Reconfigurable CPGs for the Implementation of Adaptive Rhythmic Patterns of Locomotion.

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Outline

1. Motivation
2. Problem Description
3. Objectives and Hypothesis
4. Related Work
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Motivation

- A mobile robot depends on a locomotion mechanisms that enable it to move throughout its environment.
- Robot locomotion must perform in a controlled and reliable manner through an unknown environment without the aid of a human operator.
- To achieve an autonomous robot locomotion there are a large variety of possible mechanisms to move.
- Experiments and research work have addressed the feasibility of the design of locomotion control systems based on locomotion mechanisms present in humans and animals.
Problem Description

- Legged locomotion concerns in how to determine the best sequence, **locomotion pattern**, for lifting off and placing the feet.

- Legged locomotion requires multi-dimensional coordinated rhythmic patterns that need to be correctly tuned to satisfy multiple constraints.
# Locomotion Approaches

<table>
<thead>
<tr>
<th>Approach</th>
<th>Mathematical model-based</th>
<th>Biologically inspired approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main feature</strong></td>
<td>Joint angles are calculated in advance</td>
<td>Central Pattern Generator</td>
</tr>
<tr>
<td><strong>Design methodology</strong></td>
<td>Trial-and-error or recording data</td>
<td>Trial-and-error</td>
</tr>
<tr>
<td><strong>Robot knowledge</strong></td>
<td>Exact robot model</td>
<td>It does not need a robot model</td>
</tr>
<tr>
<td><strong>Perturbation problems</strong></td>
<td>Require an additional module</td>
<td>Robust against perturbations</td>
</tr>
<tr>
<td><strong>Control scheme</strong></td>
<td>Centralized</td>
<td>Distributed</td>
</tr>
</tbody>
</table>
Central Pattern Generator (CPG)

- The CPG is a neural circuit capable of producing coordinated patterns of rhythmic activity in open loop.
- CPG can adapt to various environments by changing the periodic rhythmic patterns through simple input signals.
- The biological mechanisms underlying locomotion have therefore been extensively studied by neurobiologists.
CPG model

CPGs are often modeled as nonlinear oscillators through second order differential equations that have mutually coupled excitatory and inhibitory connections.

Oscillator model

\[ \ddot{x}_i = F(\dot{x}_i, x_i, p_{xi}, x_{ai}, S_{\text{feed}}) \]  

(1)

Coupling contribution

\[ x_{ai} = x_i + \sum w_{ij} \times x_j \]  

(2)

For \( i = 1, 2, 3, \ldots, n \), where \( x_i \) is the output signal from oscillator \( i \), \( n \) is the number of oscillators in the CPG, \( p_{xi} = [p_0, p_1, \ldots, p_n] \) is the oscillator parameters, \( S_{\text{feed}} \) is the feedback signal and \( w_{ij} \) is the coupling weight.
CPG: Open Topics

CPG Design

Environment Feedback Integration

CPG-Controller Implementation
CPG Design

- To build a CPG able to generate different basic locomotion patterns.
  - Oscillator tuning.
  - CPG structure.
  - Transition between different patterns.

Given an oscillator
\[ \dot{x}_i = F(\dot{x}_i, x_i, p_{xi}, x_{ai}) \], to find the values of vector \( p_{xi} \), feedback signal \( S_{feed} \), and the coupling weights \( w_{ij} \) to generate a specific locomotion pattern.
Environment Feedback Integration

- CPGs need environment information to modulate and react according to a sensed situation.
- The integration of feedback information in the CPG modulation process is not direct.

To find the function, $F$, that maps information sensors, $S_i$, to locomotion control parameters, $L_C$. 
Hardware Implementation

- General purpose processor
  - Providing high accuracy and flexibility.
  - Good performance on average.
  - Tasks share the processor time.
  - Real-time response cannot be guaranteed.

- Analog implementation:
  - Computation and power efficient.
  - Lack flexibility to be reused.
  - Large design cycles.
Main Objective

To design and implement an adaptive locomotion control, based on CPG principles and visual information integration, embedded in a hardware platform capable of reacting under real-time constraints.
Specific Objectives

- To design a CPG-based locomotion able to generate multiple patterns of locomotion for quadruped and hexapod robots and the transitions between them.
- To propose and implement an integration mechanism to modulate the locomotion pattern generation based on visual information.
- To design and implement efficiently a locomotion control based on biological organization embedded in a hardware platform under real-time constraints.
It is possible to design a locomotion control scheme based on CPG principles able to generate adaptable locomotion patterns through integration of visual feedback information embedded in a custom parallel hardware platform under real-time constraints.
Contributions

- CPG able to generate **three different locomotion patterns** for quadruped and hexapod morphologies.
- CPG capable of **switching between gaits**, and controlling the locomotion speed.
- **Scalable hardware architecture of CPG-based locomotion for a quadruped and a hexapod** morphologies, so as the physical implementation in a hexapod robot.
- **Integration mechanism** based on fuzzy logic and finite state machine to **modulate the CPG-base locomotion** using visual perception information.
### CPG-Based Locomotion: Quadruped Robots

<table>
<thead>
<tr>
<th>Work</th>
<th>Implementation</th>
<th>Feedback</th>
<th>Integration Mechanism</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billard and Ijspeert (2000)</td>
<td>Software</td>
<td>Internal (leg positions)</td>
<td>Linear equation</td>
<td>Three gaits</td>
</tr>
<tr>
<td>Fukuoka et al. (2005)</td>
<td>Software</td>
<td>external (object distances)</td>
<td>Linear equation</td>
<td>Walk and control direction</td>
</tr>
<tr>
<td>Feng and Wang (2008)</td>
<td>Software</td>
<td>Internal (leg positions)</td>
<td>PD-controller</td>
<td>Walk and control direction</td>
</tr>
<tr>
<td>Santos and Matos (2012)</td>
<td>Software</td>
<td>External (objects and distances)</td>
<td>Mathematical model</td>
<td>Pursuit and avoiding</td>
</tr>
<tr>
<td>Nakada et al. (2003)</td>
<td>Hardware (CMOS)</td>
<td>None</td>
<td>None</td>
<td>Three gaits</td>
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<tr>
<td>Nakada et al. (2005)</td>
<td>Hardware (VLSI)</td>
<td>None</td>
<td>P-controller</td>
<td>Three gaits</td>
</tr>
</tbody>
</table>
## Related Work

### CPG-Based Locomotion: Hexapod Robots

<table>
<thead>
<tr>
<th>Work</th>
<th>Implementation</th>
<th>Feedback</th>
<th>Integration Mechanism</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inagaki et al. (2006)</td>
<td>Software (parallel)</td>
<td>None</td>
<td>Hamiltonian function</td>
<td>Three different gaits with velocity control</td>
</tr>
<tr>
<td>Arena et al. (2004)</td>
<td>Software</td>
<td>Internal(leg speeds)</td>
<td>Neural Network (SOM)</td>
<td>Three different gaits</td>
</tr>
<tr>
<td>Arena et al. (2005)</td>
<td>Hardware (VLSI)</td>
<td>Internal speeds (leg and horizontal positions)</td>
<td>Neural networks (CNN) and PID-controllers</td>
<td>Climbing gait</td>
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<tr>
<td>Arena et al. (2006)</td>
<td>Software (microcontroller)</td>
<td>None</td>
<td>Neural networks (CNN)</td>
<td>Climbing gait and direction control</td>
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<tr>
<td>Manoonpong et al. (2008)</td>
<td>Software (Obstacle distance)</td>
<td>None</td>
<td>Neural networks (FFNN)</td>
<td>Avoiding obstacles</td>
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</table>
Methodology

It was divided into three phases:

- CPG-based locomotion.
- Visual perception and integration mechanism.
- Embedded hardware implementation.
Phase 1: CPG-Based Locomotion

- Oscillator model selection.
- Oscillator network (CPG) design.
- CPG simulations.
- Result analysis.
Phase 2: Visual Perception and Integration mechanism

- Visual perception design.
- Integration mechanism design.
- Locomotion control assembly.
- Locomotion control tests.
- Result analysis.
Phase 3: Embedded Hardware Implementation

- Hardware module designs.
  - Oscillator model.
  - CPG-based locomotion.
  - Integration mechanism.
- Hardware module simulations.
- Physical implementation.
### Timeline of activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
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<tr>
<td>Selection, implementation, testing of oscillator model.</td>
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<td>Design, implementation and testing of CPG (1).</td>
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<td>Review of visual perception (PV) models</td>
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<td>Implementation of PV model (2)</td>
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<td>Design and implementation of integration mechanism (3).</td>
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<td>X</td>
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<tr>
<td>Design and hardware implementation of the modules.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3-3</td>
<td>2-3</td>
<td>2-3</td>
<td>2-3</td>
<td>2-3</td>
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<tr>
<td>Module integration in the robot platform based on FPGA.</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>Testing and result analysis.</td>
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<td>J</td>
<td>C</td>
<td>C</td>
<td>CH</td>
<td>J/C</td>
<td>J</td>
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</table>
Conclusions

- CPG is neural circuit capable to generate locomotion patterns feasible to be used in robot locomotion.
- CPGs are able to generate complex and adaptive locomotion behaviors from manipulation of simple periodic signals.
- The presented CPG-based controller will provide flexibility to generate different rhythmic patterns, at runtime, suitable for adaptable locomotion for quadruped and hexapod robots.
- The proposed embedded locomotion architecture will exploit the distributed processing able to carry out in FPGA through units working in parallel and ensuring a real time response.
References I


References II


B. Van Der Pol and J. Van Der Mark. The heartbeat considered as a relaxation oscillation, and an electrical model of the heart. 6:763Ü775, 1928.
Thanks