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

June 22, 2004
NEURO–IT.net Workshop
Bonn, Germany
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

First term objective:
Set up of a shared knowledge between engineers and biologists for the identification of the biological models, mechanisms and control architectures which could be promising in terms of locomotion systems for the human body.

Second term objective:
Design and preliminary fabrication of biomimetic locomotion units (BLUs) mimicking some selected biological models.

Two undulatory motion systems:
- Undulatory motion based on waves longitudinal as regards the advancement direction (oligochaeta motion)
- Undulatory motion based on waves transversal as regards the advancement direction (polychaeta motion)
Hydrostatic skeleton with longitudinal and circular muscles, producing peristaltic changes in body shape and resulting in undulatory motion.

Alternate contractions of the longitudinal muscles form the wedge shape resulting in the zig zag locomotion.
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
• Spring made of SMA (shape memory alloy) wire;
• one or three springs per module;
• spring diameter approximately 600 µm or 800 µm.

• 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

![Graph showing electric field vs. axial strain](image)

![Diagram of BLU modules](image)

![Images of BLU modules](image)
**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

**Van der Waals based adhesion module**
- structured polymeric surfaces that mimic gecko toe

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

**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

<table>
<thead>
<tr>
<th></th>
<th>Polychaeta</th>
<th>Oligochaeta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoreceptors</td>
<td>Eyes, single cells distributed throughout the body</td>
<td>Single cells distributed throughout the body</td>
</tr>
<tr>
<td>Chemoreceptors</td>
<td>Palps, nuchal organ, cirri, antenna, sensory structures all over body</td>
<td>Prostomium, simple sensory structures and sensory cells all over body</td>
</tr>
<tr>
<td>Mechanoreceptors</td>
<td>Cirri, sensory structures all over body, setae?</td>
<td>Simple sensory structures all over body, setae?</td>
</tr>
<tr>
<td>Georeceptors</td>
<td>?</td>
<td>Statocysts</td>
</tr>
<tr>
<td>Proprioreceptors</td>
<td>? Associated with longitudinal and circular muscles, in parapodia, where segments join together</td>
<td>? Associated with longitudinal and circular muscles, where segments join together</td>
</tr>
</tbody>
</table>
The Sensory System

- Photoreceptors
- Chemoreceptors
- Mechanoreceptors
- Nerves

Density:
- Low
- Medium
- High
# Behavioural Sequences

<table>
<thead>
<tr>
<th>Behaviour</th>
<th>Initiation</th>
<th>Modulates</th>
<th>Termination</th>
<th>Sensory receptor</th>
<th>Poly</th>
<th>Oligo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawling</td>
<td>Attractant</td>
<td>Gradient</td>
<td>Arrival</td>
<td>Chemo</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Repellent</td>
<td>Intensity</td>
<td>Threshold</td>
<td>Chemo</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Swimming</td>
<td>Threat</td>
<td>Intensity</td>
<td>Threshold</td>
<td>Mechano/ chemo</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reproduction urge</td>
<td>Phero/ lunar light</td>
<td>Gamete release</td>
<td>Chemo/photo</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Burrowing</td>
<td>Exposure to sunlight</td>
<td>Intensity</td>
<td>Completion of burrow</td>
<td>Photo</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Low oxygen</td>
<td>Gradient</td>
<td>Adequate oxygen</td>
<td>Proprio</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Searching</td>
<td>Hunger</td>
<td>Intensity</td>
<td>Food encounter</td>
<td>Proprio/chemo</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Withdrawal</td>
<td>Threat</td>
<td>Intensity</td>
<td>In burrow</td>
<td>Photo/mechano</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Threatening</td>
<td>Antagonist</td>
<td>Distance</td>
<td>Retreat of opponent</td>
<td>Chemo/mechano</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fighting</td>
<td>Intrusion</td>
<td>Intensity</td>
<td>Retreat of opponent</td>
<td>Chemo/mechano</td>
<td>X</td>
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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.
Control for multi (up to $2^6$) segment robot

- Each segment equipped with actuator and on-board low-level control and gait generator.
- The whole robot delivers 3 wires (power and ground).
- The tail segment is the master.
- 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

Earthworm skeleton

Covering by silicone shell

Final earthworm

Electrical connection between brass disk and SMA spring by copper electrodeposition

SMA spring (100 µm)

hole with copper

electric wire

Covering by silicone shell

Final earthworm
The driver produces a sequential contraction of the 4 modules. When 1 module is active the other 3 are in rest.

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)

<table>
<thead>
<tr>
<th>Frequency (mHz)</th>
<th>Current peak duration (ms)</th>
<th>Current (mA)</th>
<th>Energy for module (J)</th>
<th>Velocity on flat surface (mm/s)</th>
<th>Velocity on sloped surface (40°) (mm/s)</th>
</tr>
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<tr>
<td>330</td>
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<td>400</td>
<td>0.15</td>
<td>0.7</td>
<td>0.45</td>
</tr>
<tr>
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<td>350</td>
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<td>2</td>
<td>1.43</td>
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<td>600</td>
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<td>350</td>
<td>0.05</td>
<td>2.5</td>
<td>1.25</td>
</tr>
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Earthworm with 4 segments and 1 spring for segment (75 µm in diameter wire, rather than 100 µm. This increases the robot speed)
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**

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

<table>
<thead>
<tr>
<th>Frequency (mHz)</th>
<th>Current peak duration (ms)</th>
<th>Current (mA)</th>
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The 5-module SMA artificial polycheata

Main features:
By exploiting the same design rules and fabrication technologies used for the oligochaeta prototype, a 5-module artificial polycheata 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) | Flexible silicone core (light blue structure) | The bottom part of each module can be endowed with small leg/pins (passive) to enhance friction, if necessary |
| Contact exiting from the top part | Flexible silicone core (light blue structure) | 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).

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Current peak duration (s)</th>
<th>Current (mA)</th>
<th>Energy for module (J) - (R = 10 ohm)</th>
<th>Velocity on flat surface (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.2</td>
<td>170</td>
<td>0.06</td>
<td>1.3</td>
</tr>
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</table>
Polychaete computational models

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

- Lagrange equations of motion on the group \( SE(2) \times S^N \).

- 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
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):

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

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