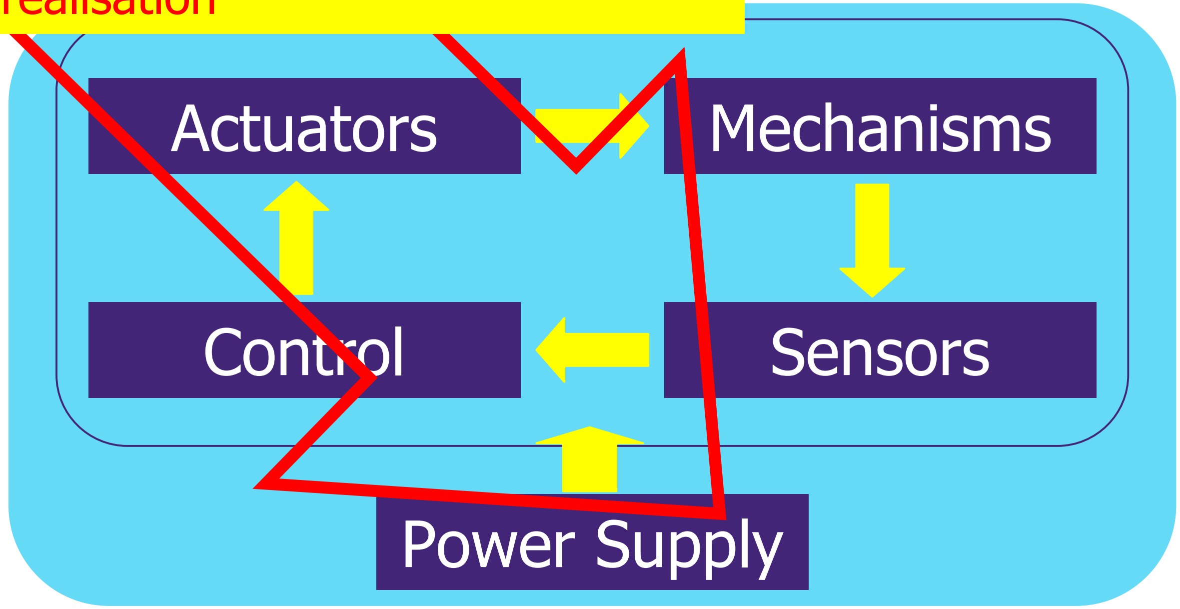
The BIOLOCH Approach



A typical biological creature exploiting locomotion strategies which can be appropriate for the human body

How to fill the gap?

1. Engineering analysis of biological modules
2. Designing and modeling of artificial modules
3. Identification of technologies suitable for biomimetic realisation



Actuators

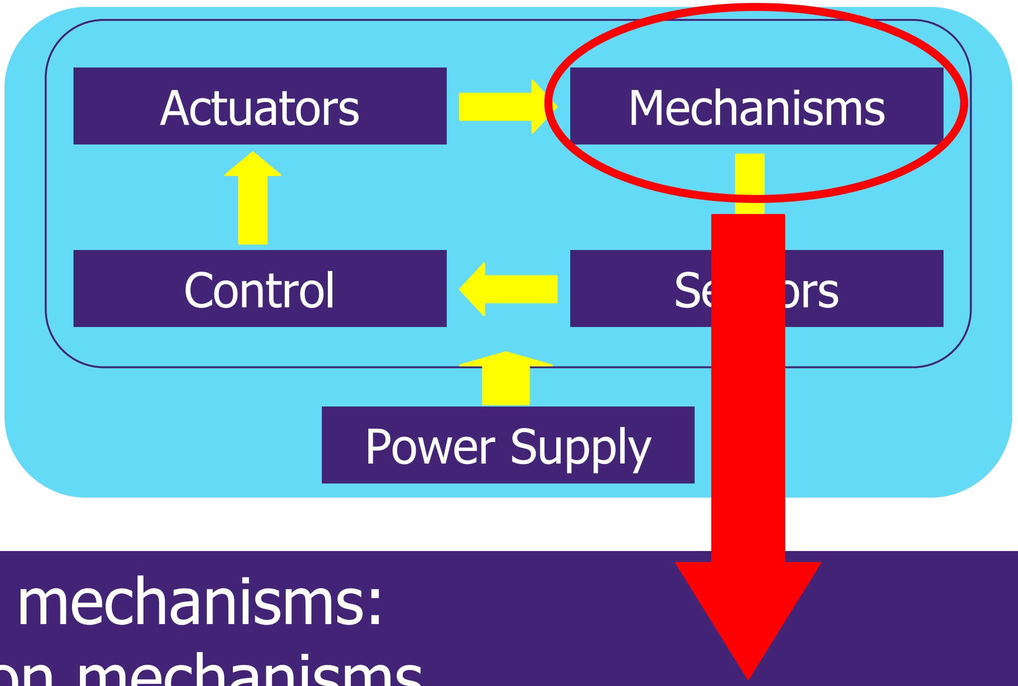
Mechanisms

Control

Sensors

Power Supply

A typical mechatronic scheme of a biomimetic machine ("animaloid")



Actuators

Mechanisms

Control

Se ors

Power Supply

Propulsion mechanisms:
- locomotion mechanisms
- adhesion mechanisms

Locomotion in the human body: constraints

Robotic endoscopy of the gastrointestinal tract and beyond: a grand challenge

The Problem: Gut Pathologies

Esophagus cancer

Stomach cancer

Small intestine pathologies

Colon Cancer

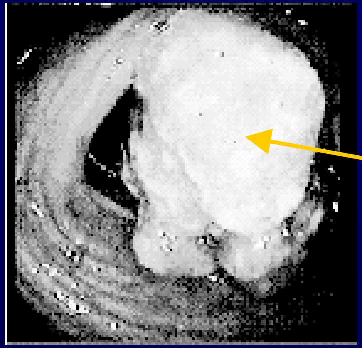
Colon-Rectum
Cancer

Importance of Colonoscopy

…..quoted from
New England Journal of Medicine (20 March, 2000)

- Colon cancers are one of the deadliest but most preventable malignancies
- Kills 437 000 people worldwide each year, 98 500 from the European Union
- Curable 90% of the time, if detected and treated in the earlier stages
- Death toll could drop by 50 to 75% with mass screening of the population

•Top medical practitioners recommend:
  Sigmoidoscopy every 5 years
  Barium Enema every 5 to 10 years
  Colonoscopy every 10 years
  Stool test every year



Endoscopic View of fungating colon cancer

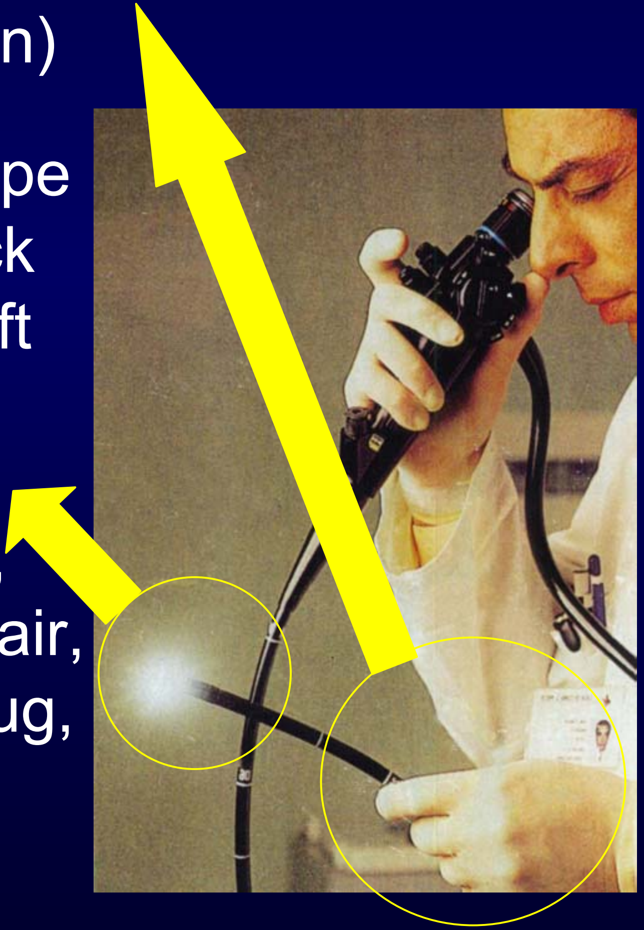
- Colonoscopy tops the list of recommendations because the entire colon can be inspected and therapeutically treated as soon as ailments are discovered

Mass screening of population for colon ailments would be desirable

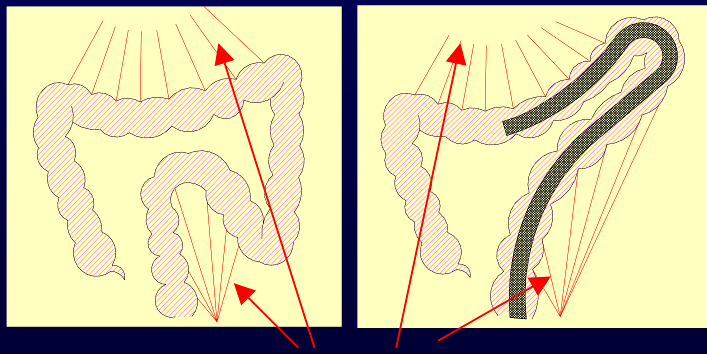
Traditional endoscopy

The endoscopist must produce a force (by his/her hand) and a torque (by his/her wrist) to push the tool into the human body (e.g. the colon)

The endoscope is a quite thick and rigid shaft containing bundles of optical fibers, channels for air, water and drug, therapy and biopsy tools



It is almost impossible to avoid the colon to be stretched quite extensively, **thus causing pain to the patient**



Possible solutions

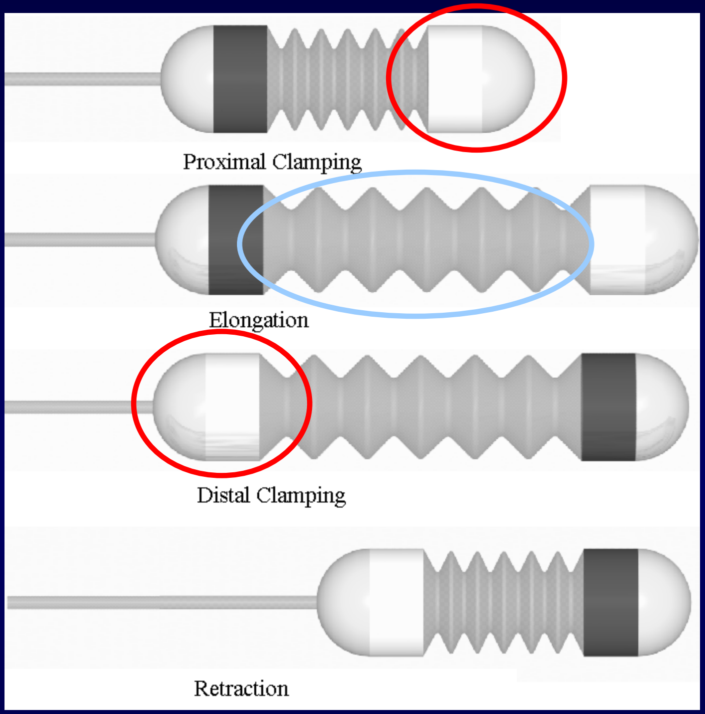
- Reducing the stiffness of the endoscope
- Transferring control functions from the brain of the endoscopist outside the body to a robotic endoscope inside the body

“Inchworm” locomotion

Distal clamper

Central elongator

Proximal clamper



Typical colonoscopy prototype

Diameter : 24 mm
Retracted Length : 115 mm
Elongated Length : 195 mm
Stroke: 80 mm

In vitro tests of a (teleoperated) prototype colonoscopy system

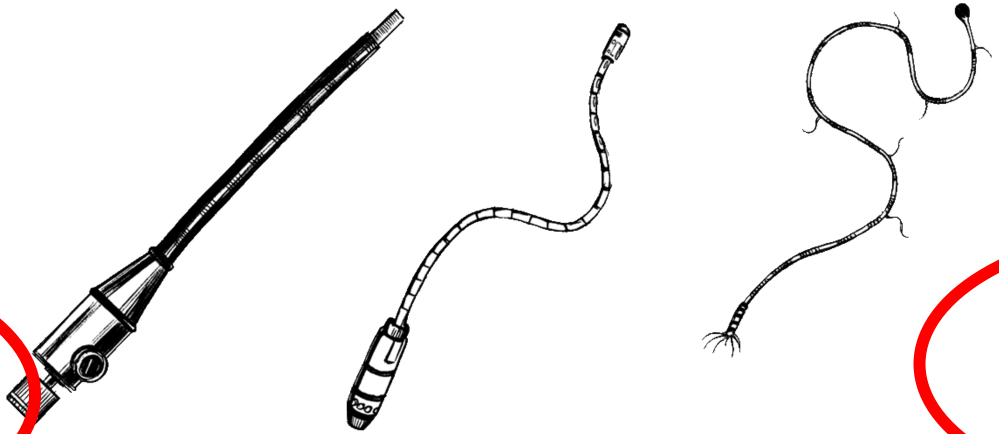
Possible solutions

- Reducing the stiffness of the endoscope
- Transferring control functions from the brain of the endoscopist outside the body to a robotic endoscope inside the body

From bio-inspired robots (the “inchworm”) to truly bio-mimetic robots

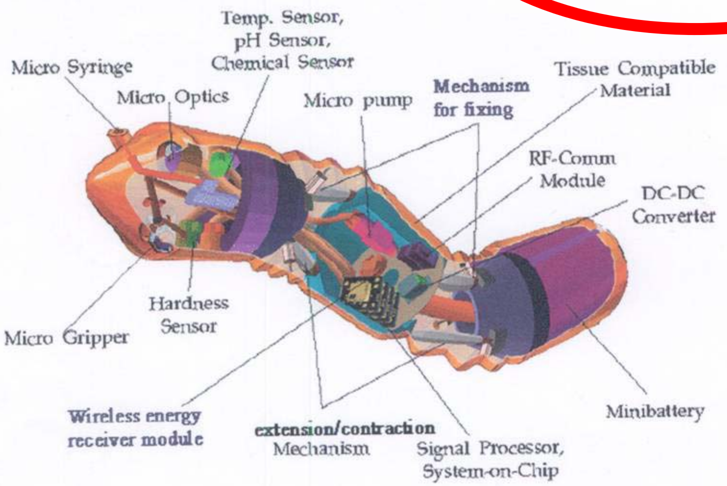
Tra

io-mimetic tool

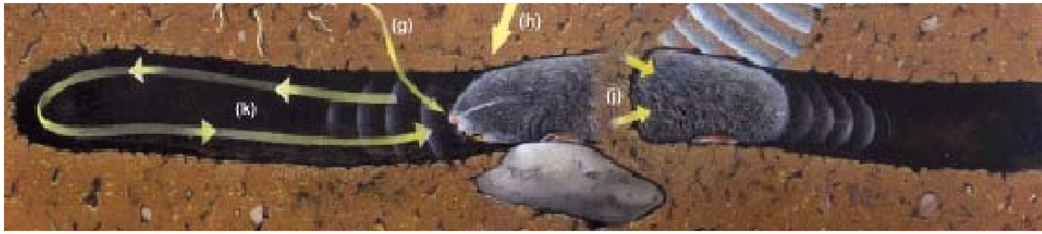


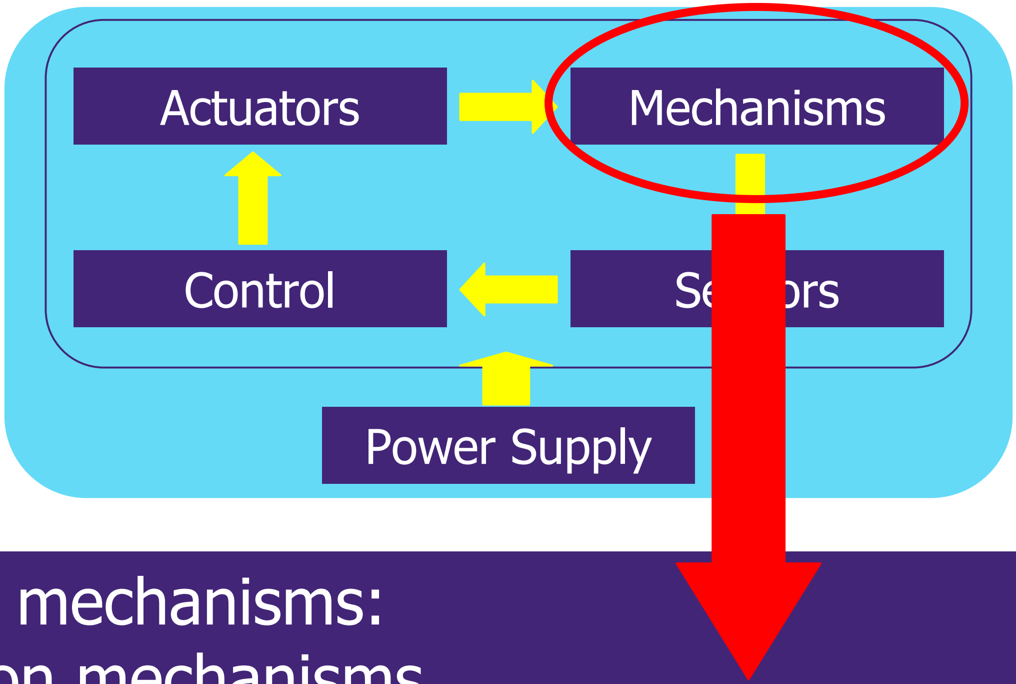
Propulsion and control (surgeon brain) outside

Propulsion and control all inside



Intelligent Microsystem Center



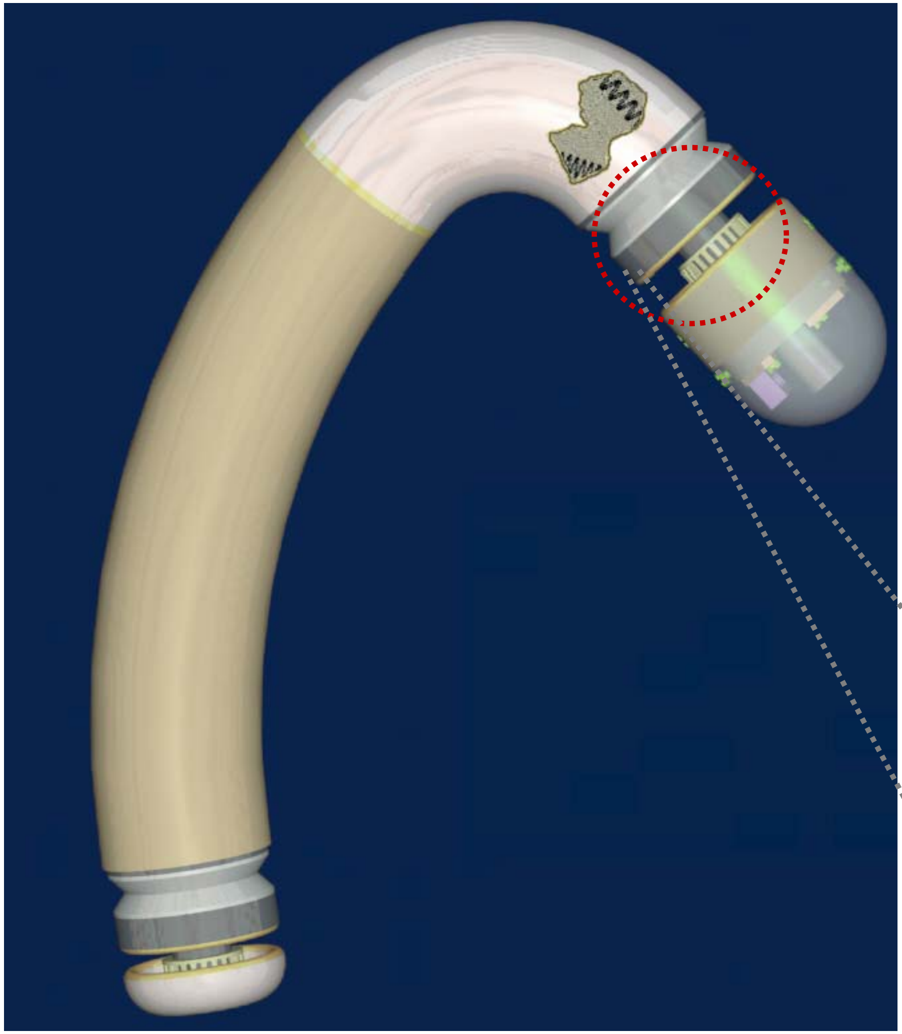


Propulsion mechanisms:
- locomotion mechanisms
- adhesion mechanisms

Mechanisms of friction enhancement and tribological studies

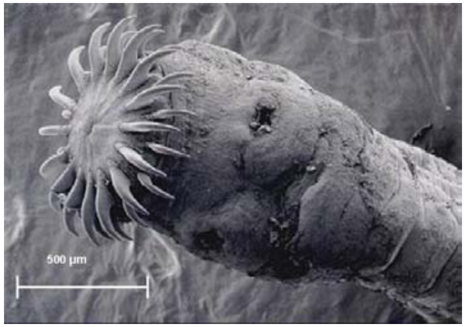
Adhesion by mechanical devices

Exploring novel adhesion mechanisms



Adhesion by Suction

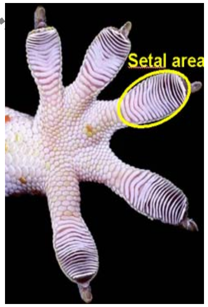
Taenia Solium



Adhesion by biological glue

Snail

Adhesion by Friction

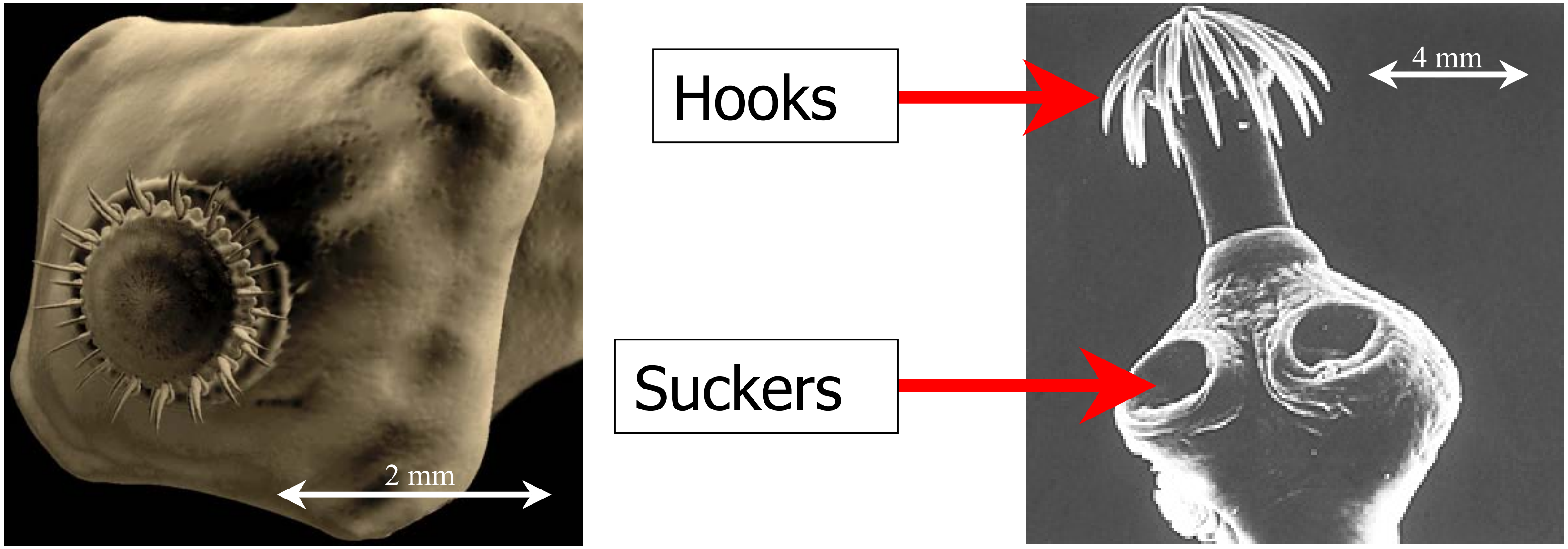


Snake

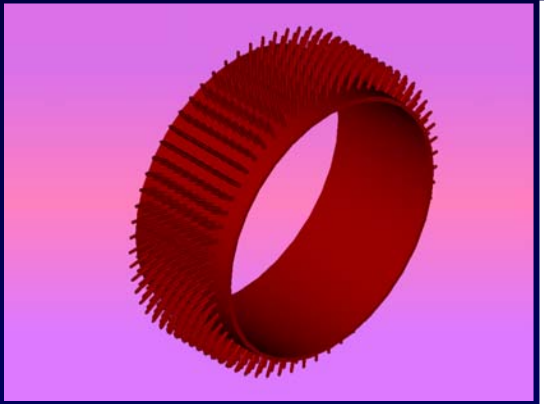
Biological system model: Taenia solium

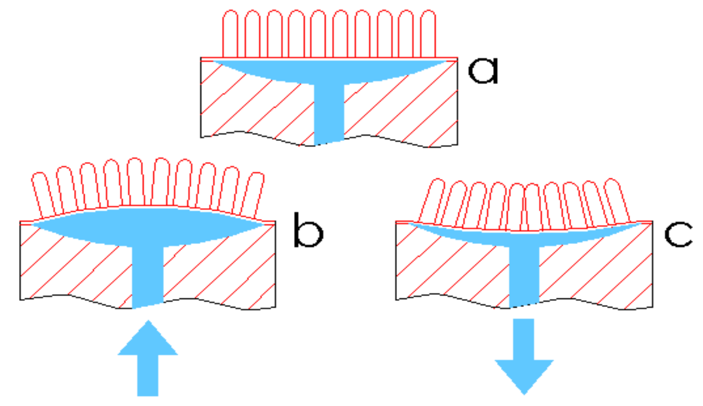
Taenia solium, the well–known parasite of the human intestine, clings to biological tissue with a two–step strategy involving:

- Mechanical clamping (hooks)
- Suction



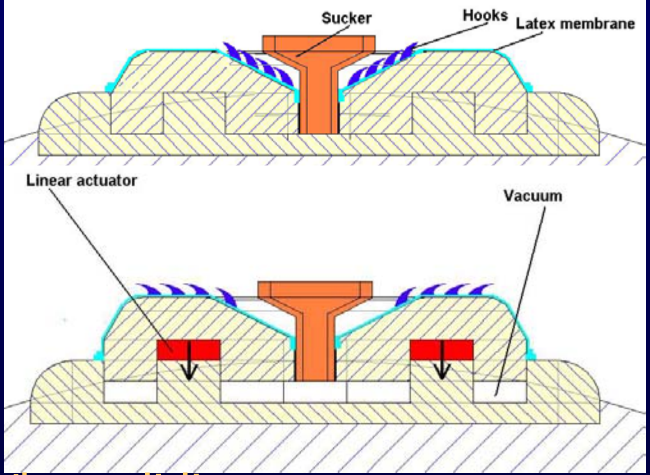
Design and fabrication of bio-inspired adhesion mechanisms





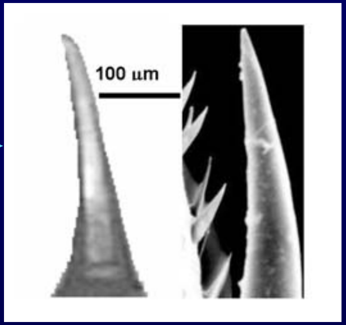
Friction is enhanced when the compliant tips are pushed outward

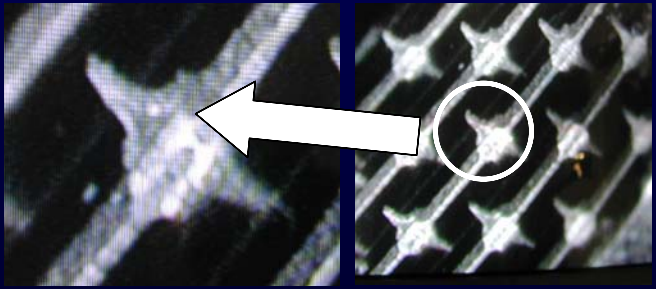
(a) normal configuration; (b) flow in; (c) flow out



When sliding part moves upward: a vacuum is generated (sucker can work); the membrane is stretched (hooks can grasp the tissue)

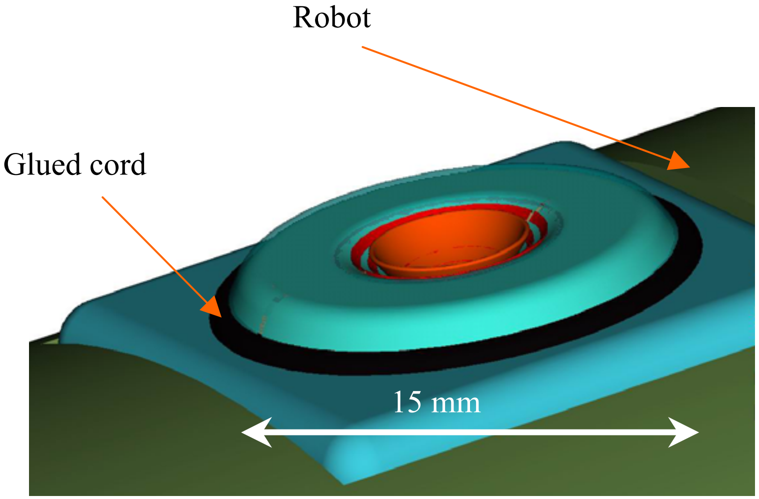
Cylinder of polimeric material (Nylon)

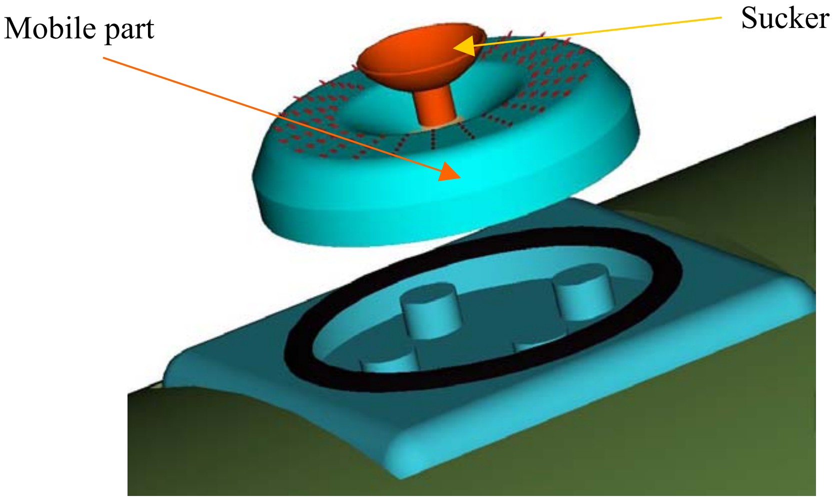




Aluminium hooks are used to create a special wax mould to fill with Epotex (epoxy bicomponent resin).

Replicating Taenia solium





At first the hooks are located in the proximity of the lateral wall. When the device is actuated, the mobile part moves outward stretching the membrane in which the hooks are embedded.

“Liquid bridge” technology

A cylinder of Nylon 6 (diameter: about 500µm) melts in contact with two high temperature metal tips.

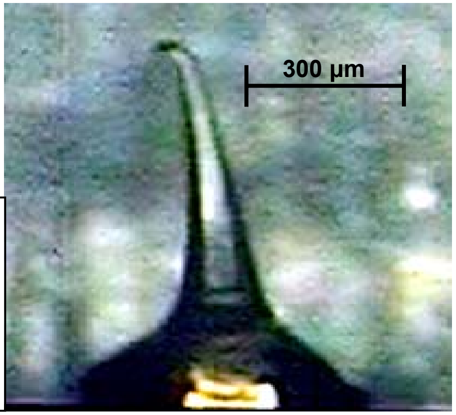
The surface tension of the melted polymer realizes a liquid bridge between the metal parts.

When the metal tips are moved apart the liquid bridge is shaped by surface forces (it splits into two hook-shaped parts when the strain exceeds a critical value).

Unmelted polymer

Melted polymer (135°C)

Artificial hook, fabricated by “*liquid bridge*” technology

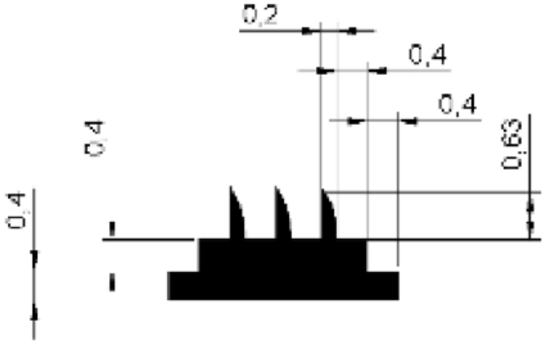


more details

µEDM technology

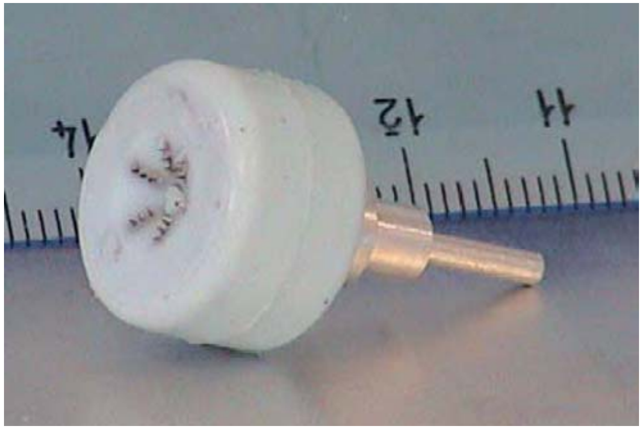
The hooks can be fabricated using stainless steel machined by Micro Electro Discharge Machining

- fabrication dimension down to 10 µm
- possible batch production

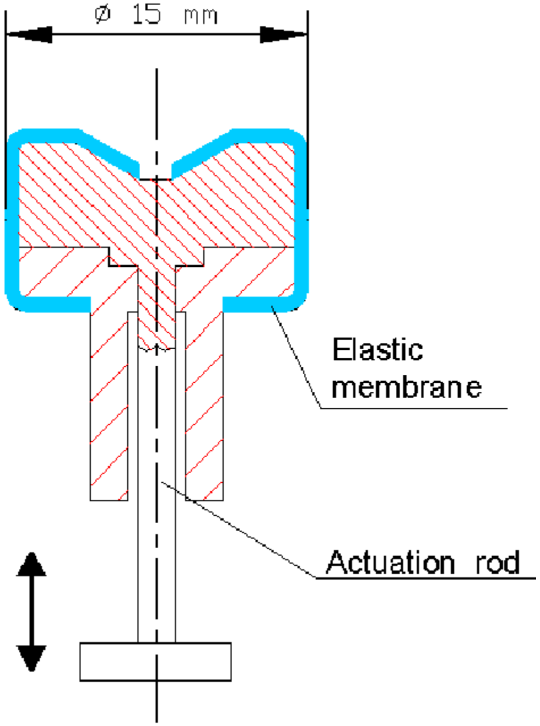


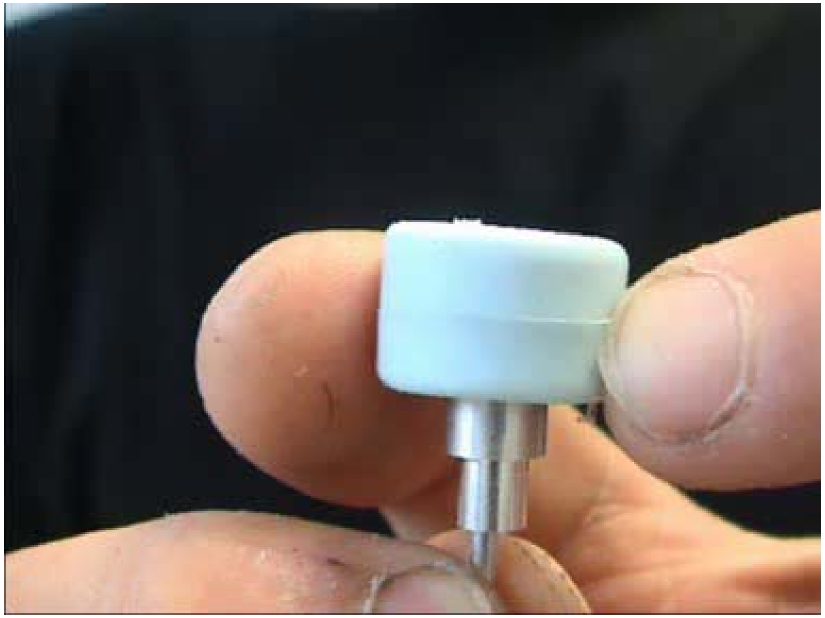
Depth: 1 mm

Prototype

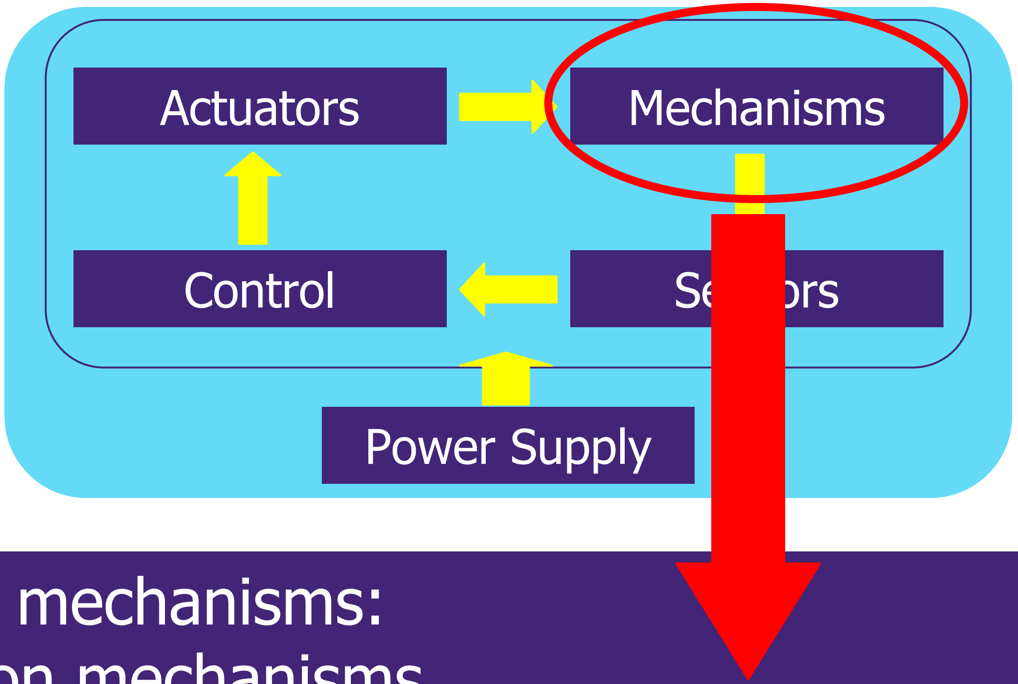


The actuation rod is manually displaced in order to stretch outward the membrane. The hooks are embedded in the polymeric membrane before curing.





The extension of the membrane pushes the micro-hooks against the tissue. The sucker will be mounted in the central hole.



Actuators

Mechanisms

Control

Se ors

Power Supply

Propulsion mechanisms:
- locomotion mechanisms
- adhesion mechanisms

Mechanisms of friction enhancement and tribological studies

Adhesion by interface modification

Adhesion by interface modification

Some materials or conditions can catalyse the adhesion process. Two processes can be pursued

- Gluing phenomena: special materials are added in proximity of an interface
- Interface alteration: some parameters of the surface are changed

The motion of snails acts as inspiration: a special gland in the foot secretes mucus that helps the snail to move.

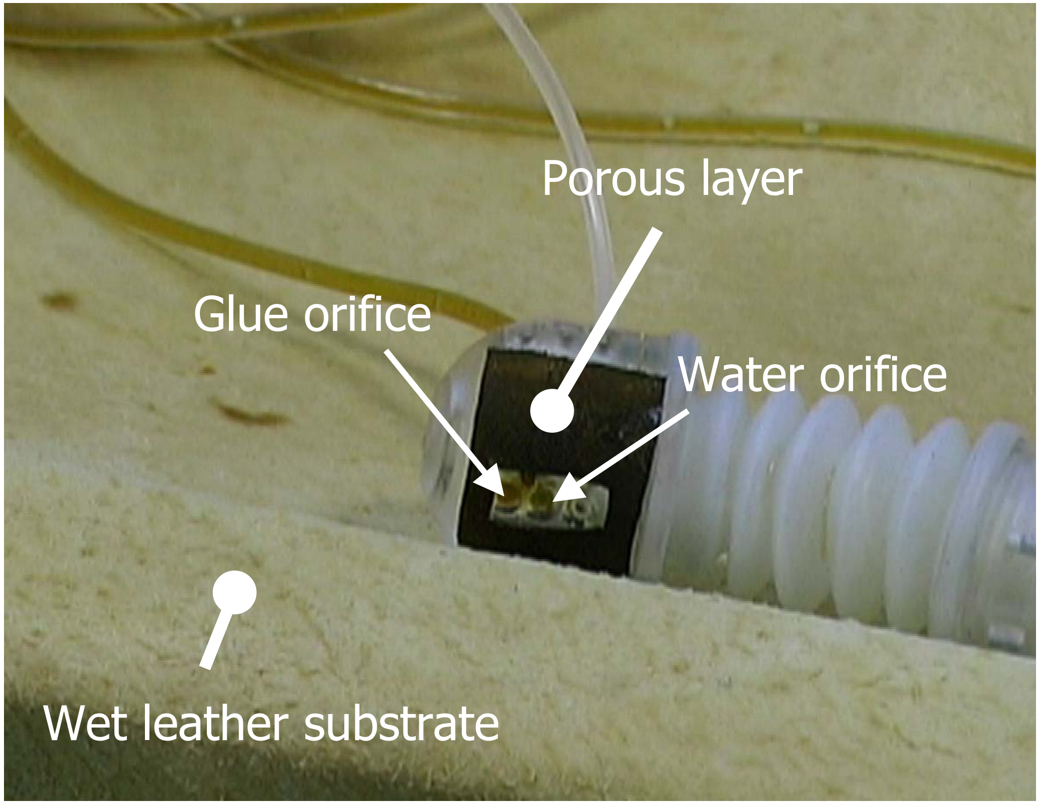
Biological adhesive clampers

The glue which has been used is composed of glucose and water. It is frequently used in sport fishing.

Water acts both as activating and detaching agent.

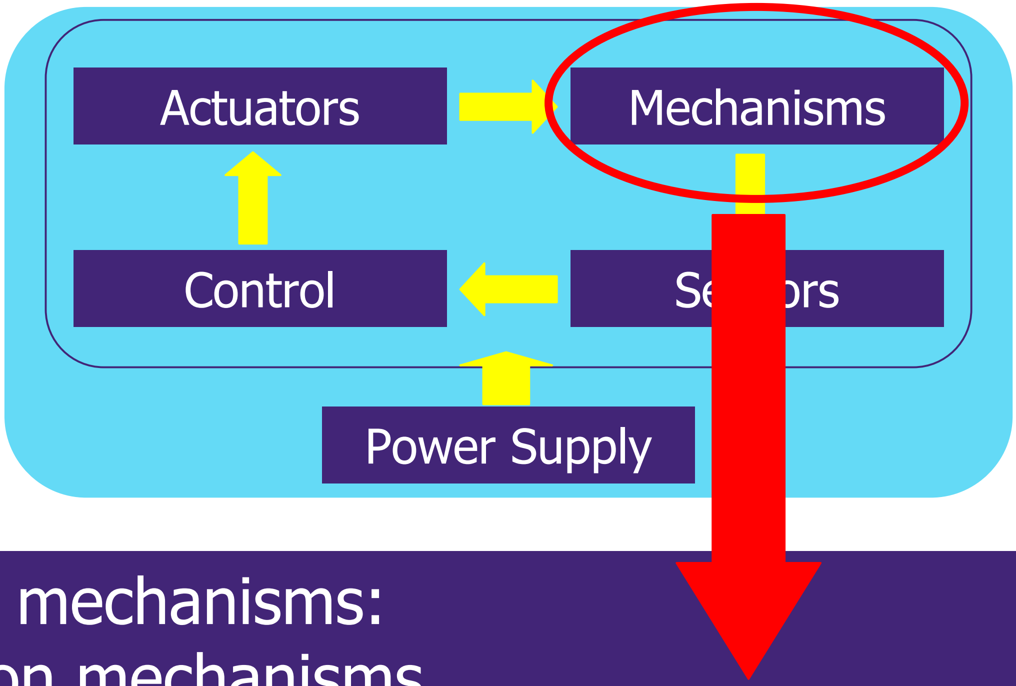
The glue is:

- non- toxic
- reversible
- easily activated by wet substances in the gut



Another option we are considering: photo-curable, reversible and biocompatible adhesives

Design and fabrication of bio-inspired adhesion mechanisms



Actuators

Mechanisms

Control

Se ors

Power Supply

Propulsion mechanisms:
- locomotion mechanisms
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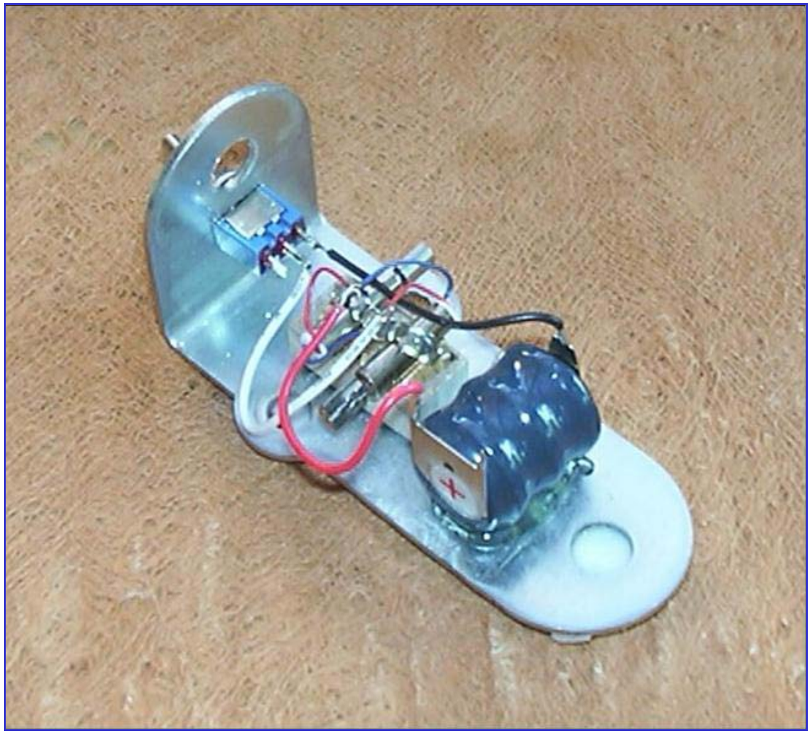
Mechanisms of friction enhancement and tribological studies

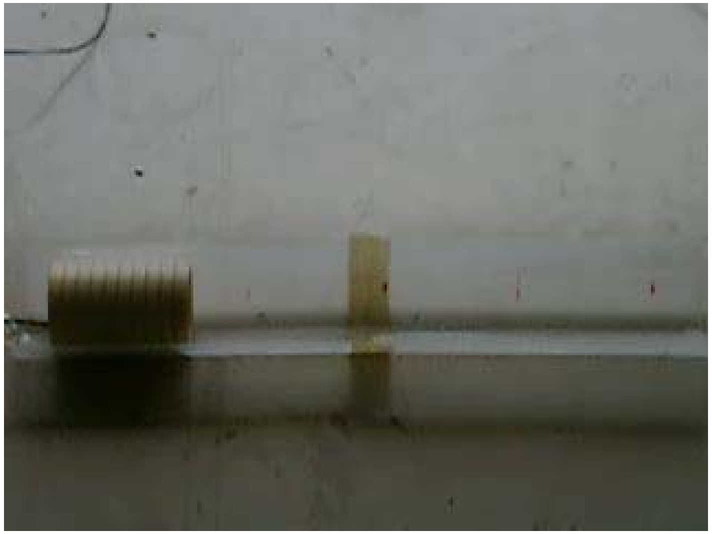
Differential friction phenomena

Differential Friction Phenomena

Mini-robot prototypes endowed with an "automatic" system able to produce pulsed movements, without the use of external sensor of perception and a complex system of control of the motion.



total weight: 70 g
length: 7 cm



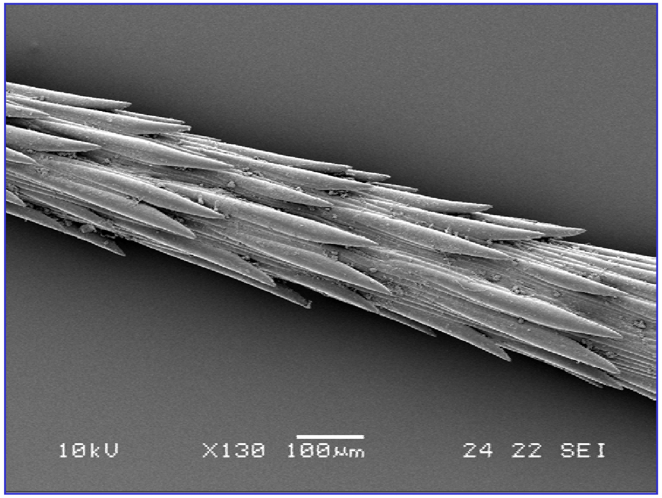
Internal structure of the system:

two counter motors on which an eccentric mass is placed. In this manner we reproduce an asymmetrical motion that is directed by asymmetrical skates under the platform on which the motors and the voltage supply are mounted.

Differential Friction Phenomena

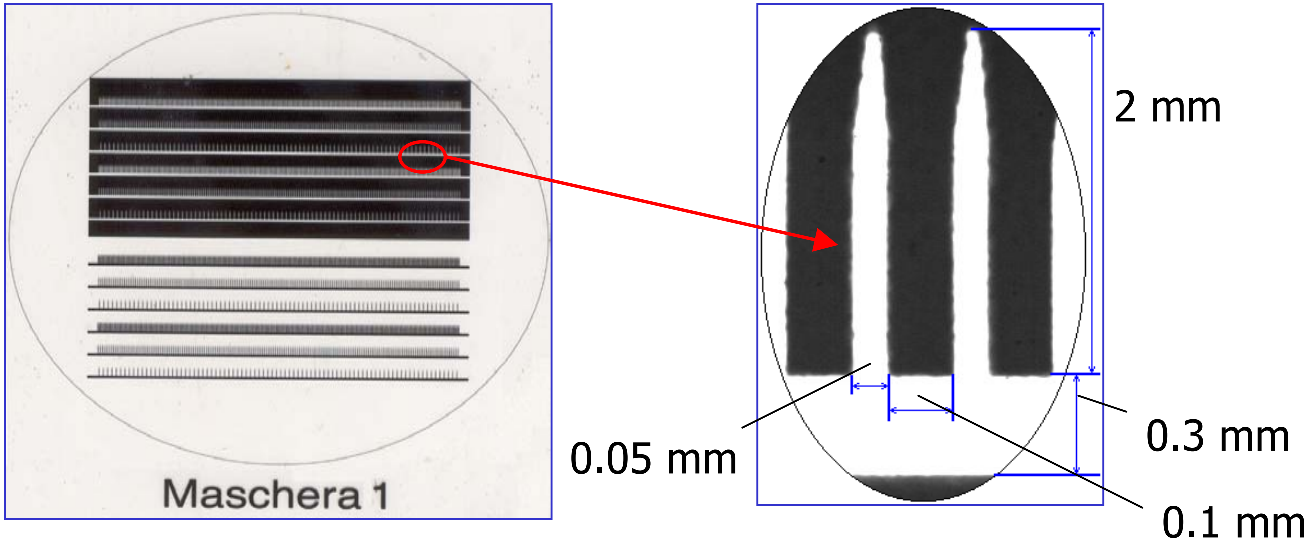
In order to optimize rectilinear movement of prototype, we choose to cover the external surface with polymeric microstructures that could guarantee to the robotic system to transform the asymmetrical motion in an symmetrical motion.

The structure of *avena sativa* can serve as a source of ispiration: this plant is able to move on different substrates with helicoidal motion under a humidity gradient and it is able to adhere to the substrate. The presence of small scales on the surface of the plant allows to move only in one direction.

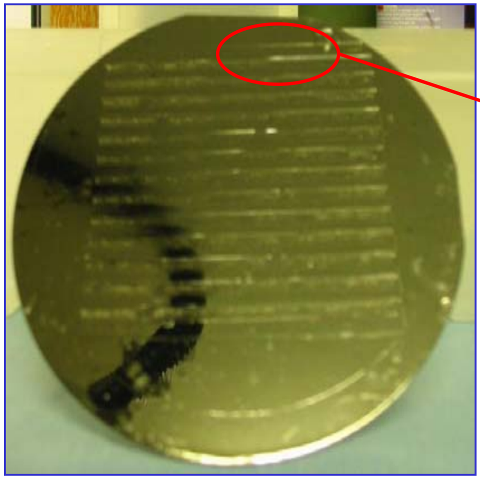


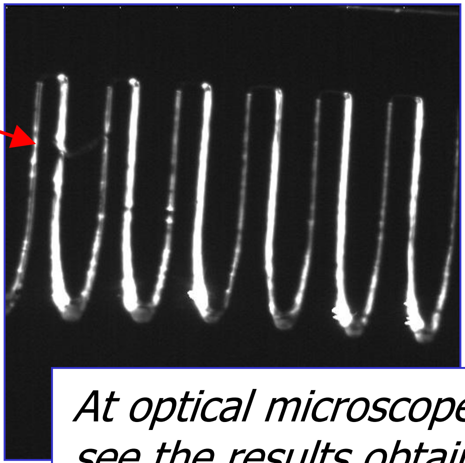
Differential Friction Phenomena

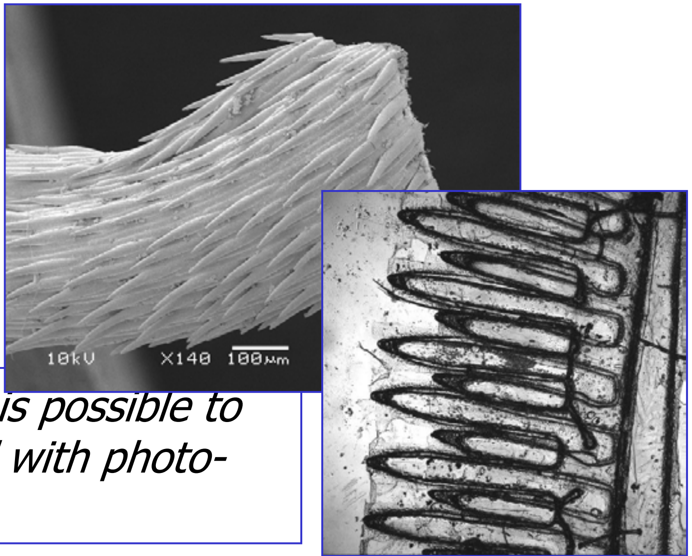
Mask utilised and details of second line at optical microscope



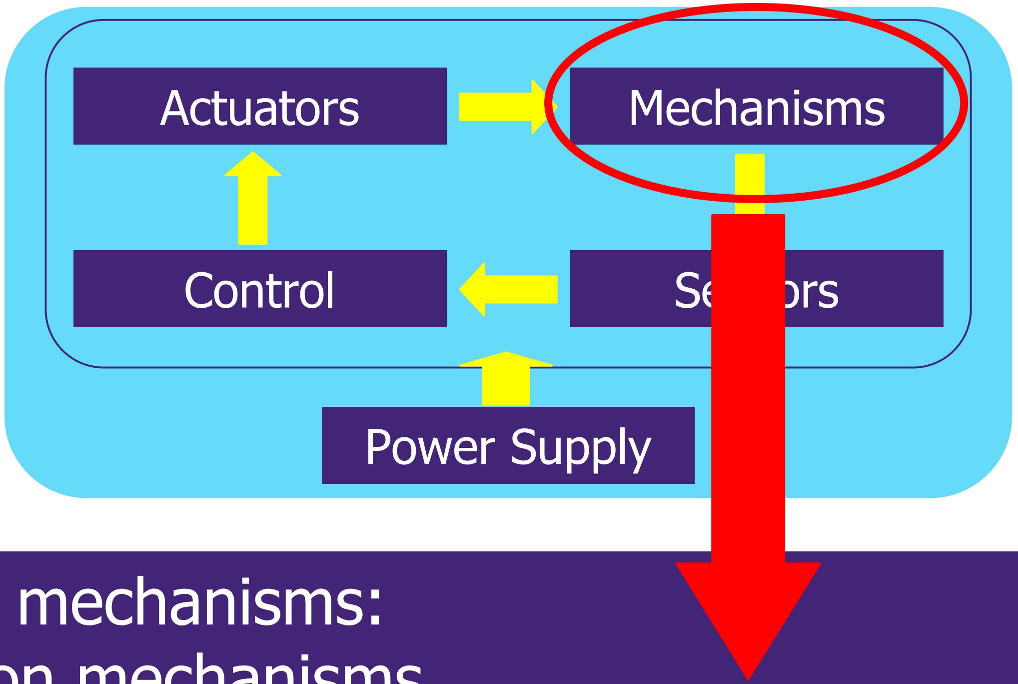
Using this mask, we obtained the master showed in the next figure through soft-lithographic process with height of photo-resist of 40 micron.







At optical microscope it is possible to see the results obtained with photo-lithographic process



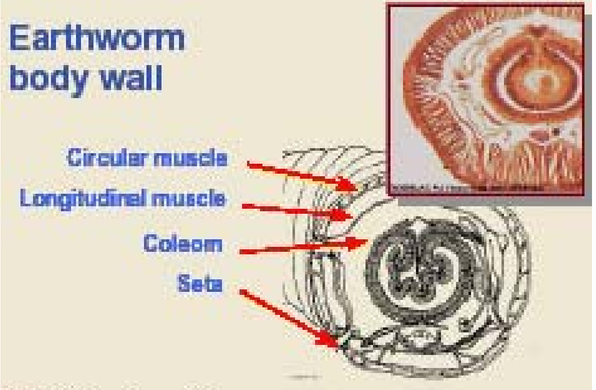
Propulsion mechanisms:
- locomotion mechanisms
- adhesion mechanisms

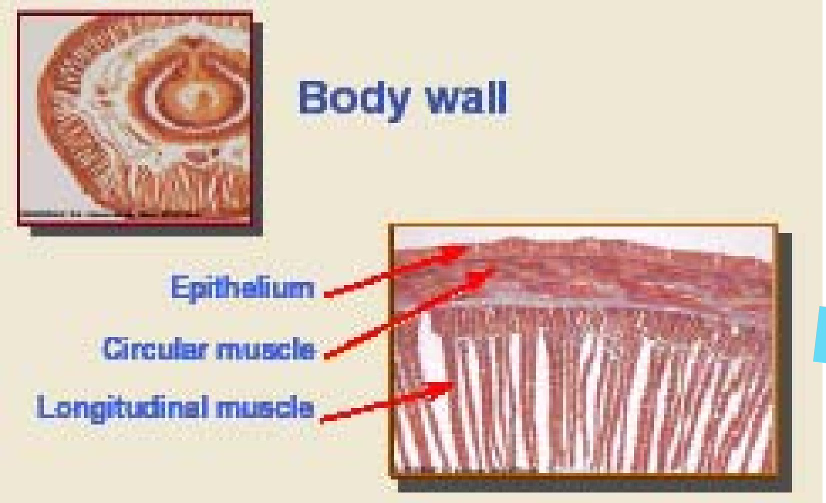
Undulatory locomotion:
the oligochaete annelids

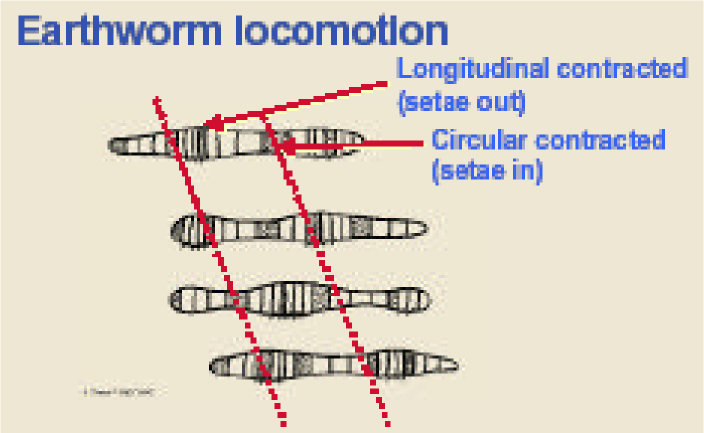
Oligochaete Annelids: peristaltic locomotion

Oligochaete use peristaltic locomotion to crawl (or burrow) on many kinds of soil

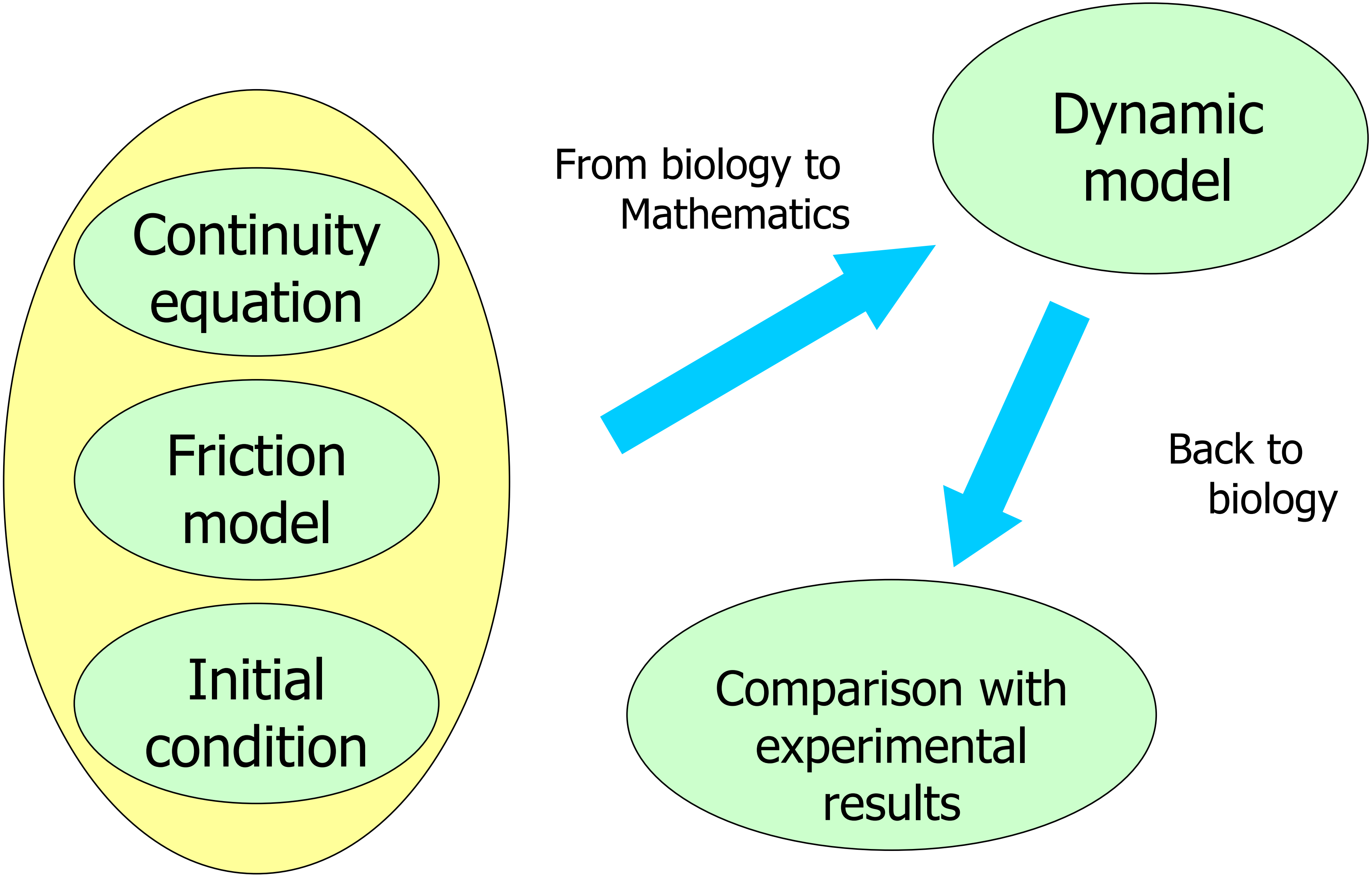
- Propulsion is generated by alternated longitudinal and circular contractions (waves flowing from the head to the tail)
- Setae come out during longitudinal contraction and come in during circumferential contraction
- The circumferential contraction generates a pressure wave in the celomic liquid


Earthworm body wall


Body wall


Earthworm locomotion

Model for peristaltic locomotion (*Lumbr. terr.)*



Continuity equation

Friction model

Initial condition

From biology to Mathematics

Dynamic model

Back to biology

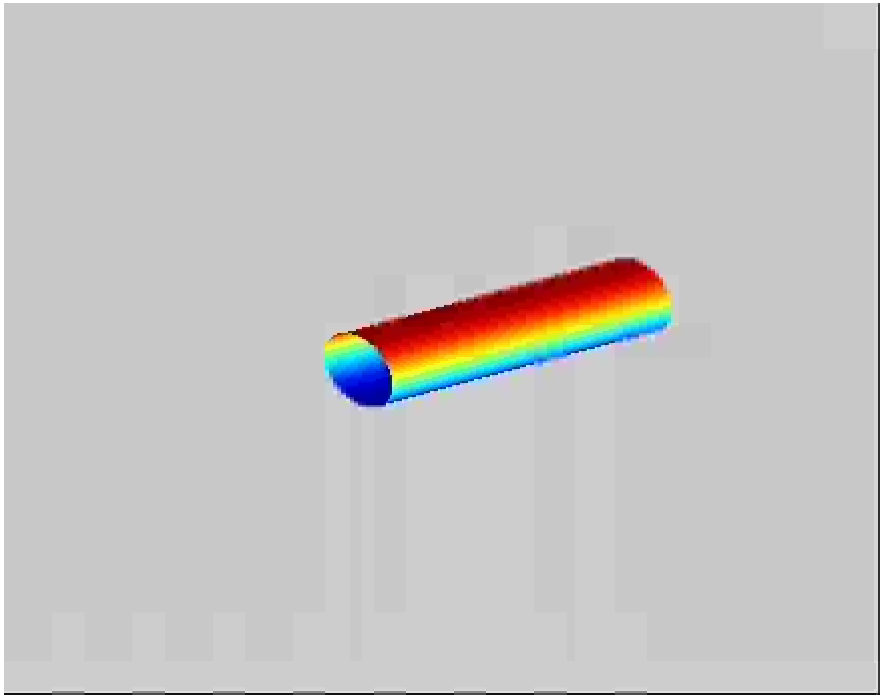
Comparison with experimental results

Model for peristaltic locomotion (*Lumbr. terr.)*

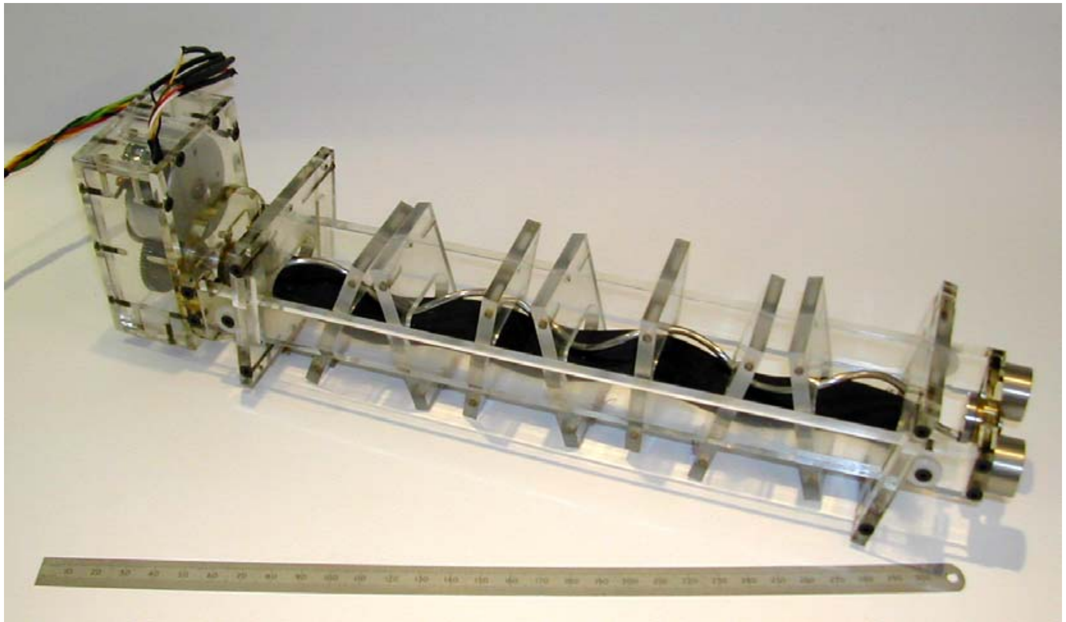
Dynamic model

$$\dot{v}_A(t) = \ddot{\Delta}(0,t) - \frac{g}{\Psi}\int_0^L \mu(x,t)\, r_0^2(x)\; sgn[v_A(t) + \dot{\Delta}(x,t) - \dot{\Delta}(0,t)]\, dx$$

$$v_A(0) = 0$$

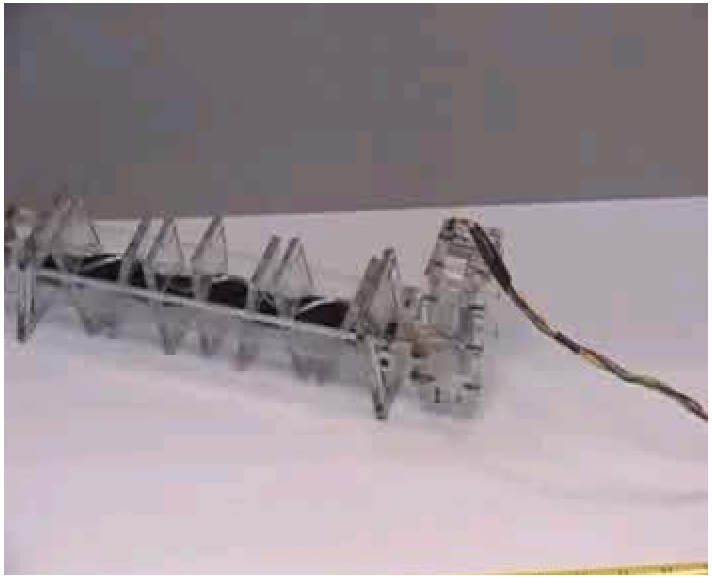


Polychaete Inspired Model



- Above is an initial model inspired by the undulatory locomotion displayed by the nereid polychaete.
- The mechanism relies on a rotating wire helix driving slotted paddles connected together along a flexible strap.
- This model has been demonstrated to move both forwards and reverse.

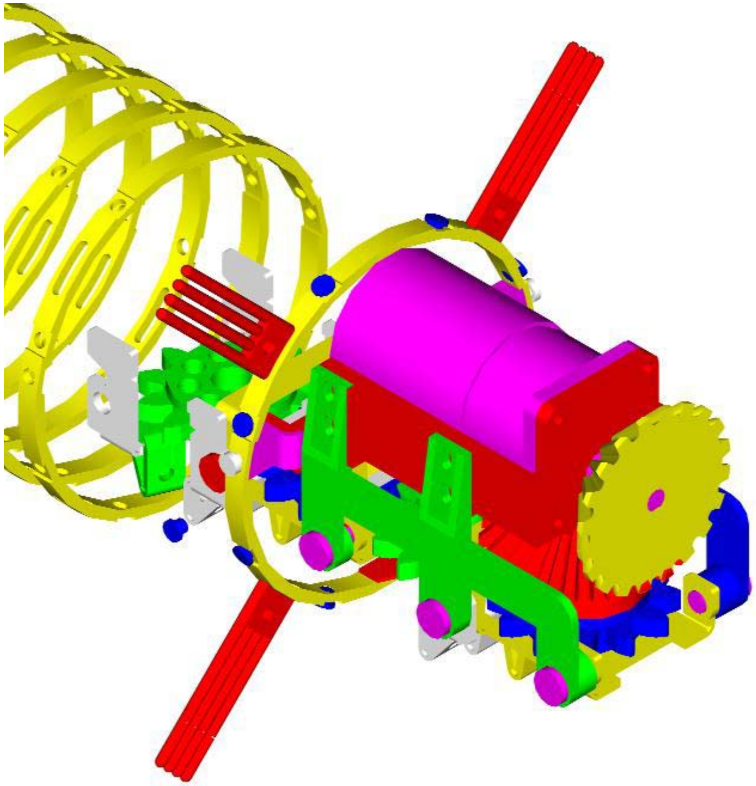
Model and simulation of the *polychaete* locomotion mechanism



Many DOFs and redundancy BUT implementation with single actuator (pattern generator)

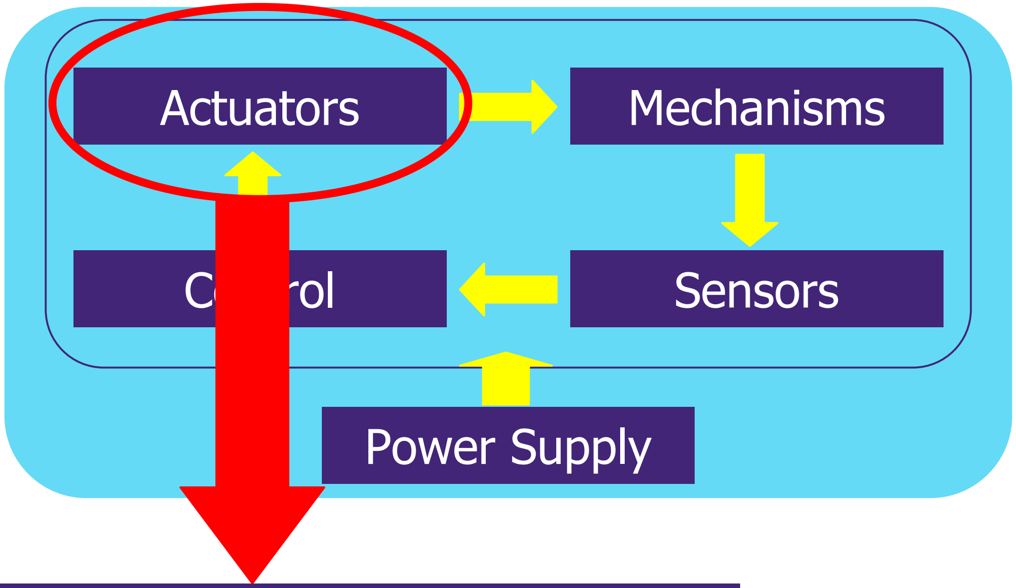
J. Vincent et al., Bath University (2002)

Driving mechanism



- Rotary movements have been chosen in the models as conventional actuators (micro / gearmotor) can be used in the development and testing of appropriate locomotion principles

- The figure shows the connection of a gear motor to the gear train through bevel gears

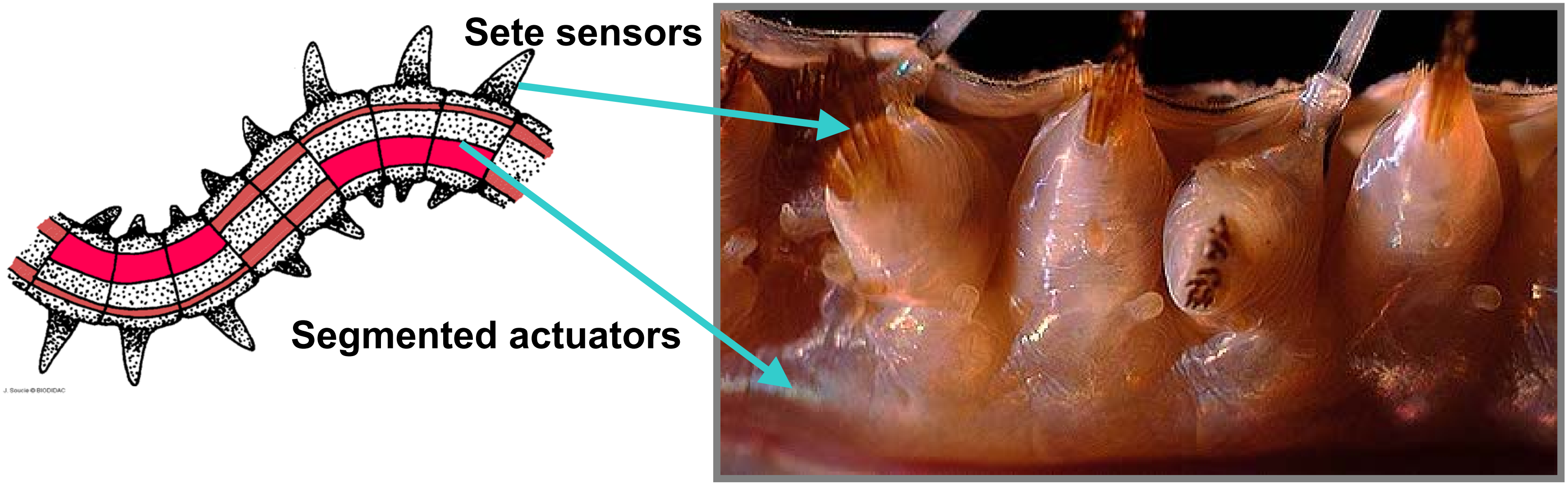


-Biomimetic actuators
    - electromagnetic motors
    - EAP
    - electrochemical
    - SMA

Enabling technologies

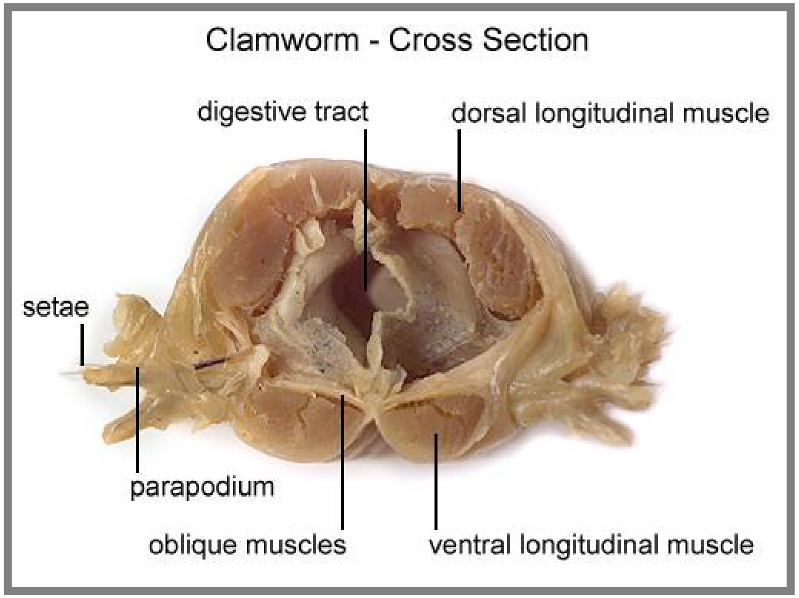
Actuators

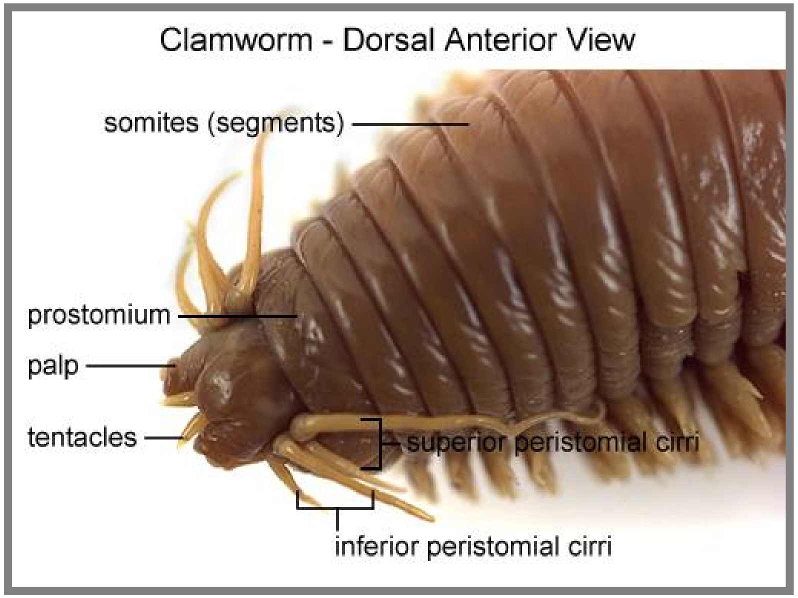
Undulatory locomotion: dedicated sensors and actuators



Sete sensors

Segmented actuators


Clamworm - Cross Section


Clamworm - Dorsal Anterior View

Biomimetic actuators

Electro-active polymers (EAP)

Our research on EAP and on EAP-based systems is presently moving towards two main directions:

- material-oriented;

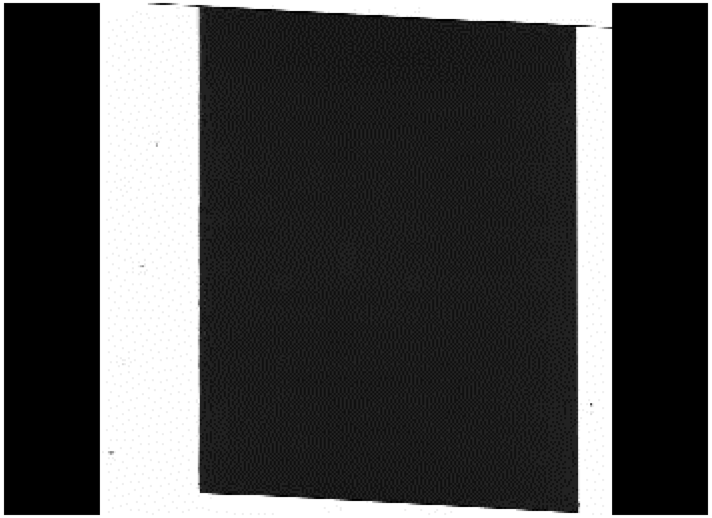
  to push actuator performances to their upper bounds

- system-oriented;

  to obtain truly biomimetic bio-inspired_systems

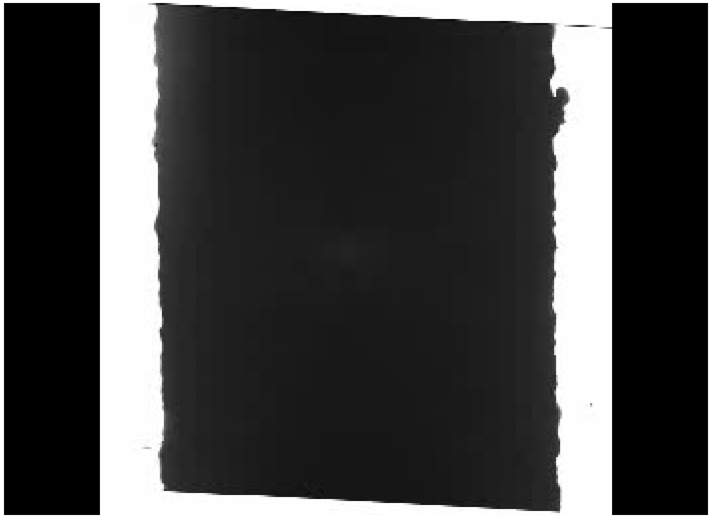
Material side: conducting polymers

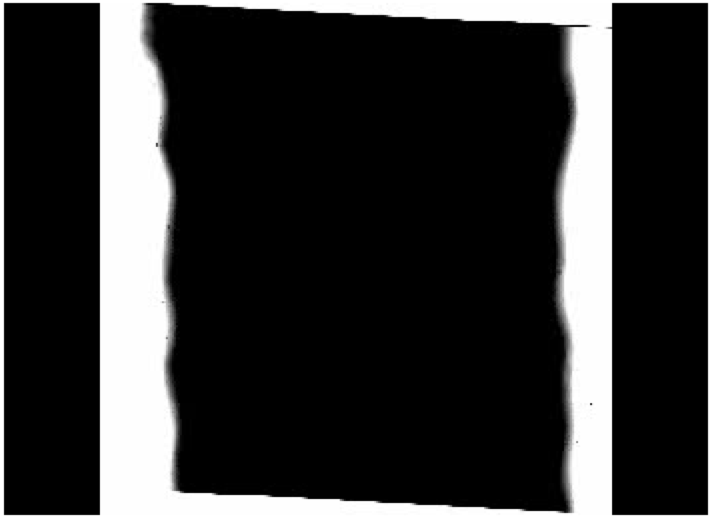
According to the calculated results we found that with this radial strain it is possible to reach axial strains of different magnitude, ranging from 25% up to 80%, depending on the inclination angle of the manufactured mesh



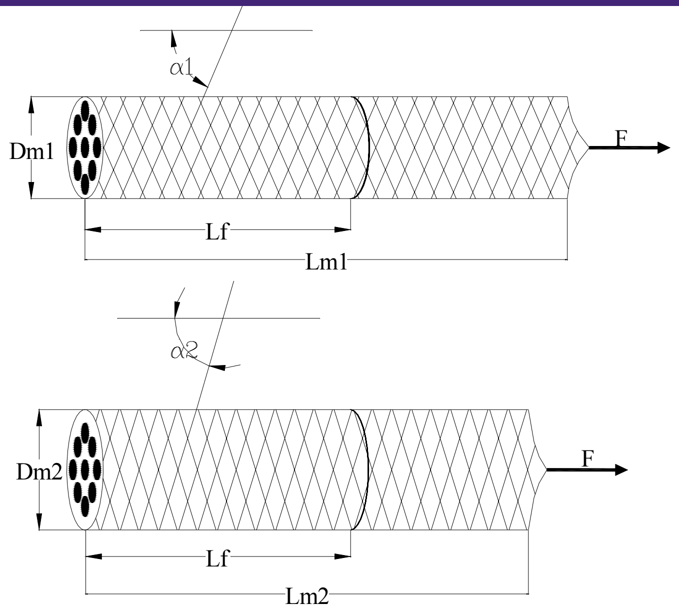
This is the bare steel wire where the polymer has been grown

These videos show two cycles of variation of the radial dimension of the electro-active polymers





System side: radial to axial conversion



L_f shows the initial and final length of the internal actuating fiber.

F is the load applied on the mesh.

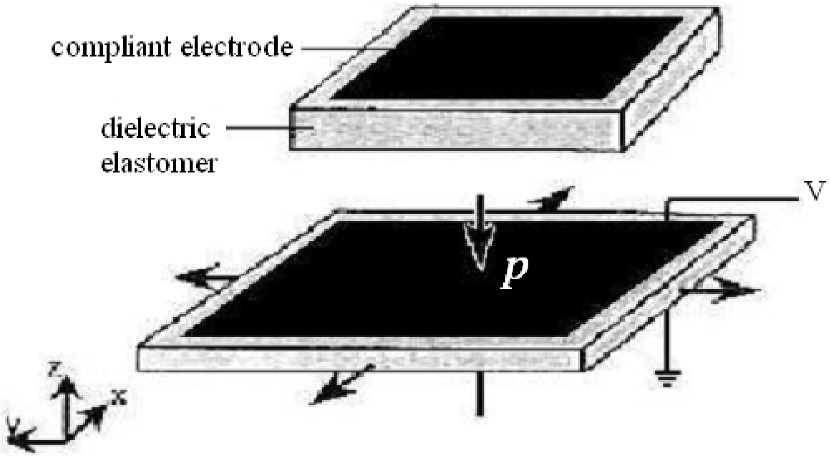
- The radial to longitudinal conversion is in principle not only possible but it can also result in an amplification effect.

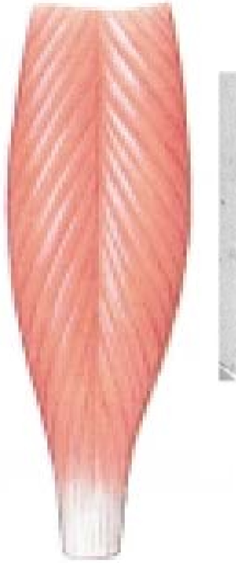
- The gain factor depends on the maximum inclination angle that the manufactured mesh allows; the higher is that angle, the higher is the gain.

- The upper bound is reached only when this angle equals 90°, an evidently ideal value that corresponds to a completely collapsed mesh having horizontal threads.

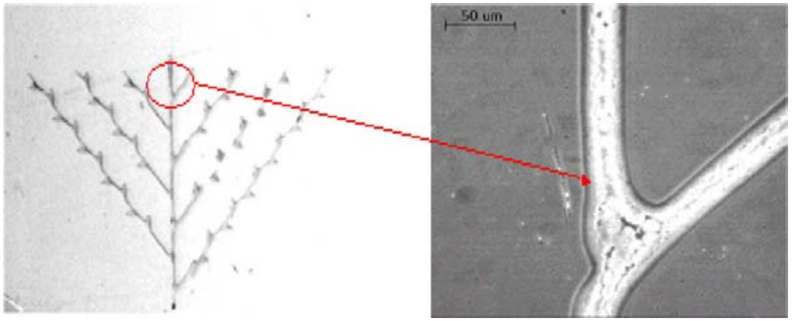
Bioinspired microfabricated structures

Dielectric elastomer actuator:





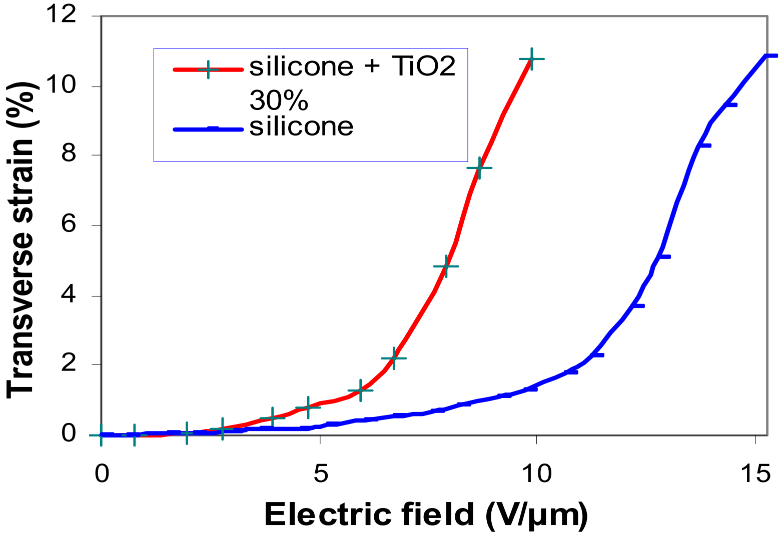
Bipennatus



Aim: high electrostatic pressures *p* with low driving voltages *V* by improving the relative dielectric constant ε_r :

$$p = \varepsilon_0 \varepsilon_r \left(\frac{V}{d} \right)^2$$

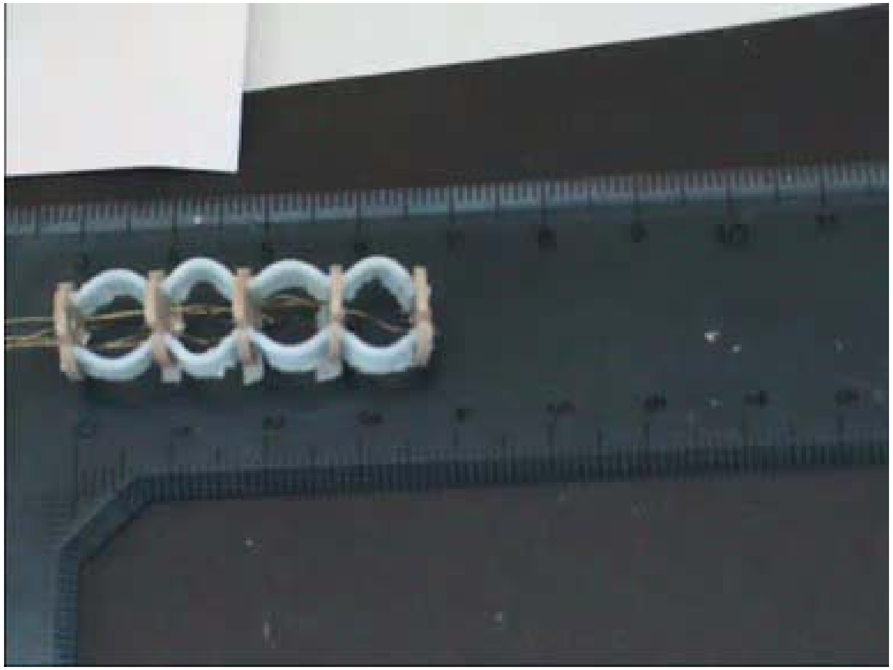
Method: high ε_r compound materials:
dielectric elastomer +
high ε_r inorganic powders
(e.g. TiO_2, PMN, PZT…)



A SMA actuated prototype

Modular structure

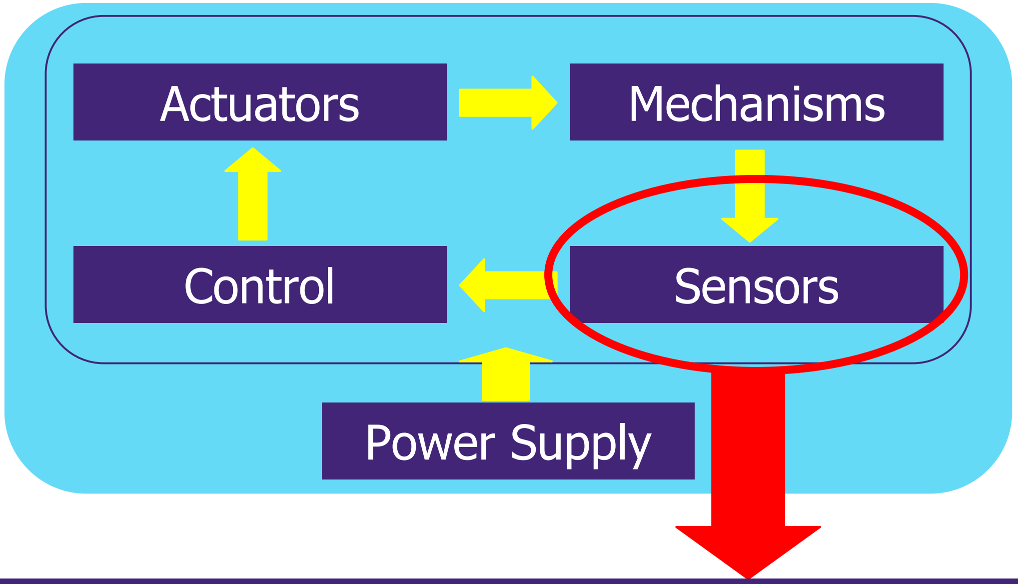
- 4 segments with 5 peek disks (diameter 10 mm) and 4 sets of silicone strips acting as returning springs
- a single SMA spring with a wire diameter of 50 mm (medium diameter of the spring: 350 mm)
- 5 sets of polyurethane feet



Control

- *the SMA spring part between two consecutive disks is autonomously activated*
- *to better simulate the peristaltic locomotion a time overlap between the activation of two adjacent segments has been implemented*
- *peak power supplied: 1.35 W*

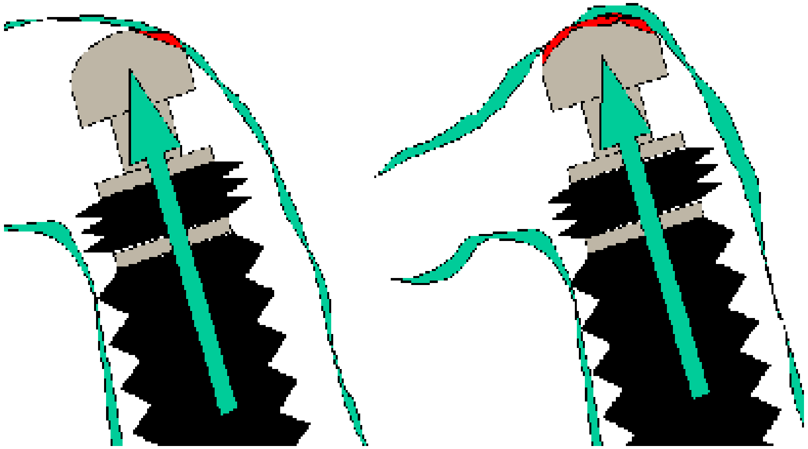
BIOLOCH

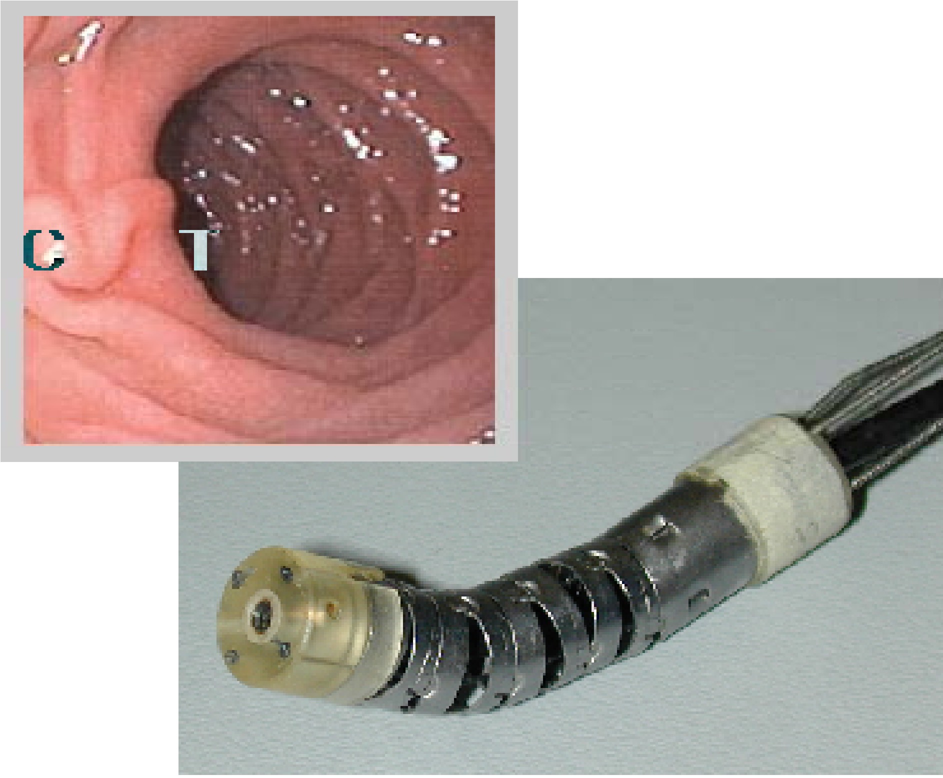


- Analysis of functional morphology of polychaete sensors
- Possible preliminary implementation of *Condylura cristata* sensing system

Enabling technologies
Sensors

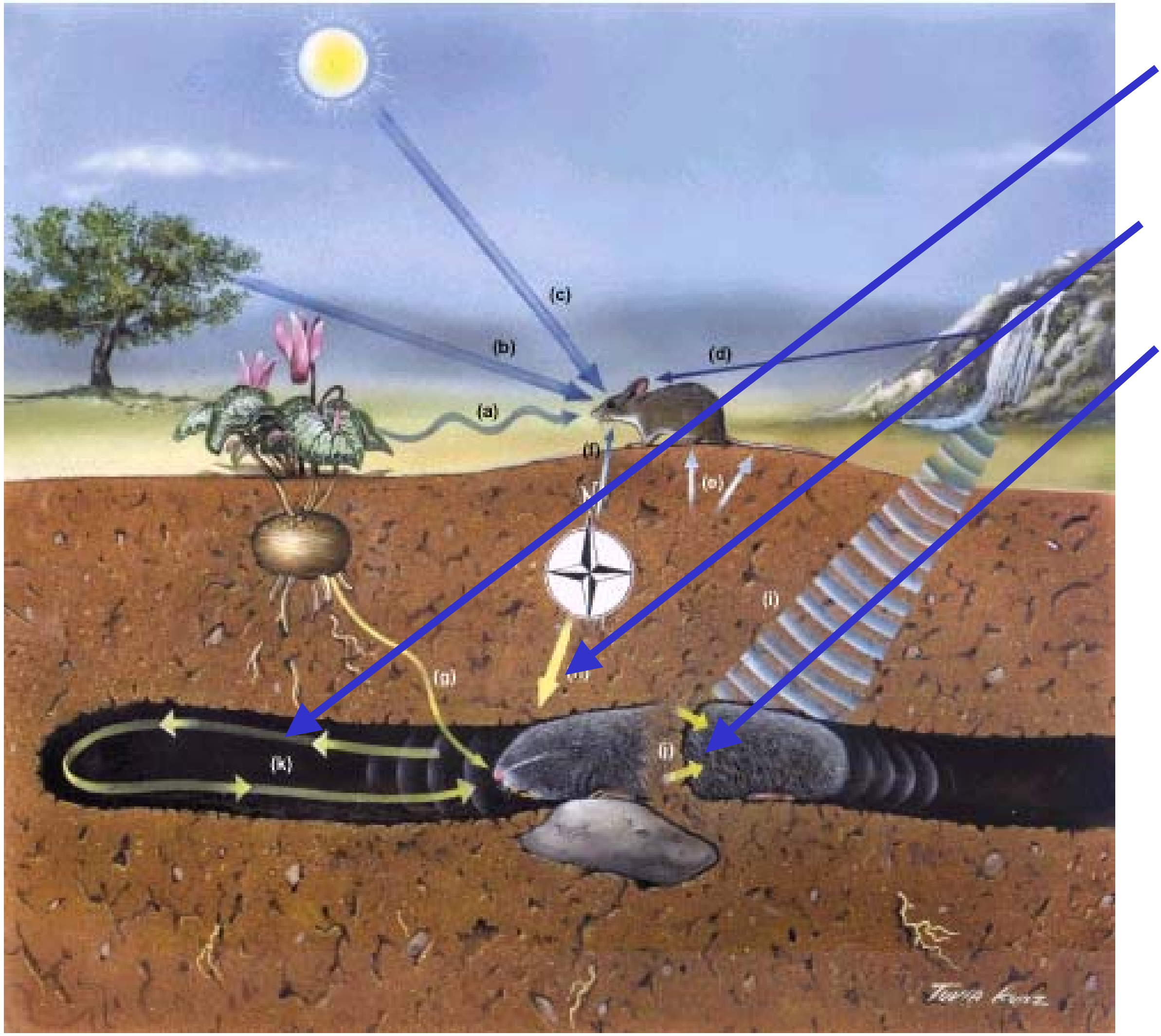
Vision Guided Locomotion





An on-board image processor discerns the intestine lumen (T) from collision point (C) and the steering tip points automatically to the direction of lumen, thus avoiding ramming collisions

Borrowing sensing systems from creatures able to propel in “difficult” environments: the mole



Sensors for perception of propelled air

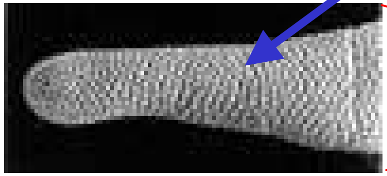
Geomagnetic sensors

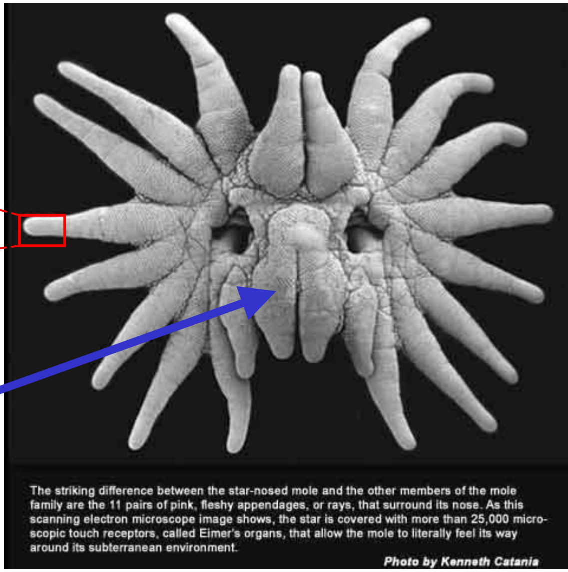
Somatosensory cues (e.g. snout with Eimer’s organs)

T. Kimchi and Joseph Terkel, Seeing and not seeing, Neurobiology of behaviour, 2002

The “visual-tactile” frontal sensor system of the Star Nosed Mole (Condylura cristata)

>25000 tactile receptors (Eimer’s Organs) on the 12 appendages

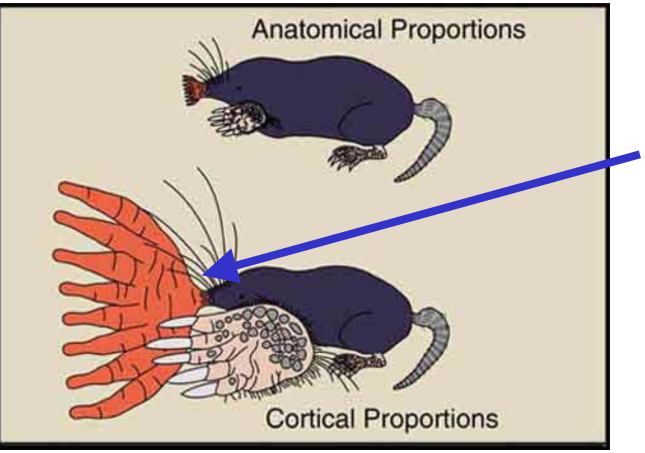




The striking difference between the star-nosed mole and the other members of the mole family are the 11 pairs of pink, fleshy appendages, or rays, that surround its nose. As this scanning electron microscope image shows, the star is covered with more than 25,000 microscopic touch receptors, called Eimer’s organs, that allow the mole to literally feel its way around its subterranean environment.

Photo by Kenneth Catania

Higher sensitivity of the 2 central appendages (“foveated” tactile system): larger brain cortex area occupation

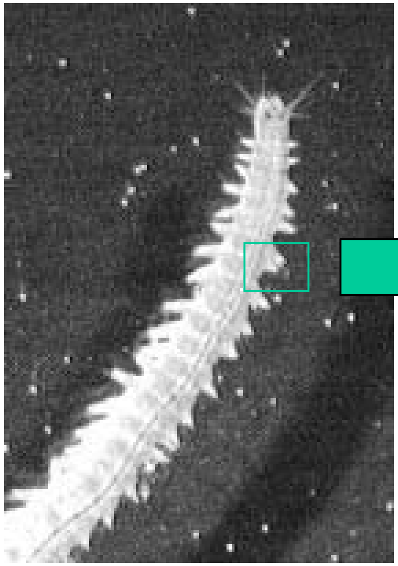


Kenneth C. Catania, Vanderbilt University, Scientific American, August 2002

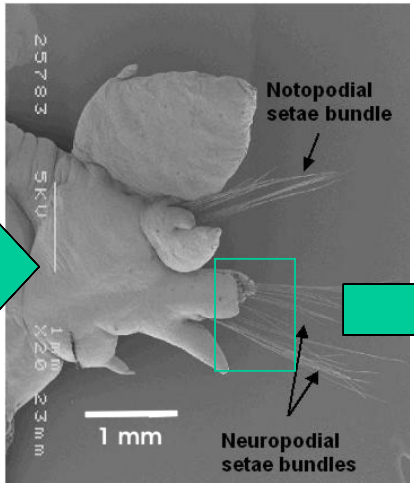
Continuous rapid movements of the appendages (fast exploration) and subsequent “focalization”: the object is put in contact with the two central and more sensitive shorter appendages

Sensory modalities found in the body region of Nereidae

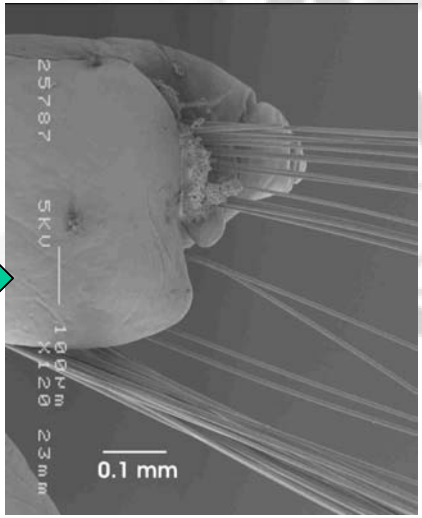
- Mechanoreceptors (mainly touch) – Sensory cells in body wall all along the body, parapodial cirri, setae
- Chemoreceptors – Parapodial cirri
- Proprioceptors – Parapodial cirri, sensory cells near longitudinal and parapodial muscles



Dorsal view



Front view

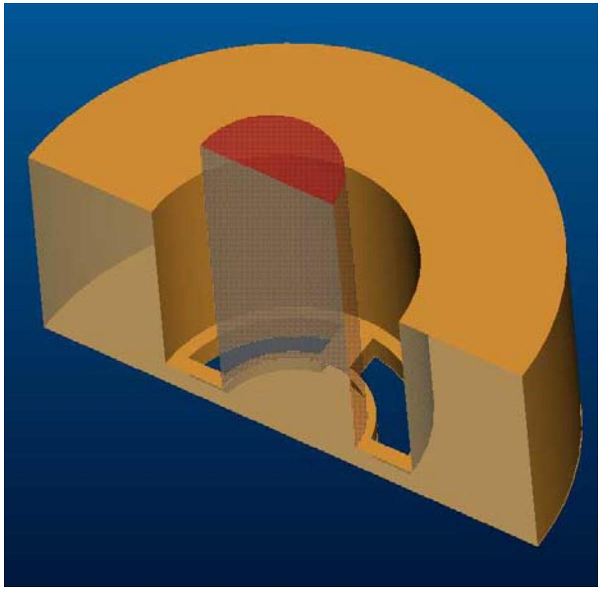


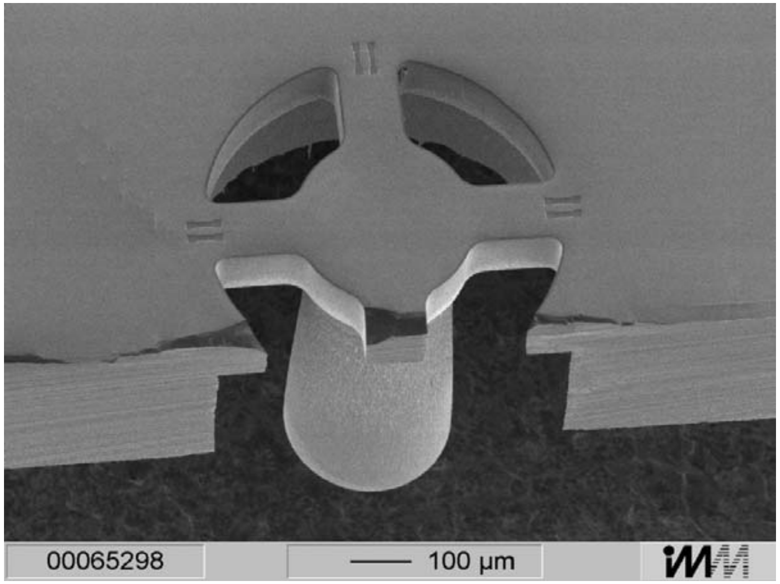
Front view

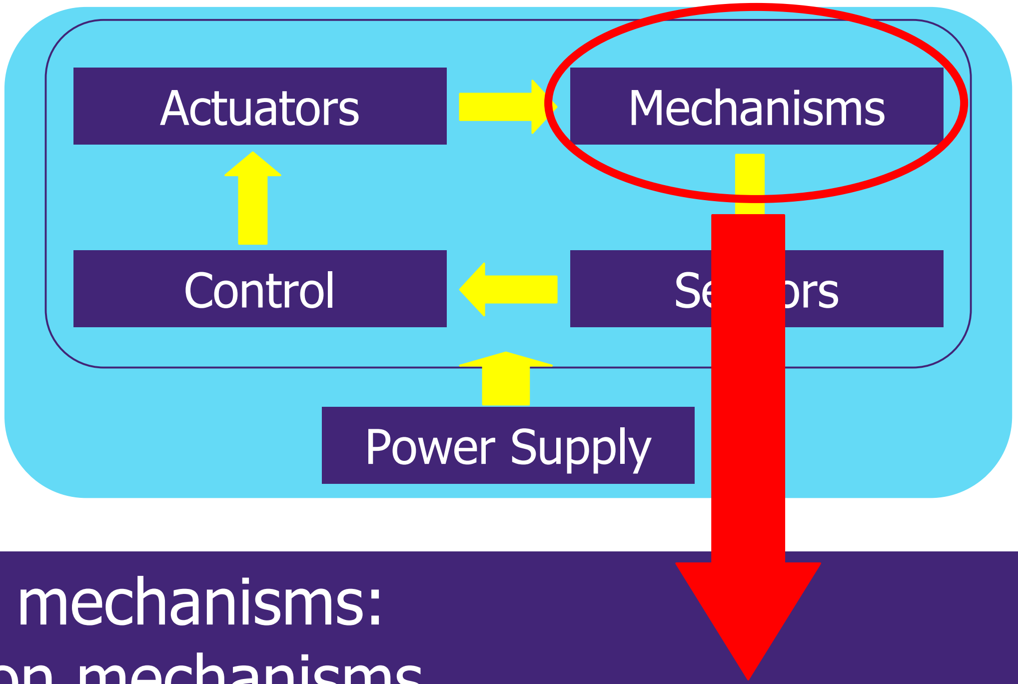
Sensorised hair: a possible solution

Sensor currently under development at SSSA:

- silicon-based three axial tactile sensor;
- based on piezoresistive transduction from piezoresistors in the suspended silicon membrane;
- dimension: 2 *x* 2 *x* 1 mm^3.







Actuators

Mechanisms

Control

Se ors

Power Supply

Propulsion mechanisms:
- locomotion mechanisms
- adhesion mechanisms

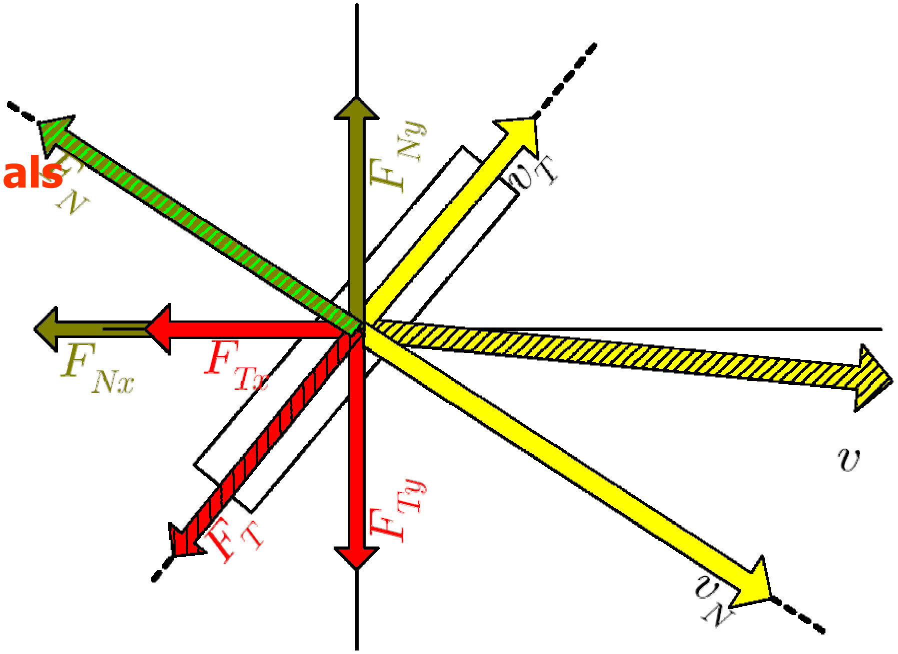
Undulatory locomotion: *the polychaete annelids*

Polychaete Annelids

- **Marine worms, members of the Annelida phylum**
- **Body consists of a large number of segments**
- **Length varies from 1mm to over 3m**
- **Have many setae, extending from lateral appendages called parapodia:**
    - **Multipurpose structures, employed in swimming, crawling, digging and breathing**
    - **Equipped with sense organs (touch receptors)**
    - **Exist in pairs per body segment**
- **Variety of habitat and locomotory behaviour**
- **Characterised as either sedentary or errant**

Undulatory locomotion of elongate animals

- **Taylor developed a theory for the undulatory swimming of elongate animals**
- **Decoupled forces are considered in the tangential and normal direction of segment movement**



Resistive Force Model

- **Viscous Friction**
  - **Force is taken proportional to the respective velocity component**

$$F_N = -c_N u_N$$
$$F_T = -c_T u_T$$

- **Fluid Drag**
  - **Force is taken proportional to the square of the velocity**

$$F_N = -\lambda_N u_N^2 \operatorname{sgn}(u_N)$$
$$F_T = -\lambda_T u_T^2 \operatorname{sgn}(u_T)$$

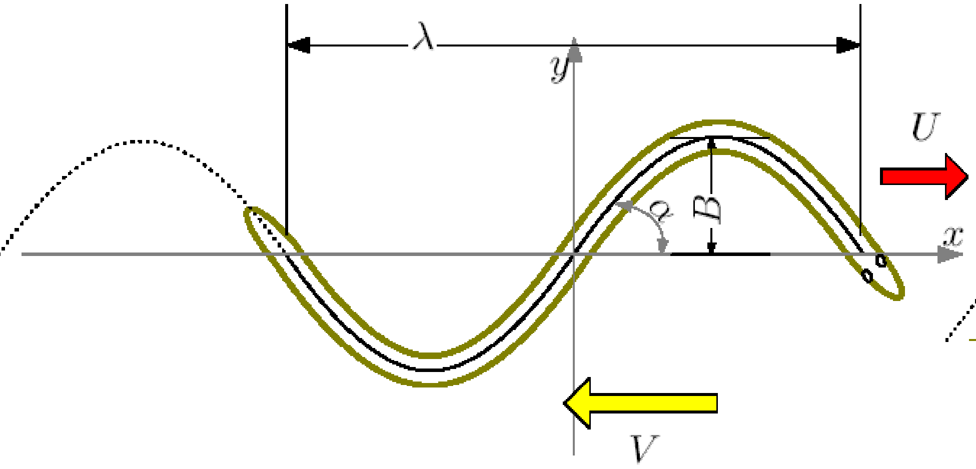
- **Coulomb Friction**
  - **Force follows the Coulomb friction law**

$$F_N = -\mu_N mg \operatorname{sgn}(u_N)$$
$$F_T = -\mu_T mg \operatorname{sgn}(u_T)$$

Undulatory locomotion of elongate animals

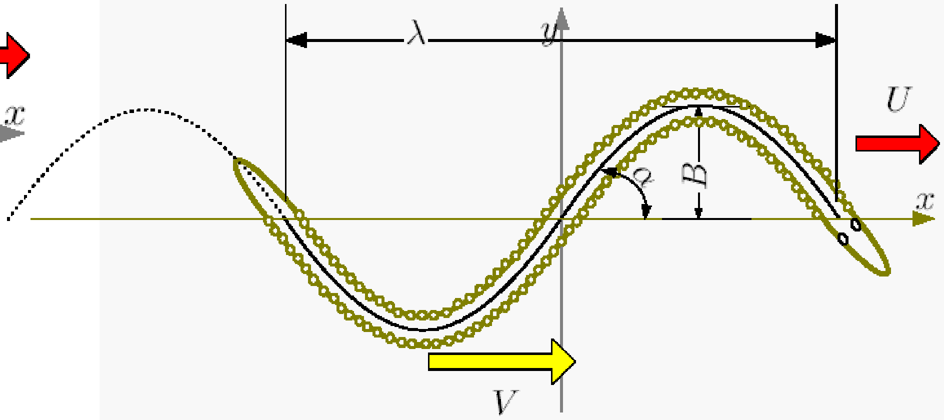
SMOOTH BODY

- For animals with a smooth body (example: eel) c_T is very small
- Forward movement is achieved by propulsive waves moving to the posterior of the body
- Backwards movement or braking is by reversing the direction of the wave

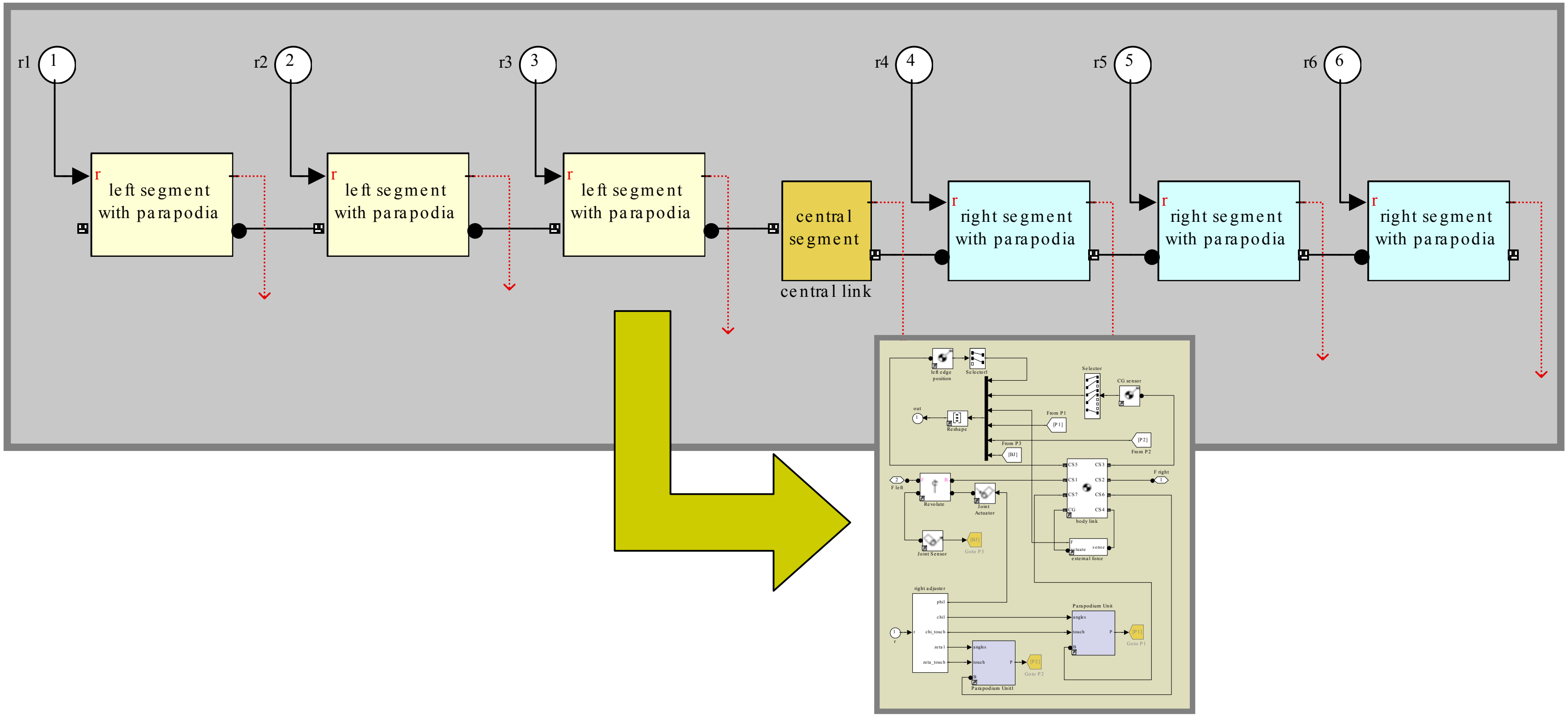


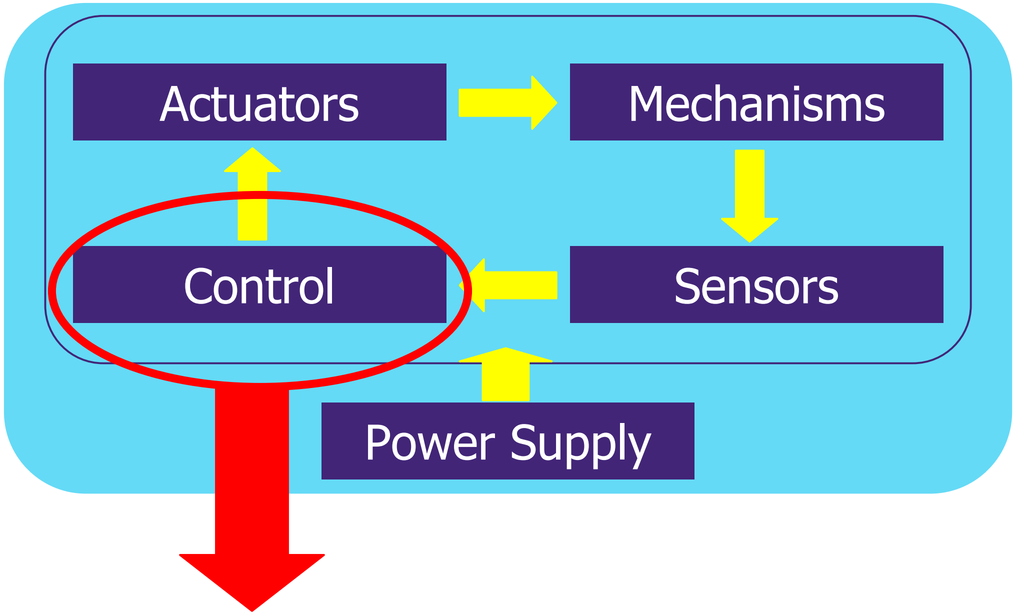
ROUGH BODY

- Roughness elements on the body generate greater tangential forces, i.e. $c_T > c_N$
- Forward movement is achieved by propulsive waves moving to the anterior of the body
- Encountered among polychaete (medium Re), as well as certain protozoan and flagellates (low Re)



Matlab/SimMechanics environment





Actuators

Mechanisms

Control

Sensors

Power Supply

Control and gaits (for polychaete locomotion)
- Open loop and closed loop control
- Sensor based control
- Neural control

Open-loop Control

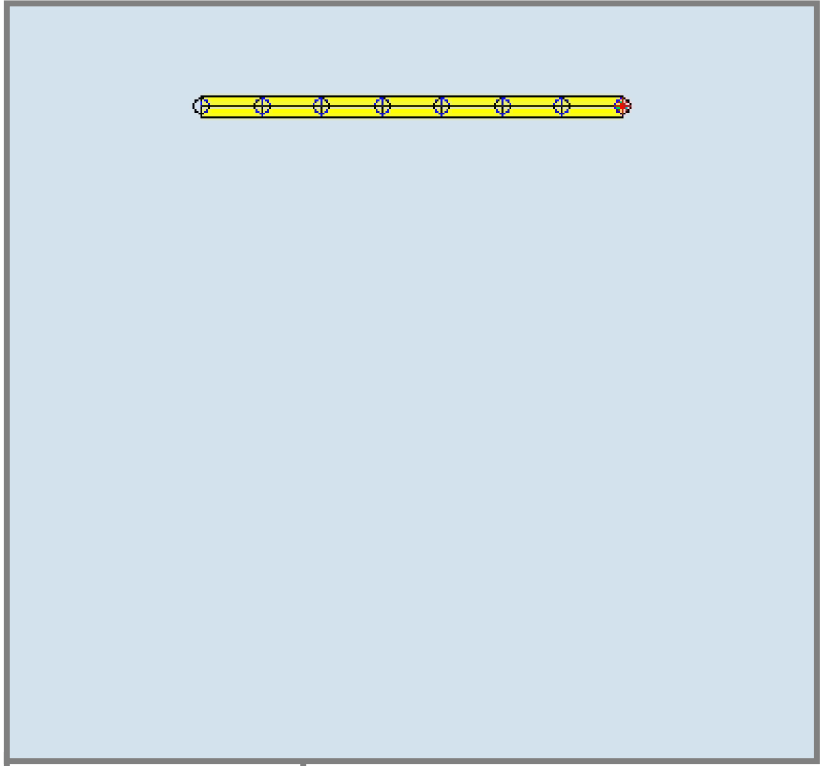
Open-loop control: Turning Gait

Joint angle control:

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

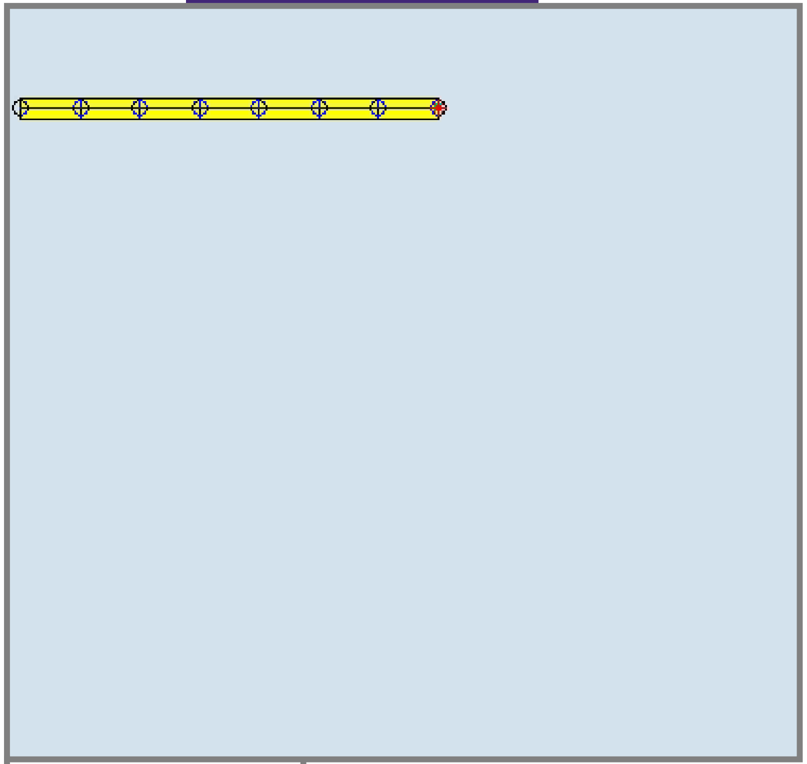
$$m = 1,\ldots,7.$$

Smooth Body



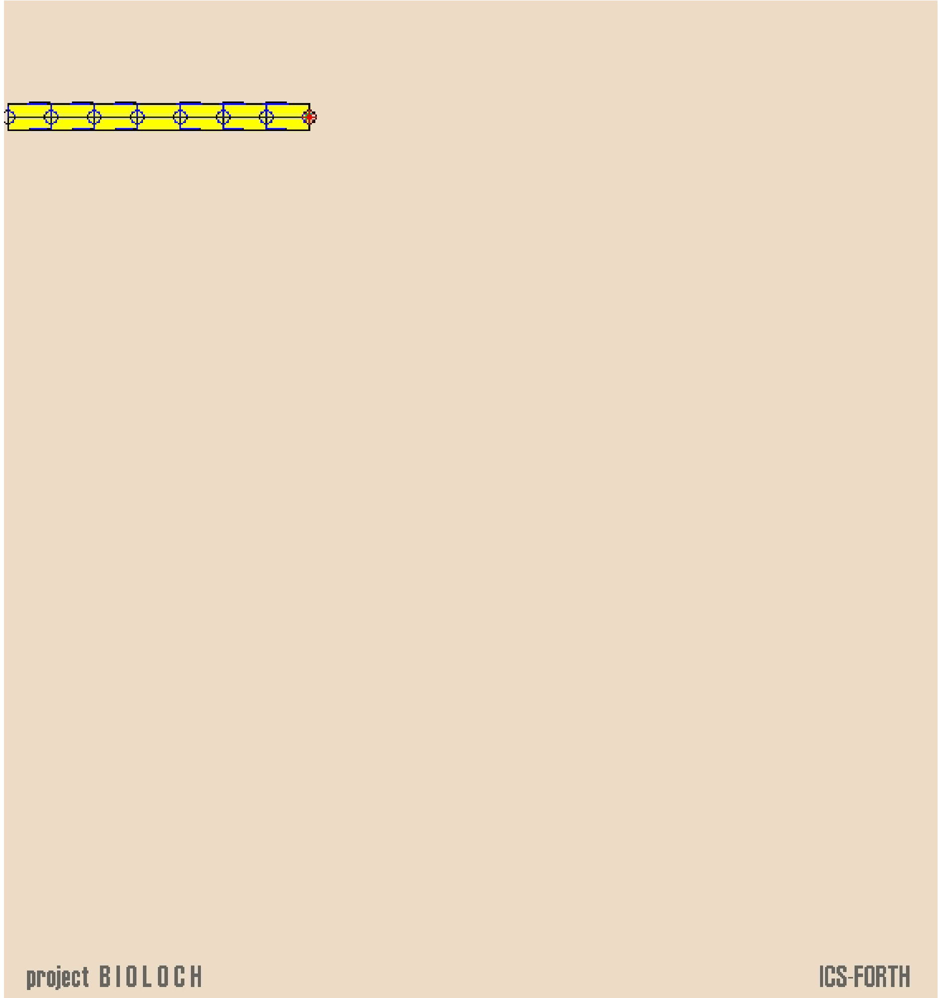
$c_N = 10 \quad c_T = 1$

Rough Body



$c_N = 1 \quad c_T = 10$

Gaits with parapodial movements

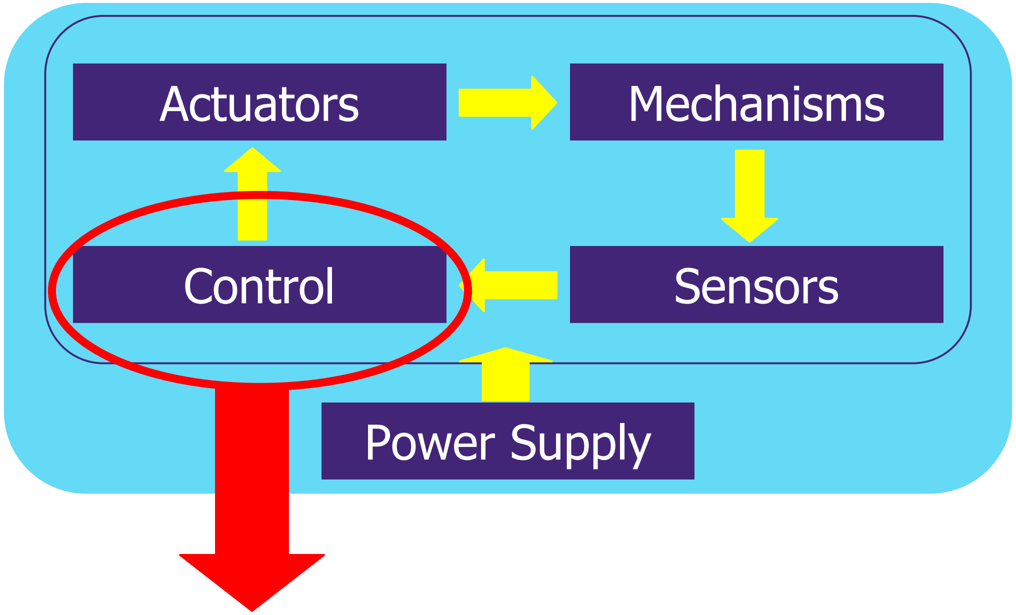


PARAPODIAL FORCES

- **Quadratic force can model (with limitations) the rowing action of parapodia in a fluid medium**
- **Coulomb friction can be used when interacting with solid environment**
  - Coupled to a ground contact detection scheme
  - Depending on the assumed motion cycle, the recovery stroke does not necessarily generate (dragging) forces.

GAIT ENHANCEMENT

- **The parapodial appendages provide additional versatility for the undulatory mechanism.**
- **E.g. Turning Gait:**
  - Normally generated by introducing angle offset in the oscillation of the body joints.
  - Parapodia offer an alternative/complementary propulsion mechanism.



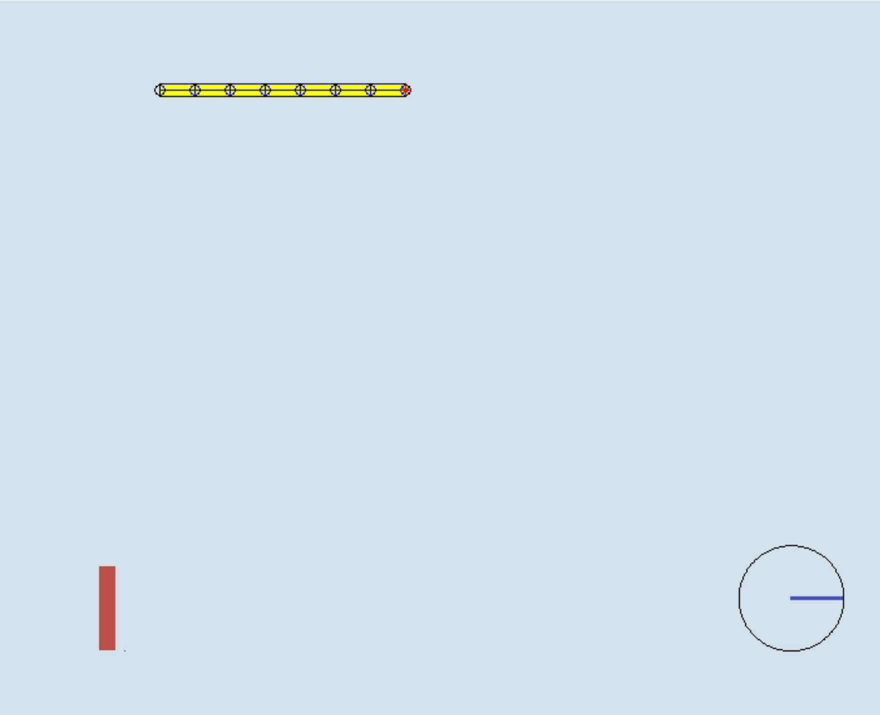
Control and gaits (for polychaete locomotion)
- Open loop and closed loop control
- Sensor based control
- Neural control

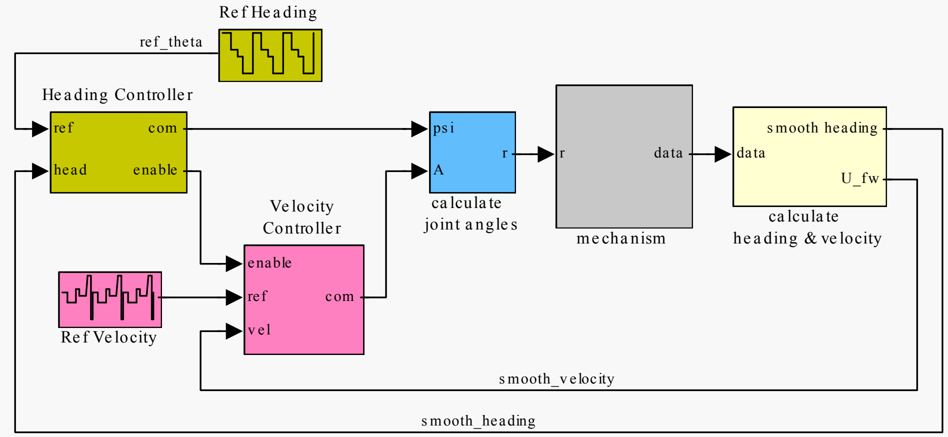
Closed-loop Control

Closed-loop control

Joint angle control:

$$\phi_m(t) = A(t)\sin\left(2\pi f t + m\frac{2\pi}{N}\right) + \psi(t), \quad m = 1,\ldots,7$$

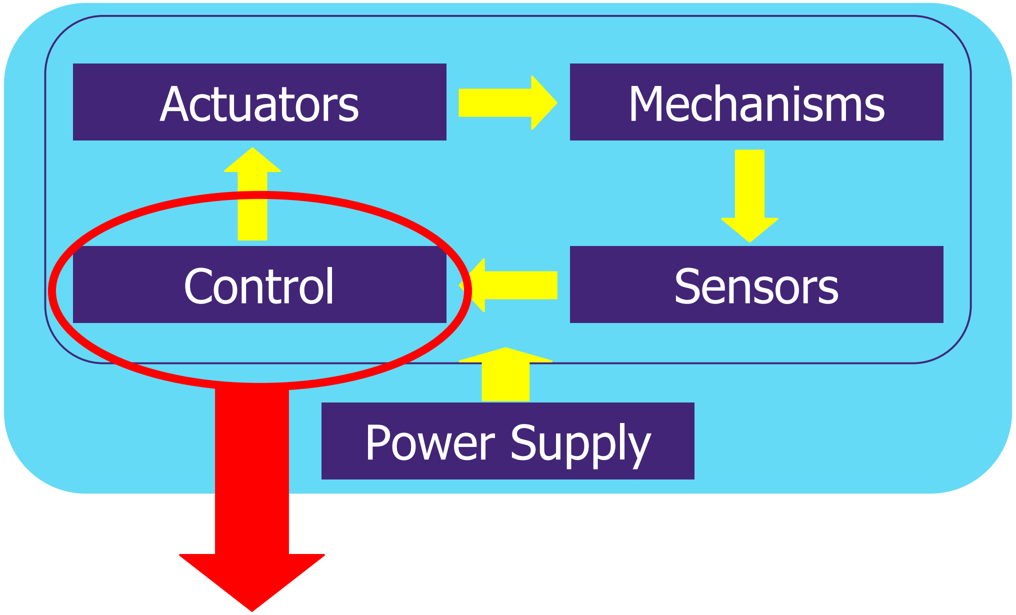




Heading speed and orientation controller

Closed-loop control of:
- **joint oscillation amplitude A (alters heading speed)**
- **joint angle phase lag ψ (alters orientation)**

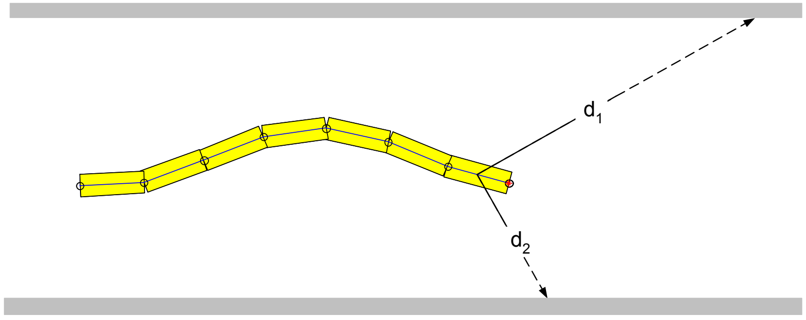
Decoupled controllers for A and ψ.
Structure for both controllers is PI(e) + D(y)
Orientation control has priority over heading speed control.



Control and gaits (for polychaete locomotion)
- Open loop and closed loop control
- Sensor based control
- Neural control

Sensor-based Control

Sensor-based control: Undulatory centering response

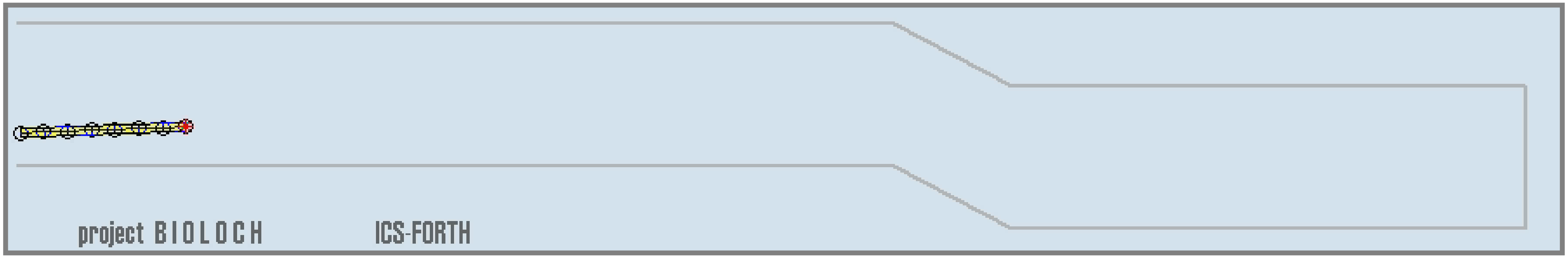


- Undulatory corridor-following
- Sensory data: distances of "head" link from walls

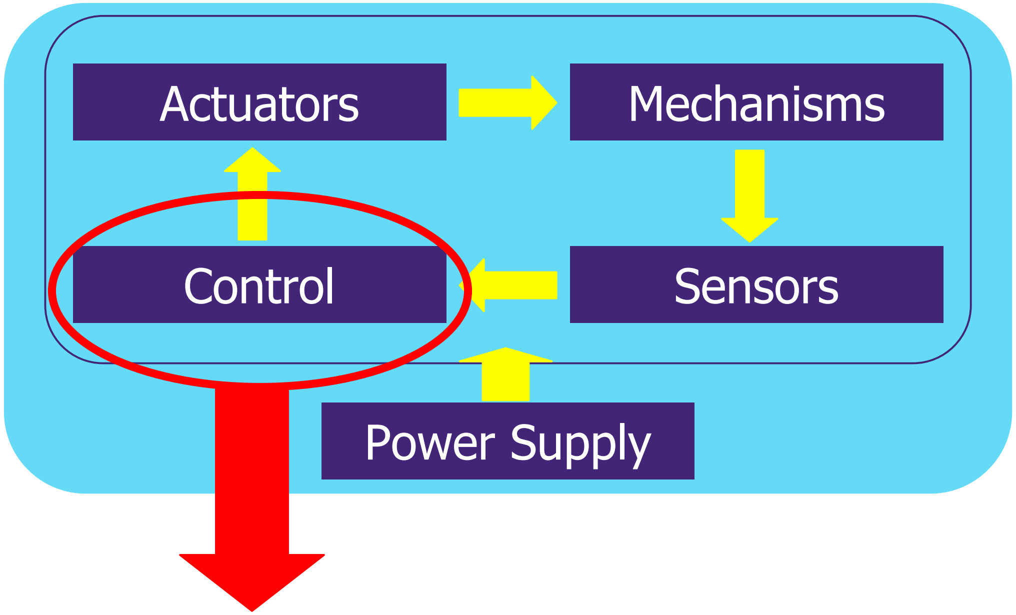
- Sensor-based joint angle control:

$$\varphi_m(t) = A\sin(2\pi\, f\; t + m\,\varphi_{lag}) - k\left(\frac{1}{d_{1,avg}(t)} - \frac{1}{d_{2,avg}(t)}\right)$$

where $k > 0,\ \ m = 0,\ldots,5 \text{ and } d_{i,avg}(t) \square \int_{t-T}^{t} d_i(\tau)\, d\tau\,.$



"Swimming" smooth-body polychaete model



Actuators

Mechanisms

Control

Sensors

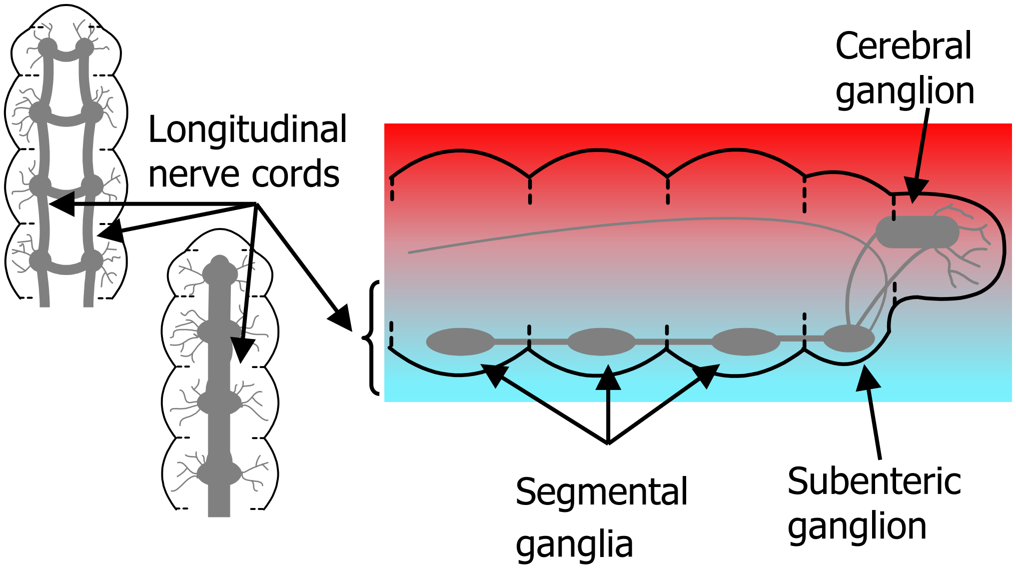
Power Supply

Control and gaits (for polychaete locomotion)
- Open loop and closed loop control
- Sensor based control
- Neural control

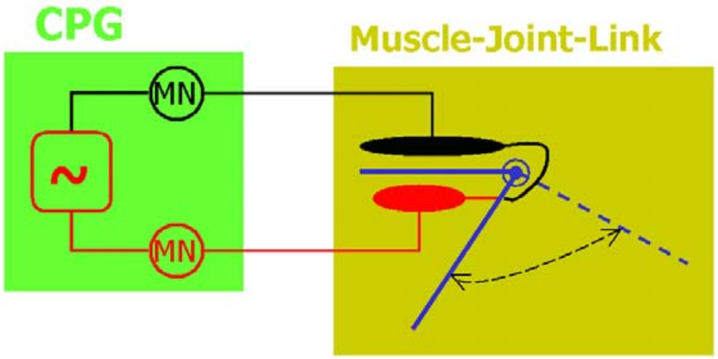
Neural Control

Polychaete Neural System

- The polychaete **neural system** exhibits a distributed organization.
- Nerves from the segmental ganglia innervate the muscles of adjacent segments.
- Evidence of **central pattern generators** exists in annelid locomotion (polychaete, leeches).
- *Giant fibers* bypass the ganglia and allow **rapid reflexes** to emerge.



Neural control: Motion control by CPGs



The CPG produces rhythmic activity, which is modulated by input from:

- **sensors and**
- **higher cognitive elements.**

This affects:

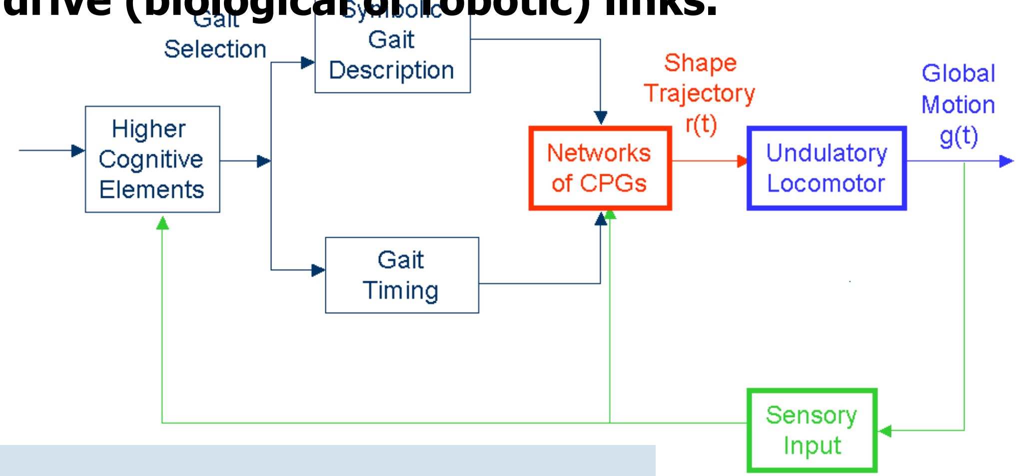
- **the frequency of oscillation and**
- **the phase between neurons.**

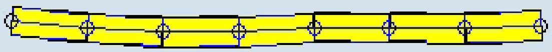
Central Pattern Generators are neural circuits able to produce rhythmic motor patterns, even in the absence of sensory input or input from higher cognitive elements.

(*E.g.* The CPG controlling lamprey swimming is located in its spinal cord.)

Rhythmic activity may emerge due to the (mutually inhibitory) connectivity of non-oscillating neurons.

Interneurons produce the oscillatory activity and drive motoneurons, which control the muscles that drive (biological or robotic) links.





Benchmarking with conventional endoscopic techniques

Description of force parameters of the colonic tract in interaction with endoscopic devices and techniques

Different experimental series have been performed to describe the interaction of tools and bowel.

Mesenteric resistance

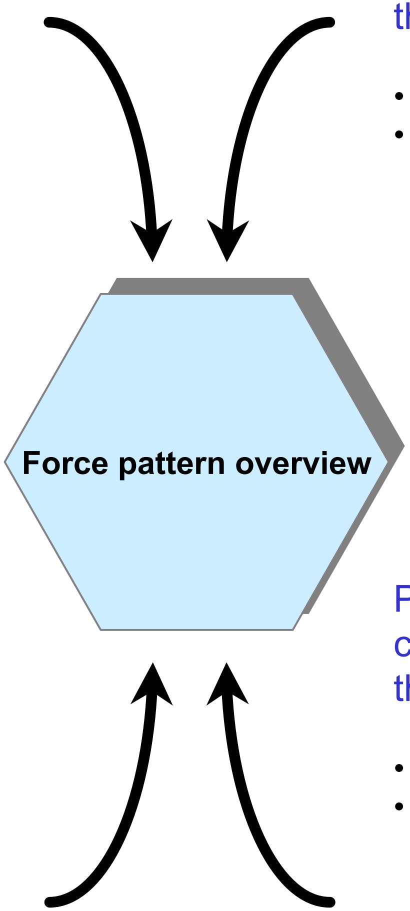
Mesenteric hazards:

- Tears
- Ruptures

Parameters for walking inside the colon

- Forces
- Wall elasiticity

Force / step ratio



Force pattern overview

Colonic wall resistance

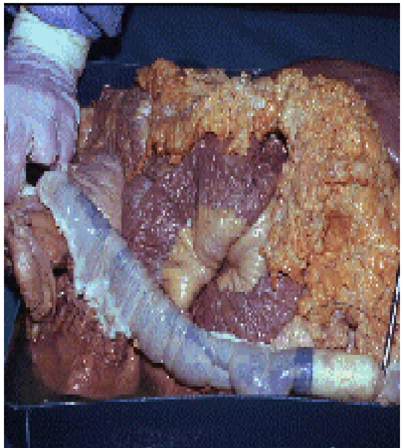
Colonic hazards

- Perforation

Paremeters for creeping inside the colon

- With tail
- Without tail

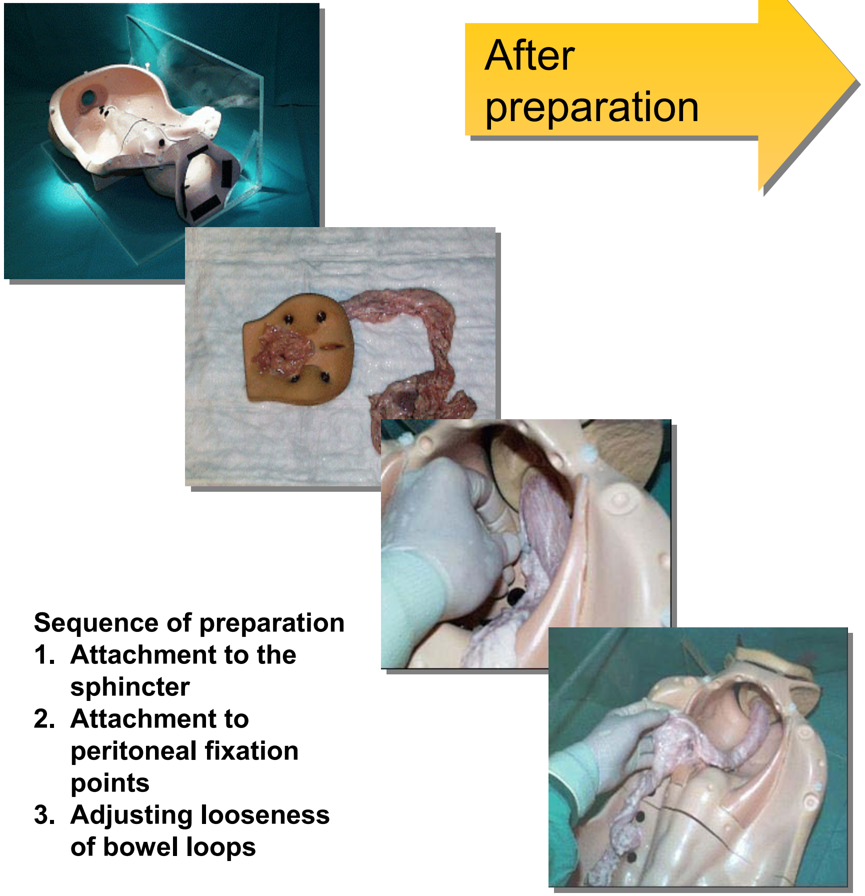
Device advancement forces



Creation of testbed modalities for qualitative studies

Realization of a biohybrid phantom model for assessment of locomotion systems

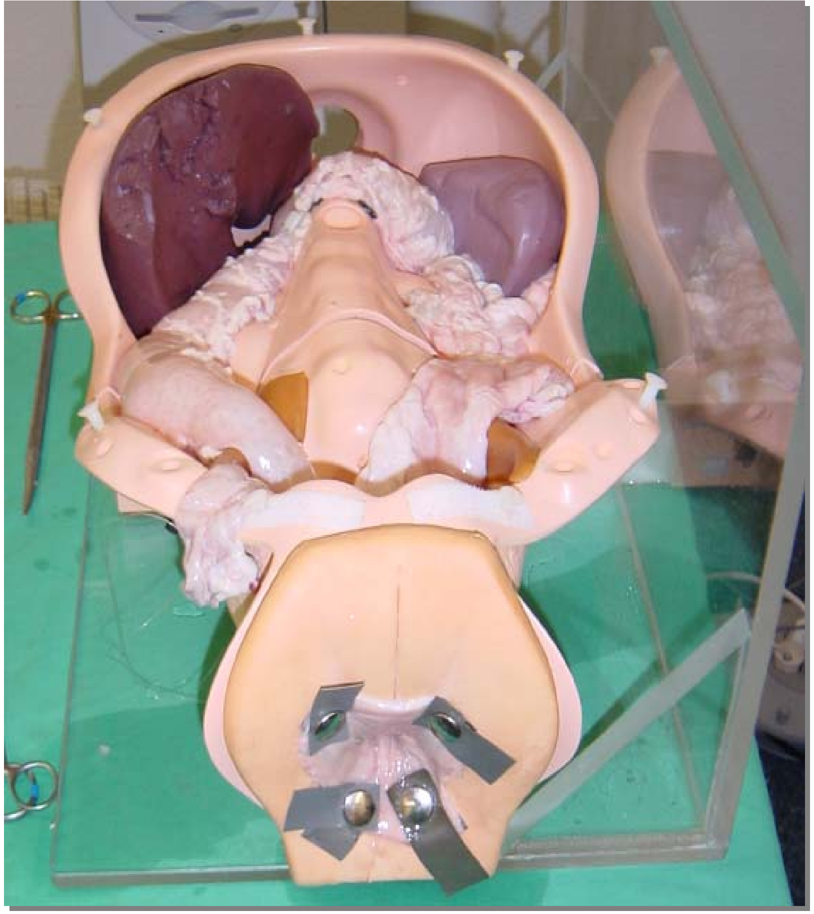
IHCI has developed a biohybrid phantom model which consists of a combination of plastic bodyform and specifically modified fresh animal tissue. The animal tissue (e.g., pig colon) is fixed in a humanoid geometry.



Sequence of preparation

1. **Attachment to the sphincter**
2. **Attachment to peritoneal fixation points**
3. **Adjusting looseness of bowel loops**

After preparation

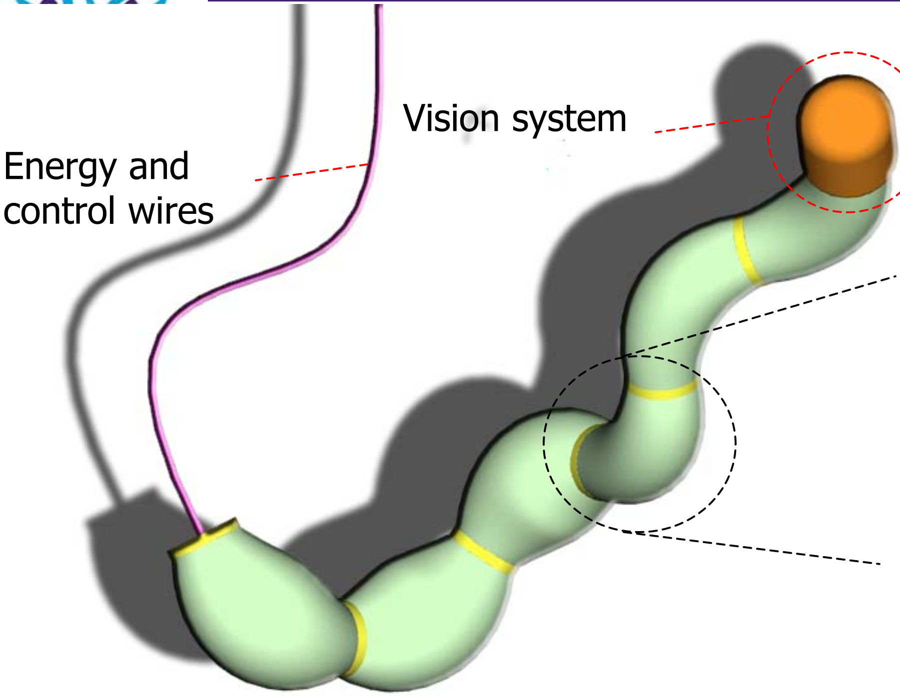


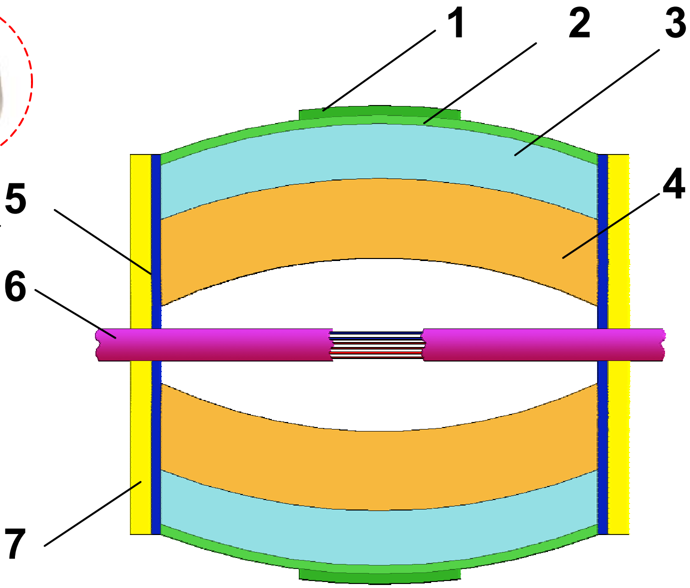
Biohybrid phantom model with fresh pig colon

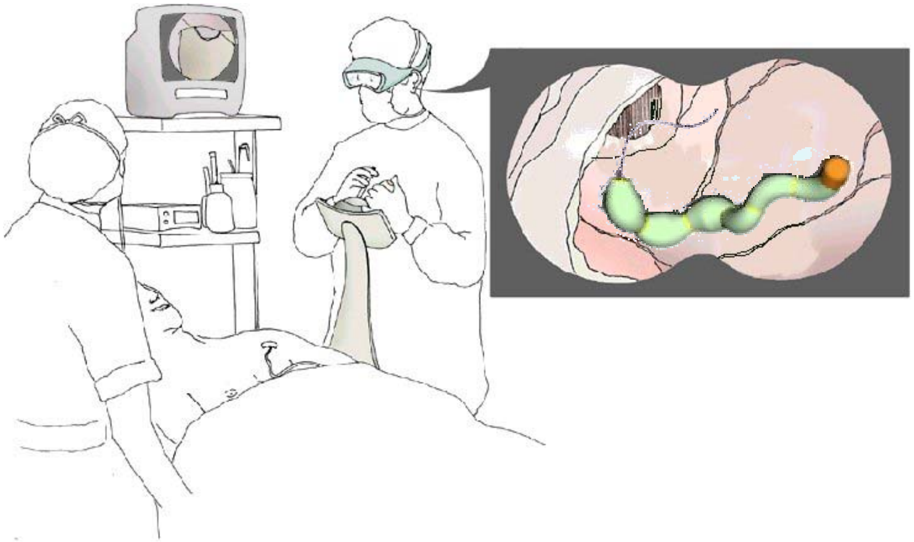
BIOLOCH

Conclusions
and Future Activities

Concept of biomimetic (annelids-like) device







1) Friction enhancement surface
2) Smart skin with embedded sensors
3) Silicone body
4) Actuator
5) Electric contacts for actuator powering
6) Energy and control wires
7) Electric contacts for signal transmission