A CPG-driven Autonomous Robot

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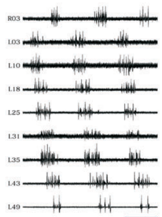
1 Introduction

We have built an autonomous mobile robot which facilitates exploring motion principles based on neural Central Pattern Generator (CPG) circuits in a truly distributed system.
The main aim of the project is to demonstrate elegant motion on a robot with a large number of degrees of freedom under the control of a simple distributed neural system as found in many animals' spinal cord. Currently, the robot consists of up to 60 individual segments that all run a local CPG. Sparse adjustable short- and long-range coupling between these CPGs synchronizes all segments, thus generating overall stable motion. A wireless connection between a host computer and the robot allows changing parameters during operation (eg. individual coupling coefficients, traveling speed, and motion amplitude). Additionally, users can modify the CPG algorithm and reprogram the segments during operation.
The robot can demonstrate various motion patterns based on extremely simple neural algorithms. We are currently implementing more advanced neural CPGs and will compare them in terms of motion robustness and traveling speed.
This poster presents the neural inspiration behind the robot (2, 3) as well as its physical design (4), discusses some experimental results in locomotion (5-7), and suggests some open questions for future research (8).

2 The Lamprey, a Simple Example for CPG-driven Locomotion

Pictures of lampreys



Activity of CPGs in a 50 segment isolated piece of spinal cord

- No paired fins sticking out
- Oscillation frequency of body proportional to traveling speed
- Distributed CPG segments along the spinal cord
- Left and right alternating activity, traveling uniformly down the body
- Intersegmental coupling to generate stable traveling wave
- One wavelength / body length (of roughly 100 segments)
- Other examples for CPG-driven motion: Eels, Snakes

Data and Image courtesy of Avis Cohen, University of Maryland

3 A Mathematical Model for CPG-driven Locomotion

$\theta_i \in [-\pi, \pi[$ — Current phase of the i[th] CPG oscillator

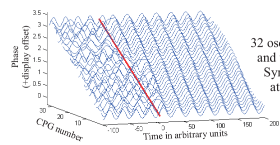
ω_i — Frequency of the i[th] oscillator

$$\frac{d\theta_i}{dt} = \omega_i + \sum_{j=1}^{N} \alpha_{ij} \sin\left(\theta_j - \theta_i + \eta\,(i-j)\right) \qquad \alpha \ll 1$$

Change of oscillator phase, depending on ω_i, coupling coefficients α_{ij} along the spinal cord, phase offset η between neighboring segments

$$\varphi_i = \varphi_{max} \sin(\theta_i)$$

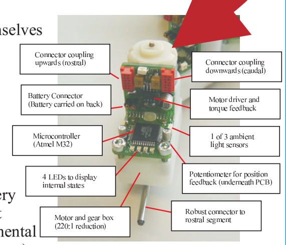
Transform of instantaneous internal phase to external bending angle



32 oscillating CPGs, with and without synchronization. Synchronization is enabled ($\alpha_{ij} \neq 0$) at t=0 (red line), when the segments start forming a traveling wave.

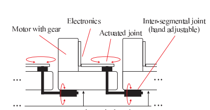
4 Physical Design of the Segments

- Small, lightweight design
- Strong enough to lift themselves
- Modular design
- 3-wire "spinal cord"
- On-board power supply (rechargeable battery)
- True local control (CPG algorithm on segment)
- Local sensory input: rotary position, motor torque, temperature, battery voltage, 3 x ambient light
- Reconfigurable inter-segmental connections (0 or 90 degrees)



Frontal view of a segment

- A specialized head segment:
  - wireless communication with PC
  - report and modify states of all other segments
  - reprogram CPG-algorithms during operation



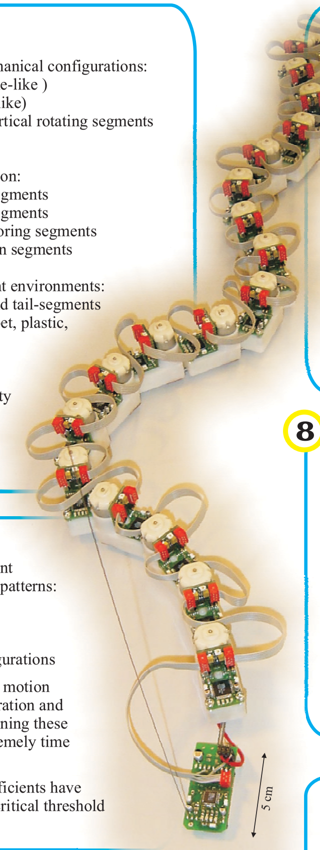
Sketch of the robot in side-view

5 Experiments

- Robot motion in different mechanical configurations:
  - planar horizontal robot (snake-like)
  - planar vertical robot (worm-like)
  - alternating horizontal and vertical rotating segments (motion in 3D)
- Parameters for generating motion:
  - frequency of oscillation in segments
  - amplitude of oscillation in segments
  - phase offset between neighboring segments
  - coupling coefficients between segments
- Motion experiments in different environments:
  - on table with fixated head and tail-segments
  - on different surfaces, eg carpet, plastic, wood, stone
- Data collection:
  - hand-recorded overall velocity (forward and sidewinding)
  - sequences of desired and true angular positions

6 Results

- Simple CPG algorithm sufficient for generating various motion patterns:
  - sliding motion
  - side-winding motion
  - self-lifting traveling wave in planar and alternating configurations
- Parameter settings for efficient motion depend on the robot's configuration and on surface properties. Determining these parameters empirically is extremely time demanding
- Variations in the coupling coefficients have no effect on motion (above a critical threshold for synchronization)



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7 Discussion

Large number of segments, high number of degrees-of-freedom, inherently scalable

Robust and failure tolerant system

Elegant control by an incredibly simple model

Highly complex motion patterns relative to algorithmic cost

Different mechanical configurations possible

We do not suggest that the robot is a good approximation to a biological system. Rather, we hope that the distributed nature of the robot's control will allow for interesting experiments pertaining to the function of the spinal cord or other, possibly artificial, neural system.

Further documentation and demonstration videos of the robot are available on the web at:
http://www.ini.ethz.ch/~conradt/projects/WormBot

8 Future Directions

- Integrating local sensor signals (adapting local CPG behavior to external stimuli)
- Implementing more detailed CPG algorithms
- Adding an accelerometer, using signals to learn parameters for efficient forward motion
- Stabilizing the head during motion (accelerometer)
- Adding vision, processing data onboard (eg. simple color blob tracking), goal directed motion
- Finding sparse coupling network
- Commercializing the robot: targeting academia or the toy-market?

References:

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- Conradt, J., Varshavskaya, P. (2003). Distributed Central Pattern Generator Control for a Serpentine Robot. Joint International Conference on Artificial Neural Networks and Neural Information Processing (ICANN/ICONIP), Istanbul, Turkey.