Evolution and Online Optimization of Central Pattern Generators for Modular Robot Locomotion

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http://birg.epfl.ch/page32031.html

Master Thesis

Swiss Federal Institute of Technology Lausanne

Biologically Inspired Robotics Group (BIRG)

Outline

Please do not hesitate to ask questions at any time!

1. Introduction
2. Co-evolution of configuration and control
3. Online optimization / adaptation
4. Questions

Goals

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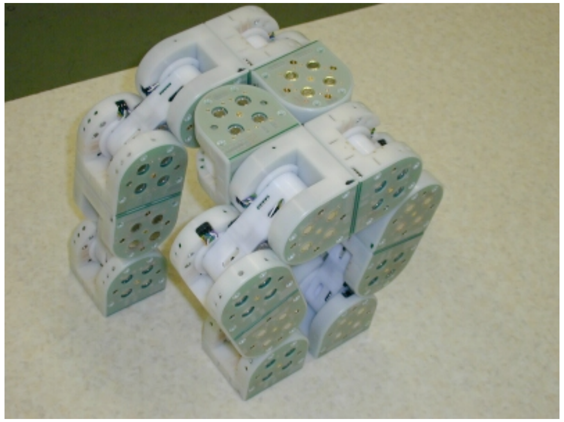
- Modular robot locomotion control
  - Distributed, asynchronous and reliable controller
  - Testing YaMoR in simulation
- Bio-inspired locomotion control
  - Nonlinear oscillators as canonical subsystem of CPG
  - Which coupling types are appropriate?
  - Which coupling schemes should we use?
- Self-organization of locomotion
  - Offline: Co-evolution of configuration + CPG
  - Online: Fast optimization / adaptation of locomotion

Motivation

- Autonomous machines
  - 'Emergent functionality' is becoming increasingly important in today's technology
  - Self-organization and adaptation are key concepts
  - MR is a perfect framework to design autonomous machines (versatility, adaptability, reliability)
- Test bed for research in:
  - Complex, distributed and synergetic systems
  - Multi-agent systems, distributed learning
  - Many degree of freedom robot control

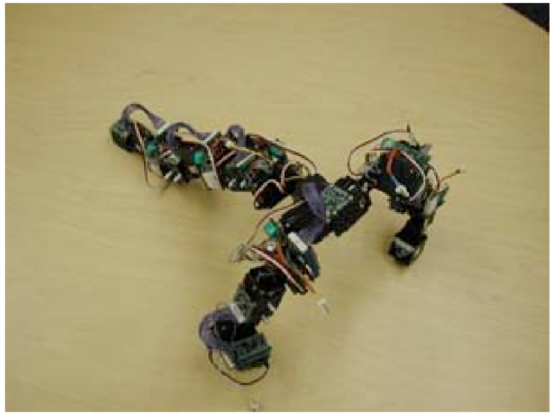
Modular Robotics

- Hardware



M-TRAN II
(AIST)

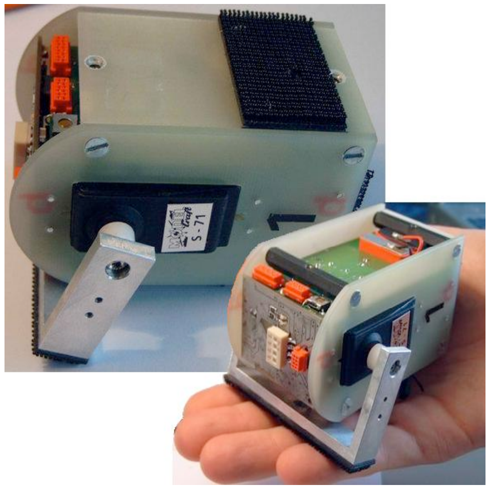
PolyBot G3
(PARC)

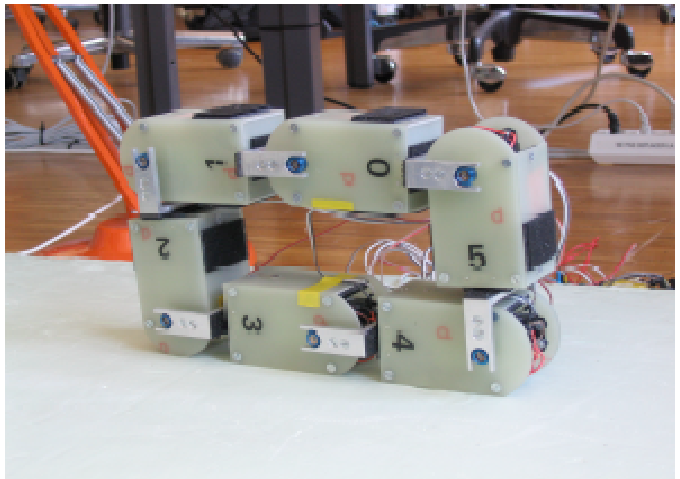


CONRO
(USC)

Modular Robotics

- YaMoR
  - Length: 94 mm; Weight: 250 grams
  - Manual reconfiguration (Velcro)
  - Modules are self-contained
  - RC-servo strong enough to lift three other modules
  - Each module is equipped with an FPGA
  - Wireless communication via BlueTooth





Modular robot control

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- Gait control tables
  - Each column contains the action sequence of a module
  - Centralized master-slave approach
  - E.g. M-TRAN
- Hormone-based control
  - MR is a distributed system with dynamic topology
  - Synchronous distributed approach, CONRO.
  - Digital hormones are used to implement distributed synchronization algorithms.

Modular robot control

- Role-based control
  - Asynchronous distributed approach
  - Modules periodically send synchronization signals to the children
  - Each module acts as master of its sub tree
  - Disadvantage: Abrupt jumps in the generated trajectories
- Constraint-based control
  - MR is *not* a multi-agent system
  - MR is a distributed network of N embedded processors

Vertebrate locomotion

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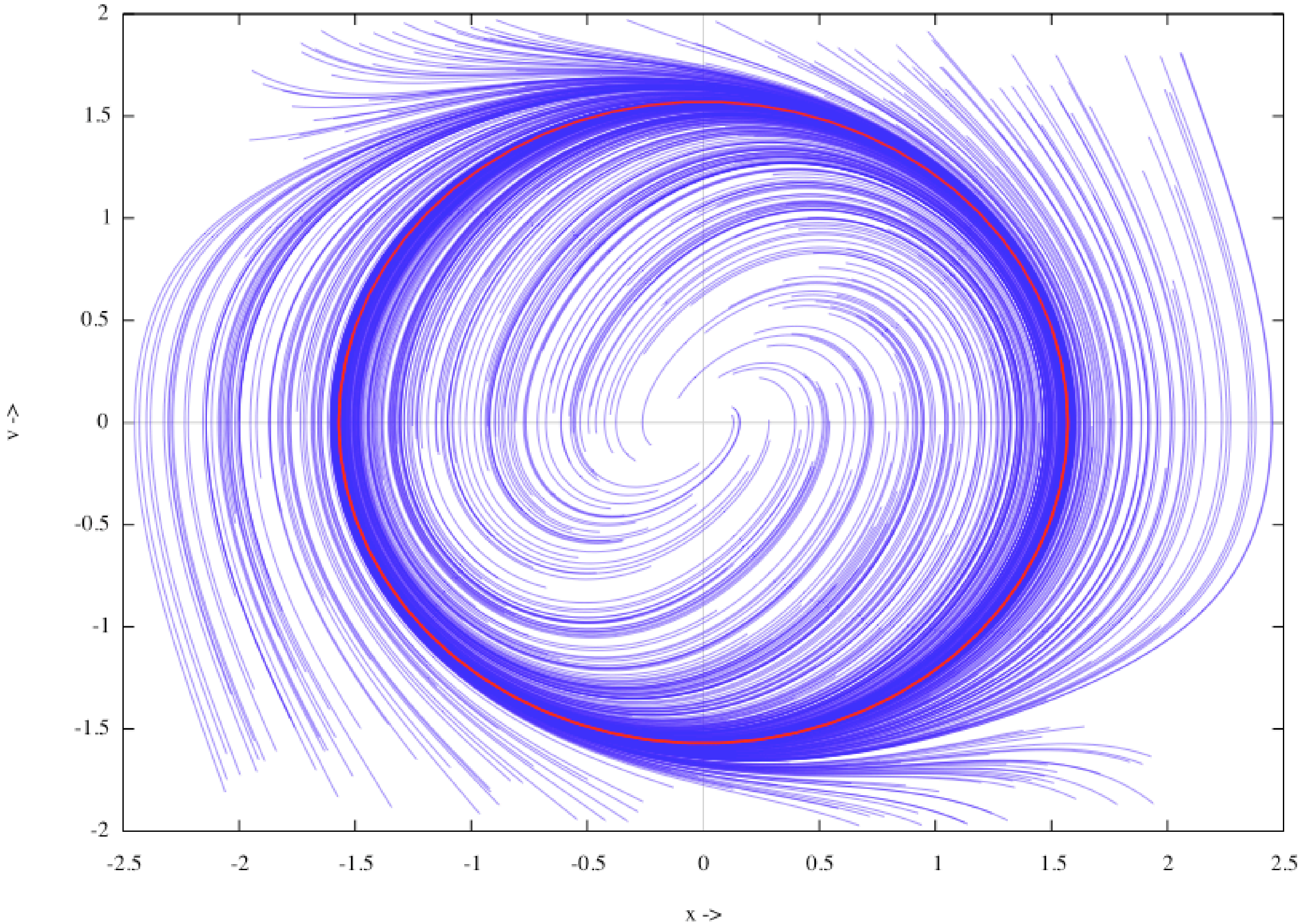
- Rhythmic activities
  - Efficient locomotion but complex control
  - Synchronization at specific phase differences is essential
- Central Patter Generator (CPG)
  - Rhythmic neural activity induced by simple (tonic) input
  - Capability of generating distinct patterns in function of the input
  - Smooth gait transitions
  - Hierarchical decomposition into coupled oscillators
  - Sensory feedback shapes the output signals
- Symmetry of the morphology and the controller

Nonlinear Oscillators

- Harmonic oscillator: $x = A\sin(2\pi ft + \varphi)$
  - Synchronous control
  - Gait transitions are not smooth
- Standalone nonlinear oscillator:
  - Asynchronous distributed control
  - Smooth gait transitions

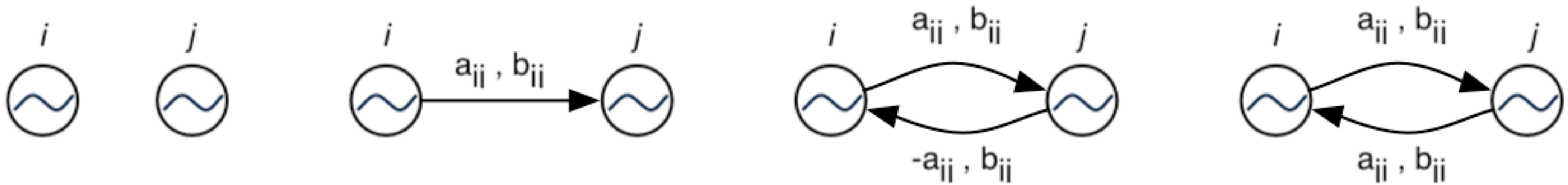
$$\begin{cases} \tau\dot{x} = v \\ \tau\dot{v} = -\alpha \dfrac{x^2 + v^2 - E}{E} v - x \end{cases}$$

Standalone oscillator



Coupled oscillators

$$\begin{cases} \tau \dot{x}_i = v_i \\ \tau \dot{v}_i = -\alpha \dfrac{x_i^{\,2} + v_i^{\,2} - E_i}{E_i} v_i - x_i + \displaystyle\sum_j \dfrac{a_{ij} x_j + b_{ij} v_j}{\sqrt{x_j^{\,2} + v_j^{\,2}}} \end{cases}$$

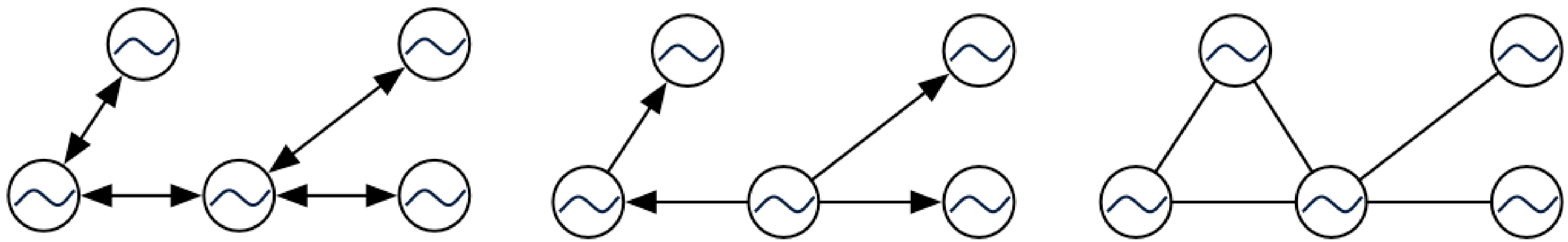


a) uncoupled

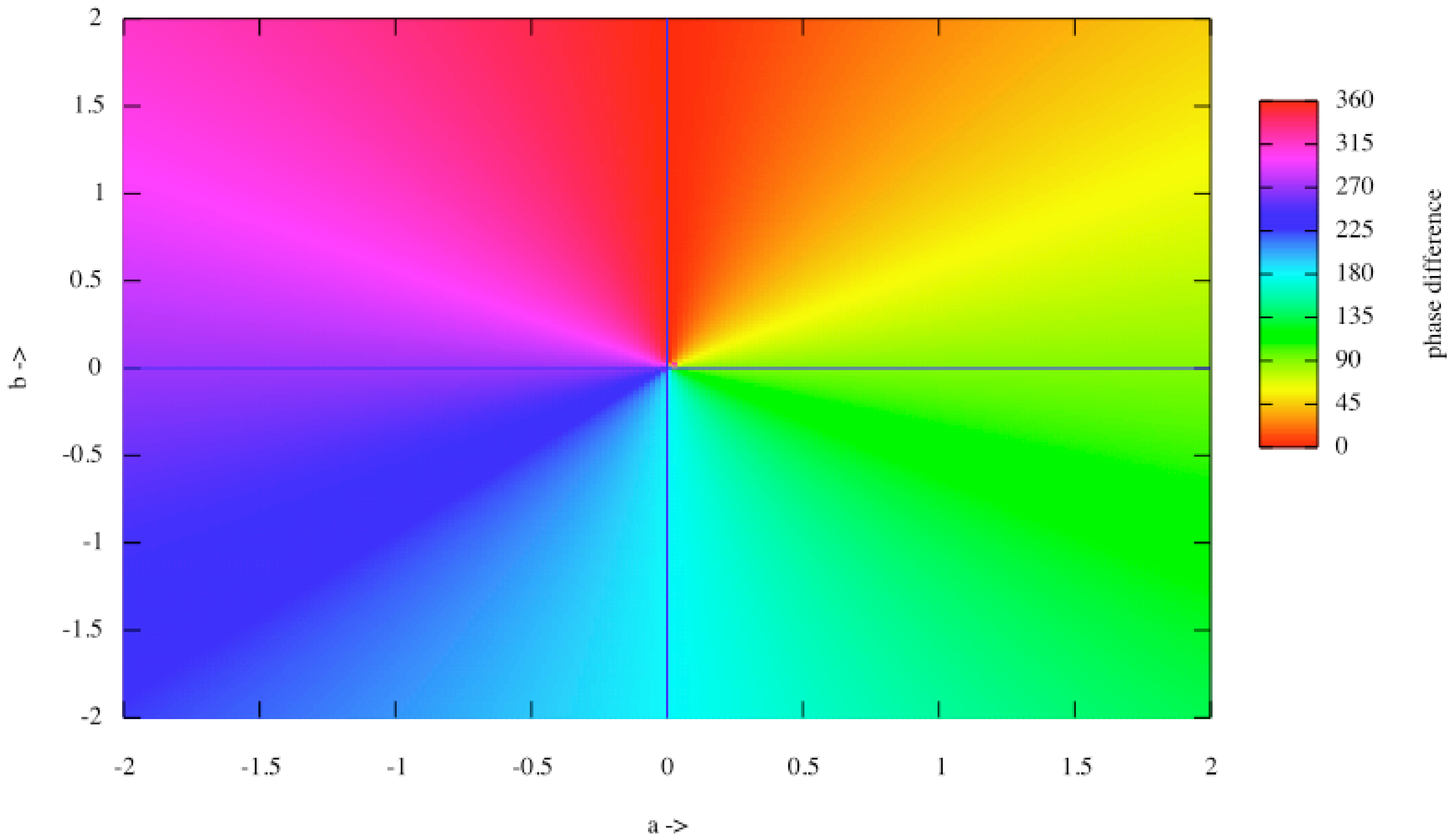
b) unidirectional

c) bidirectional with two free parameters

d) bidirectional with four free parameters



Coupled oscillators



Coupled oscillators

- Predicting the phase difference:

$$g(a,b) = \begin{cases} \pi/2 & (a>0 \;\wedge\; b=0) \\ \arctan\left(\dfrac{a}{b}\right) & (b \neq 0) \\ -\pi/2 & (a<0 \;\wedge\; b=0) \end{cases}$$

- Setting the actual phase diff. ϕ_{ij} to a specific phase $\tilde{\phi}_{ij}$

$$p_{v,ij} = r_{ij} \cdot \frac{\cos\left(\dfrac{\pi}{2} - \tilde{\phi}_{ij}\right) x_j + \sin\left(\dfrac{\pi}{2} - \tilde{\phi}_{ij}\right) v_j}{\sqrt{{x_j}^2 + {v_j}^2}} \quad \Rightarrow \quad \phi_{ij} = \tilde{\phi}_{ij}$$

Coupled oscillators

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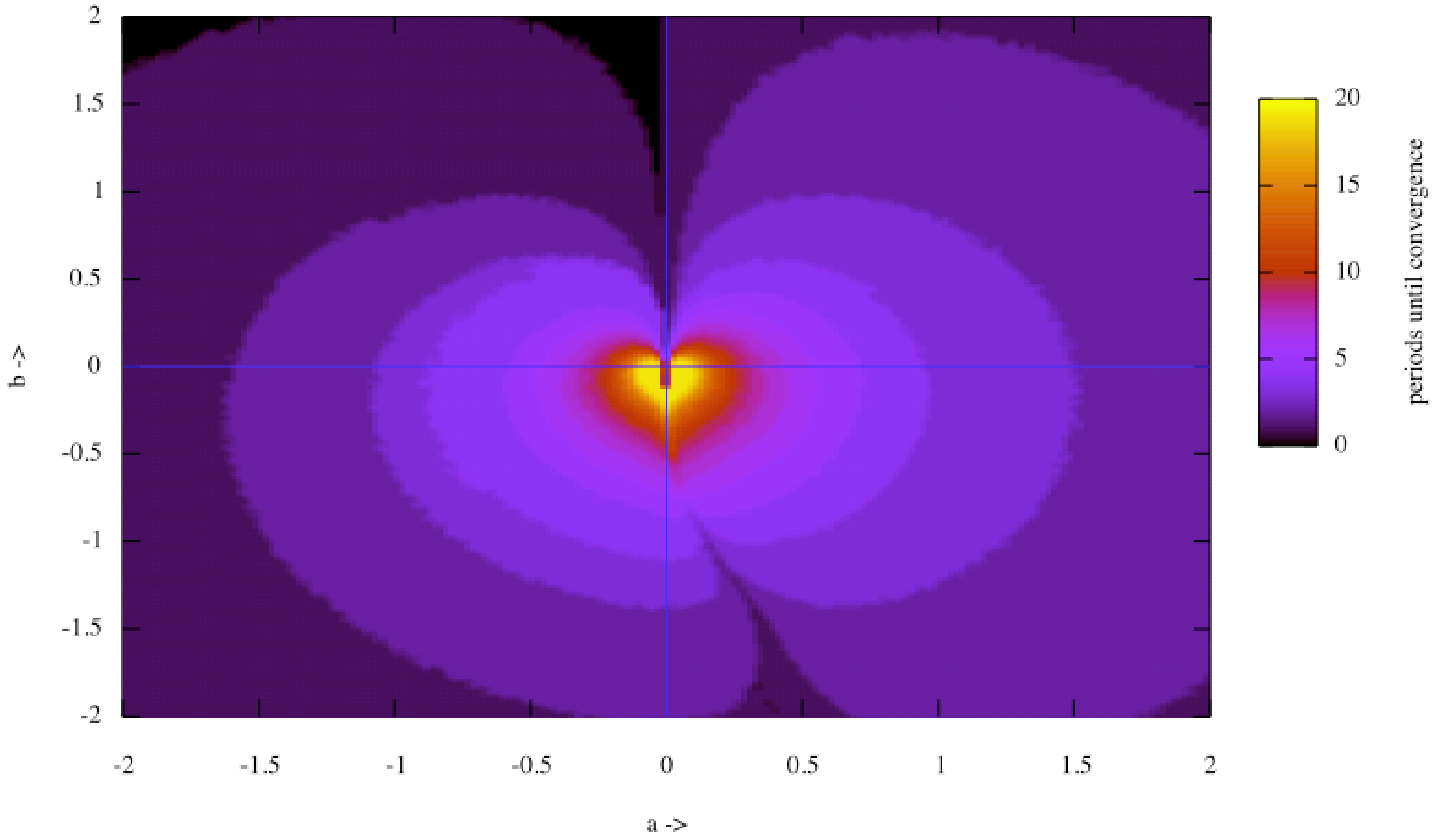
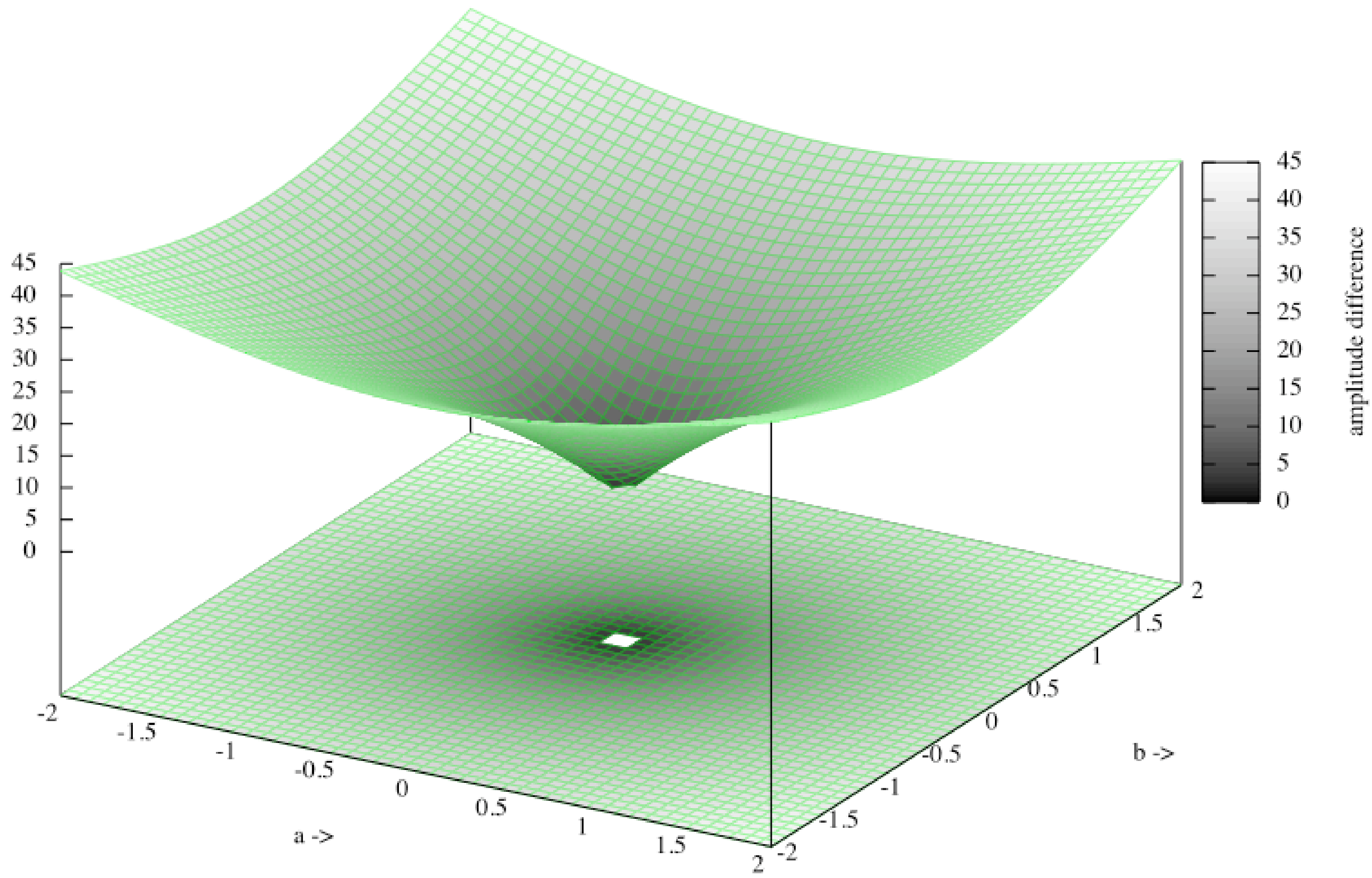


Coupled oscillators



Coupled oscillators

- Energy balanced couplings:

$$\begin{cases} \tau \dot{x}_i = v_i \\ \tau \dot{v}_i = -\alpha \dfrac{x_i^2 + v_i^2 - E_i}{E_i} v_i - x_i + \sum_j \left(r_{ij} \cdot \left(\dfrac{\cos(\xi_{ij}) x_j + \sin(\xi_{ij}) v_j}{\sqrt{x_j^2 + v_j^2}} - \dfrac{v_i}{\sqrt{x_i^2 + v_i^2}} \right) \right) \end{cases}$$

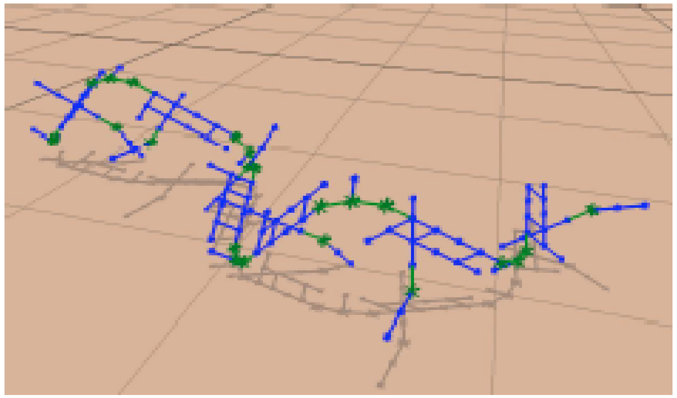
$$\begin{cases} \tau \dot{x}_i = v_i \\ \tau \dot{v}_i = -\alpha \dfrac{x_i^2 + v_i^2 - E_i}{E_i} v_i - x_i + \sum_j \left(\dfrac{a_{ij} x_j + b_{ij} v_j}{\sqrt{x_j^2 + v_j^2}} - \sqrt{a_{ij}^2 + b_{ij}^2} \dfrac{v_i}{\sqrt{x_i^2 + v_i^2}} \right) \end{cases}$$

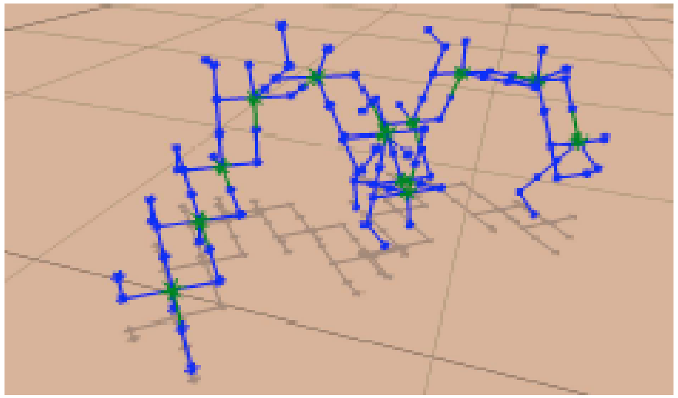
  - The coupling term represents the phase error
  - Asynchronous distributed and *reliable* control possible
  - Analytical proof that the oscillators converge to a sine
  - Possibility to set desired phases and amplitudes

=> The same set of parameters as harmonic oscillators!

Co-evolution

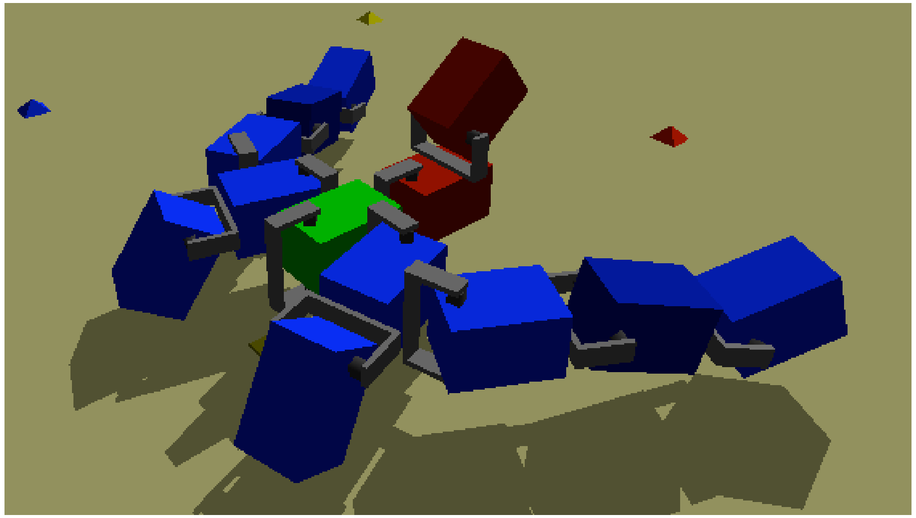
- Co-evolution of configuration and control
  - Bio-inspired
  - MRs are meant to operate in many different configurations
  - Manual design of configurations is not scalable
- Previous research
  - Evolutionary motion synthesis method for M-TRAN
  - Automatic locomotion pattern generation for M-TRAN
  - Artificial life: Sims block creatures, Hornby, and many others.





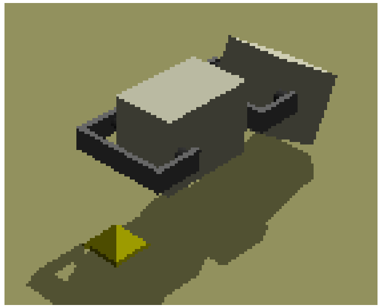
Co-evolution

- Encoding the configurations of YaMoR robots
  - Tree: Nodes represent modules and links physical connections
  - Male / female connection scheme. Advantages:
    - The only free lever is the one of the head
    - The control algorithm is simplified
    - The implementation is simplified
    - The GA benefits from a smaller phenotype space

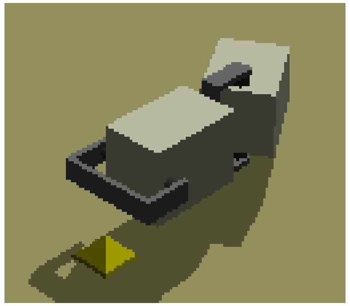


Co-evolution

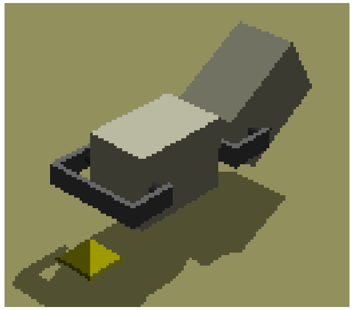
- Orientations and docking positions



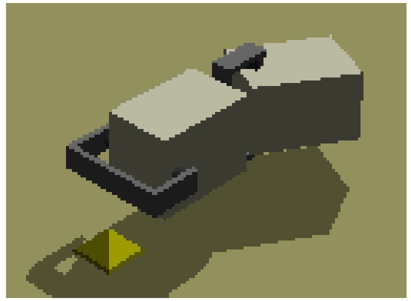
NORTH



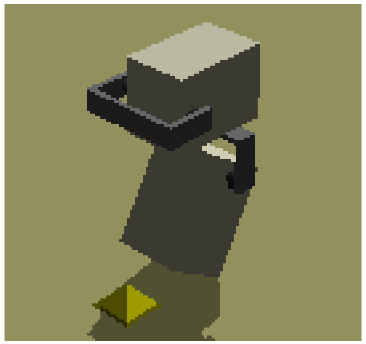
EAST



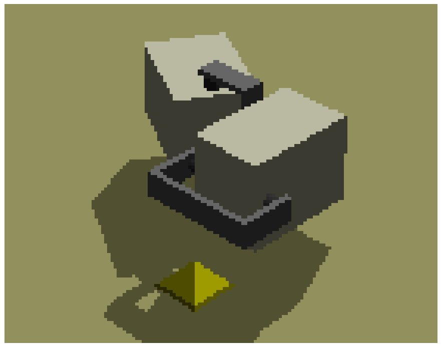
SOUTH



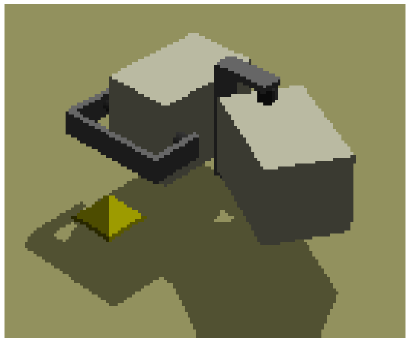
WEST



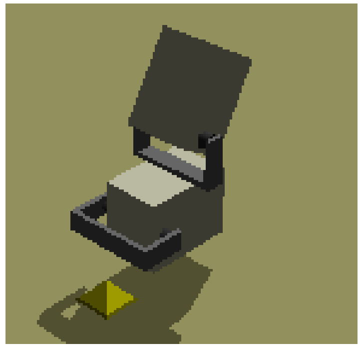
DOWN



LEFT



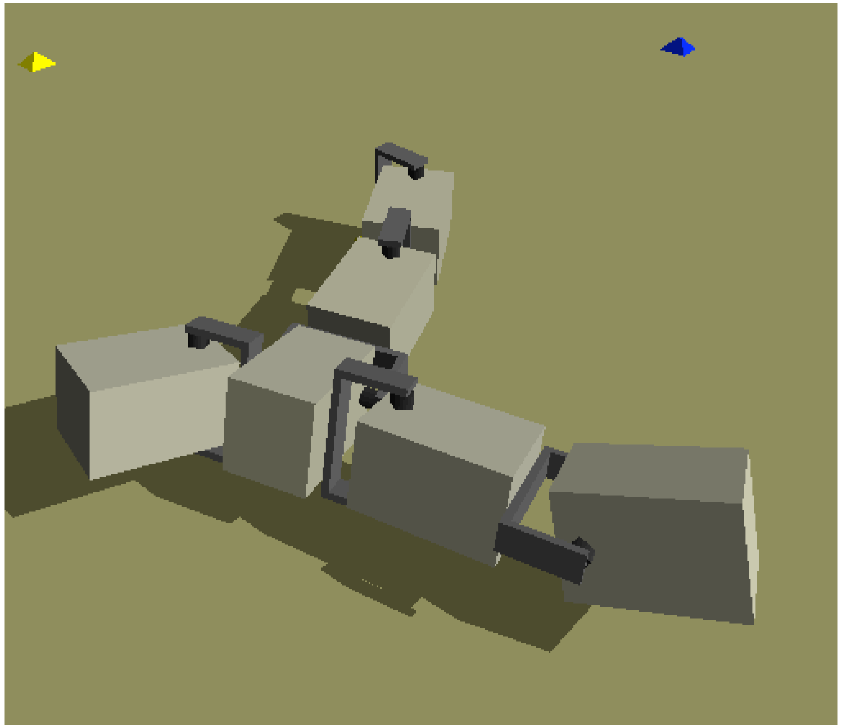
RIGHT

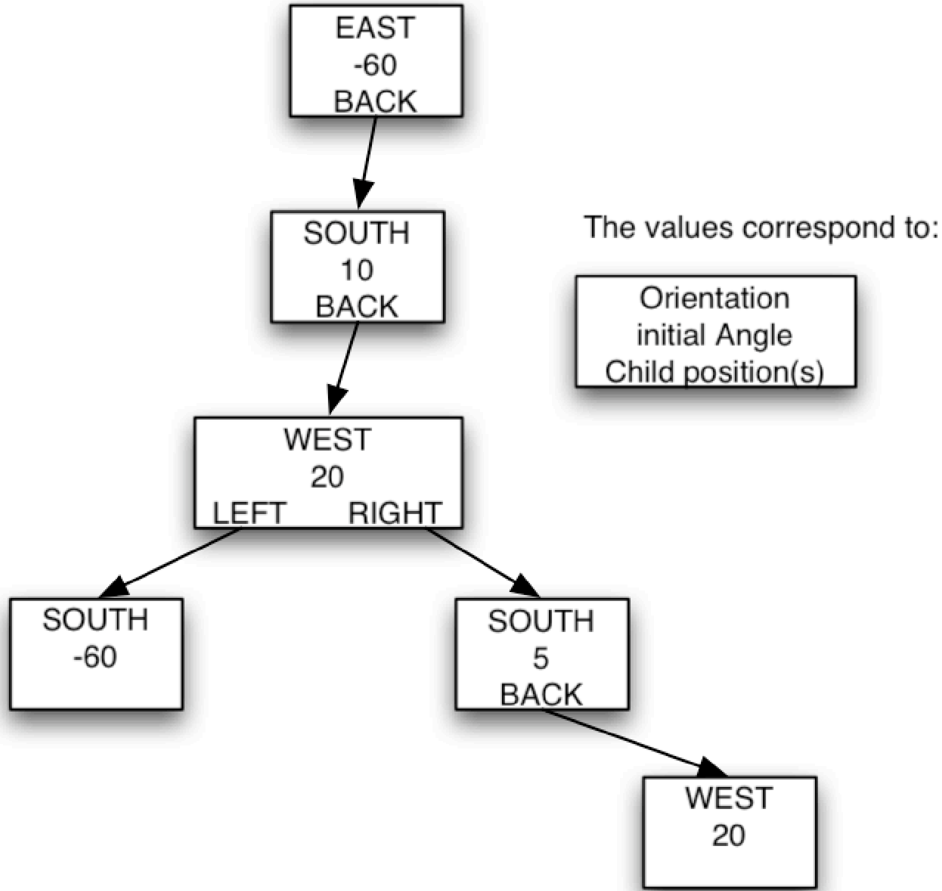


UP

Co-evolution

- Phenotype and genotype





Co-evolution

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- Structural parameters

Parameter	**Range**	**Description**
Orientation	{NORTH, EAST, SOUTH, WEST}	The orientation of the module
Initial angle	[-pi/2, pi/2]	The initial angle of the hinge joint.
Child position(s)	{BACK, LEFT, …, DOWN}	The docking position for every child

- Control parameters of a harmonic oscillator

Parameter	**Range**	**Description**
IS_RIGID	{true, false}	Determines if the module is rigid or not.
A	(0, π/2]	The amplitude.
phi	[0, 2π]	The phase.

Co-evolution

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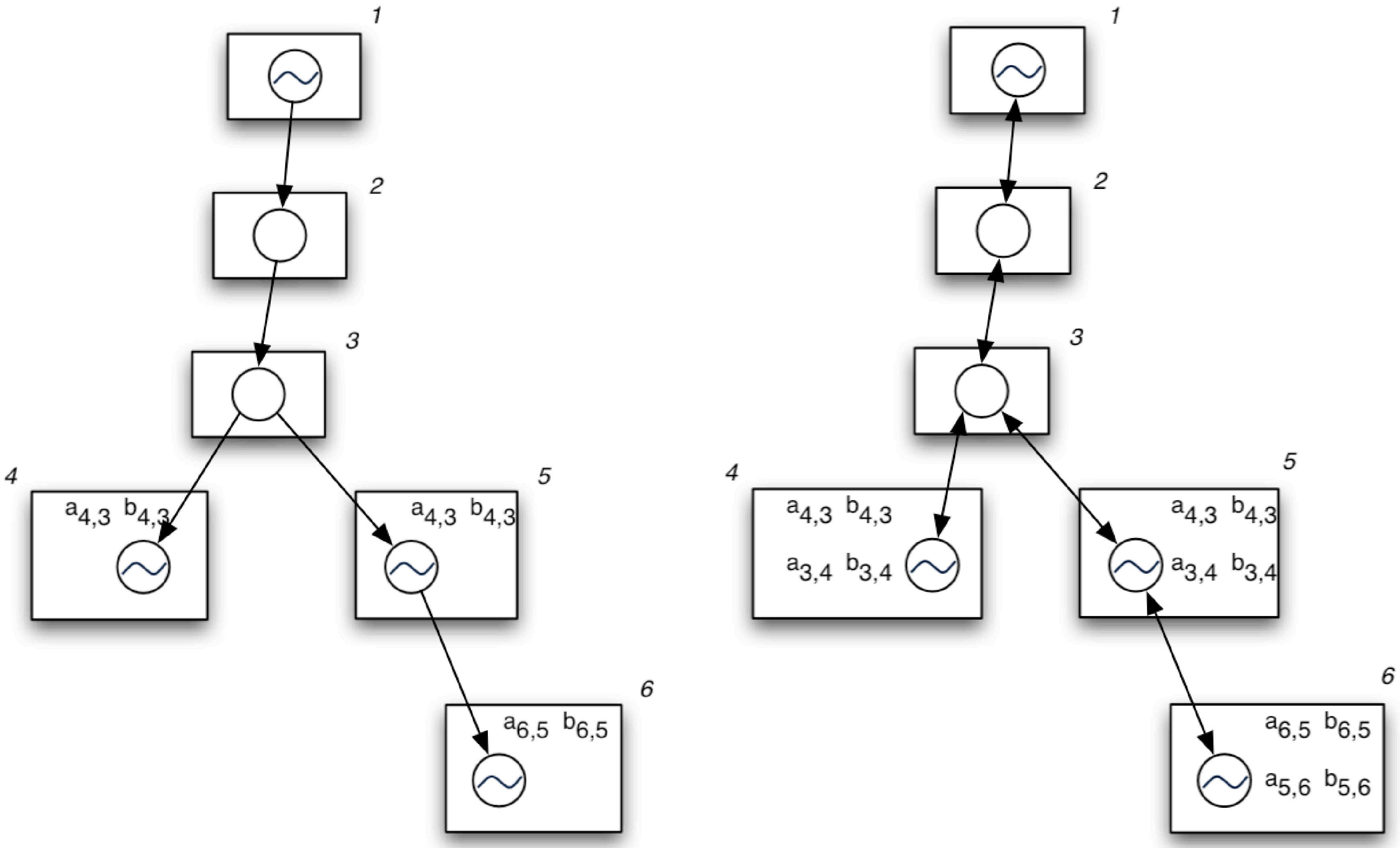
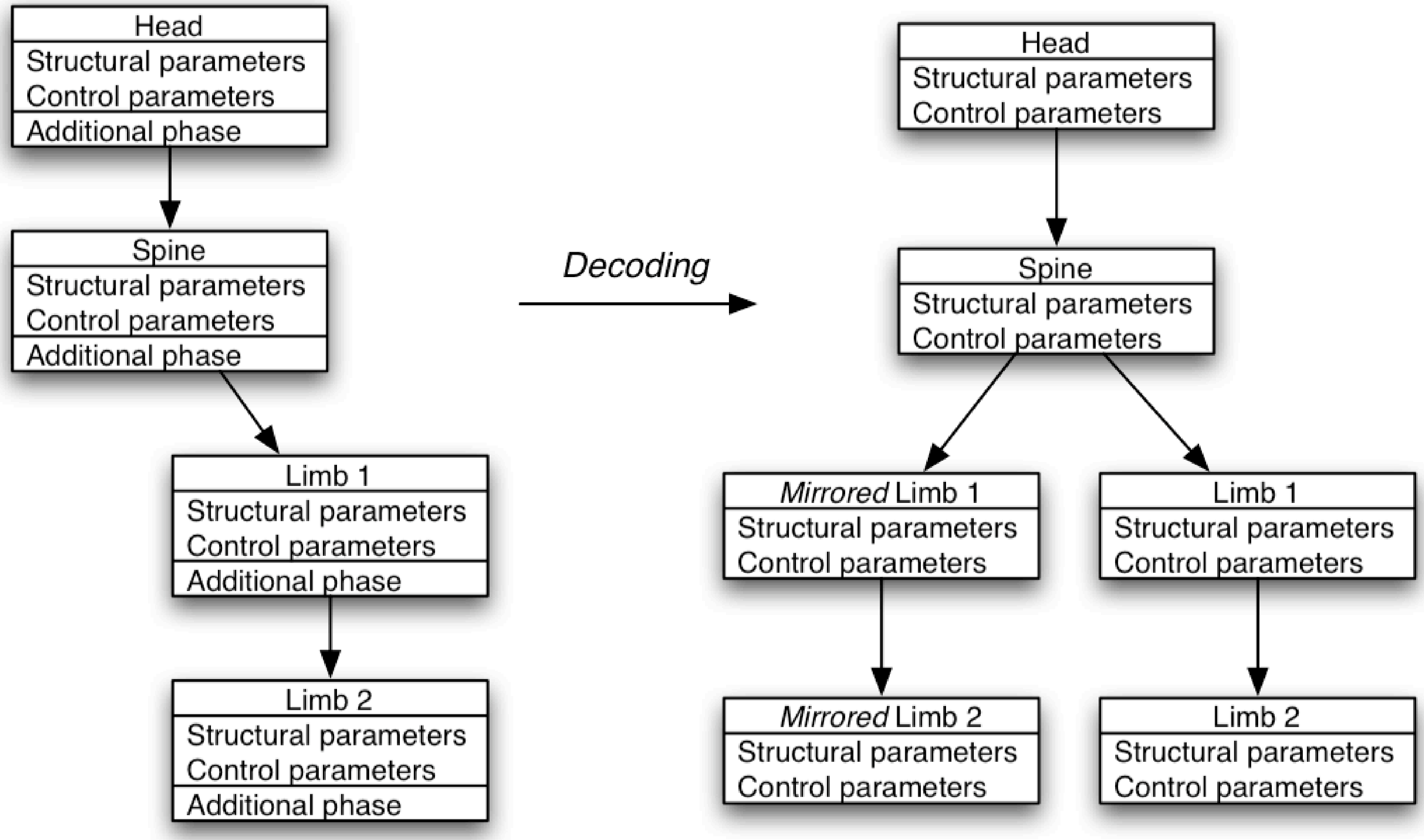
- Free parameters of a coupled nonlinear oscillator

Parameter	**Range**	**Description**
IS_RIGID	{true, false}	Determines if the module is rigid or not.
E	(0, pi/4]	The energy parameter of the nonlinear oscillator.
a_ij	[-2, 2]	The weights of the coupling from the parent to this oscillator.
b_ij	[-2, 2]	
a_ji	[-2, 2]	The weights of the coupling from this oscillator to the parent (*only for bidirectional couplings with four free parameters*).
b_ji	[-2, 2]	

Co-evolution



Co-evolution



Co-evolution

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- Simple but effective fitness function: Distance from the starting point after a certain amount of time.
- Mutation
  - Change parameter value
  - Delete a sub tree or ‘grow’ a new node
  - Switch two sub trees or two modules
- Crossover
  - Single point crossover by swapping sub trees
  - Swap identical sub trees if the parents are similar
- GAs: Incremental, steady state, migrating populations
- Rank-proportional roulette wheel selection

Co-evolution

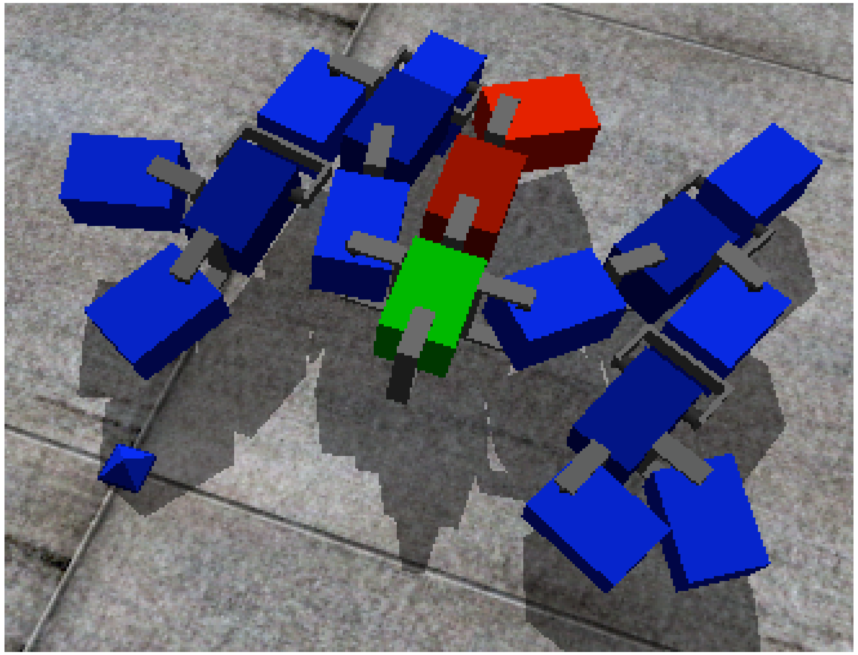
- Results
  - An evolutionary run takes about two hours on a high-end PC
  - Bidirectional couplings don't perform well
  - Incremental GAs with small / medium populations perform best
  - Symmetric encoding evolves fitter and more complex robots in shorter time. Averages of 15 GAs:

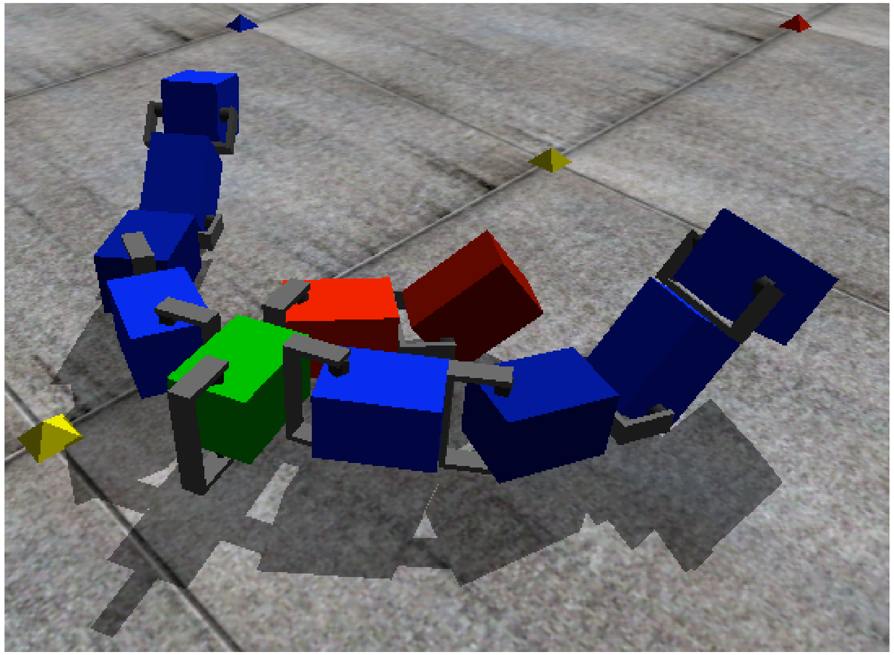
Encoding	**Evaluations**	**Max. fitness**
General	2435.66	2.74
Symmetric	2208.21	2.91

QOOL

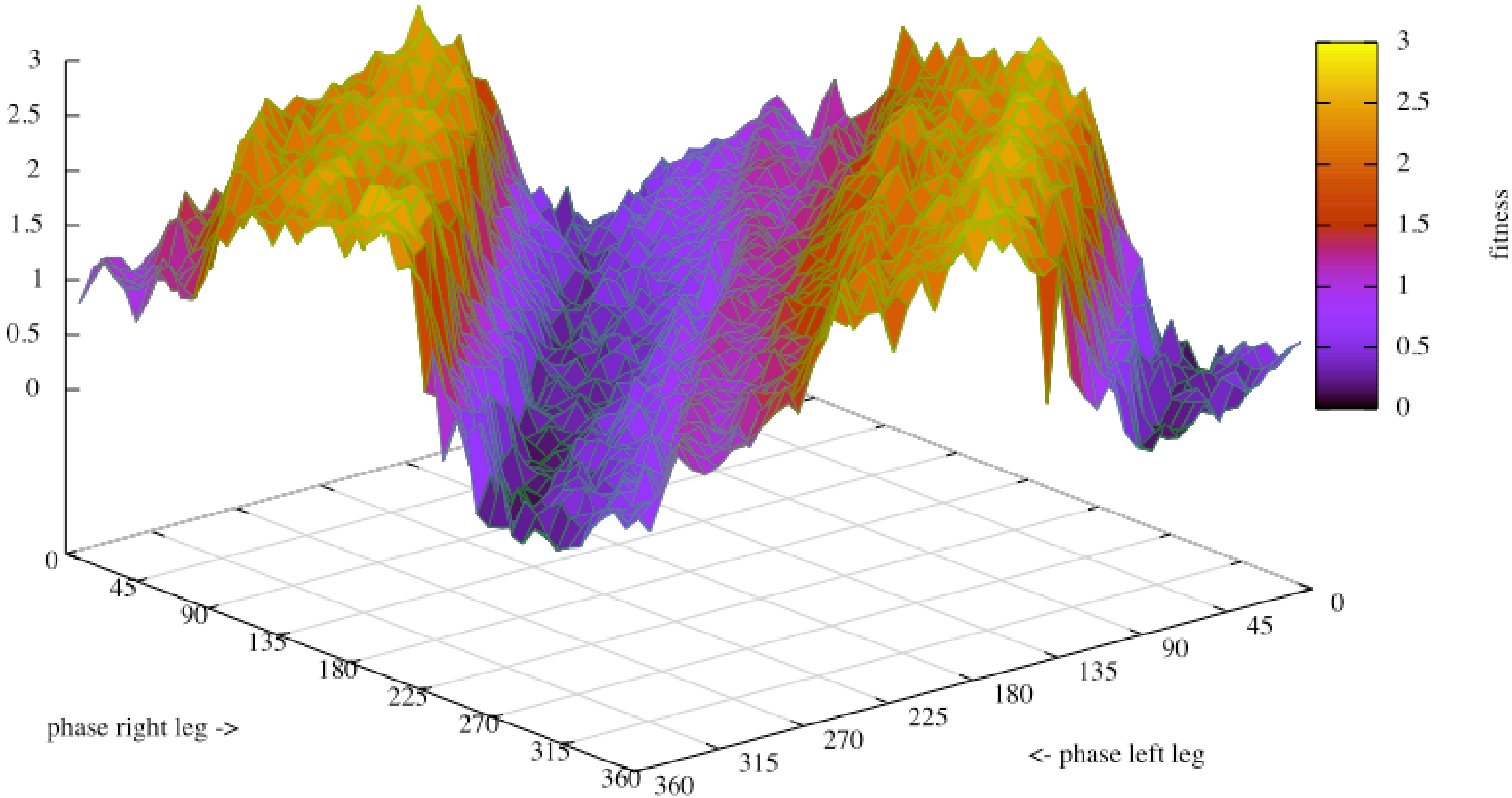
- **Q**uick **O**nline **O**ptimization of **L**ocomotion (QOOL)
  - Optimization of multiple degree of freedom robot locomotion
  - Quadratic convergence to a local optimum
  - In contrast: Heuristic optimization algorithms (previous research)
- Applications
  - Optimization from scratch
  - Adaptation of a gait to changing environmental constraints
- Fitness function
  - Distance from the starting point after three periods
  - One must detect stabilization of the mechanical dynamics before starting fitness evaluation
  - Analyze average speed of each module

QOOL



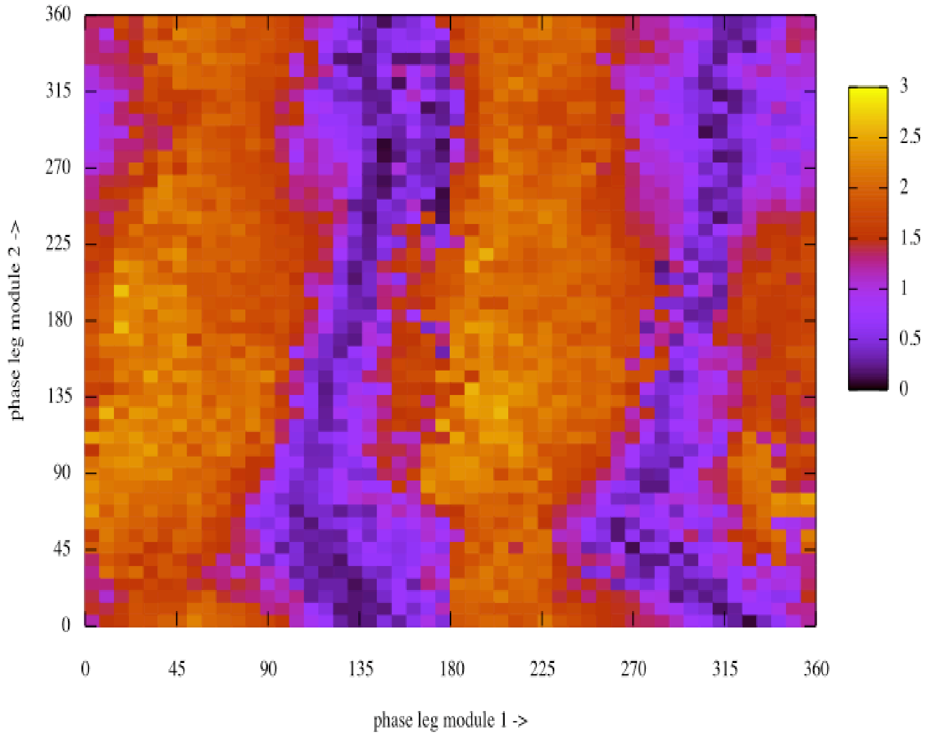


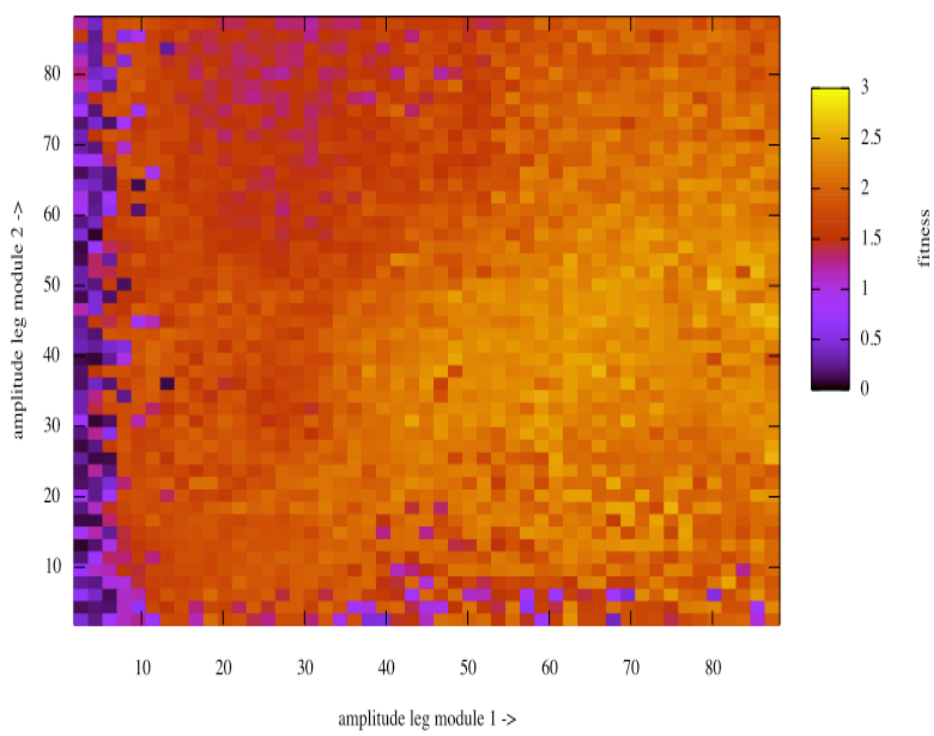
QOOL



3
2.5
2
1.5
1
0.5
0
0
45
90
135
180
225
270
315
360
phase right leg ->
0
45
90
135
180
225
270
315
360
<- phase left leg
fitness

QOOL


phase leg module 2 ->
phase leg module 1 ->
0
45
90
135
180
225
270
315
360
0
0.5
1
1.5
2
2.5
3


amplitude leg module 2 ->
amplitude leg module 1 ->
10
20
30
40
50
60
70
80
fitness
0
0.5
1
1.5
2
2.5
3

QOOL

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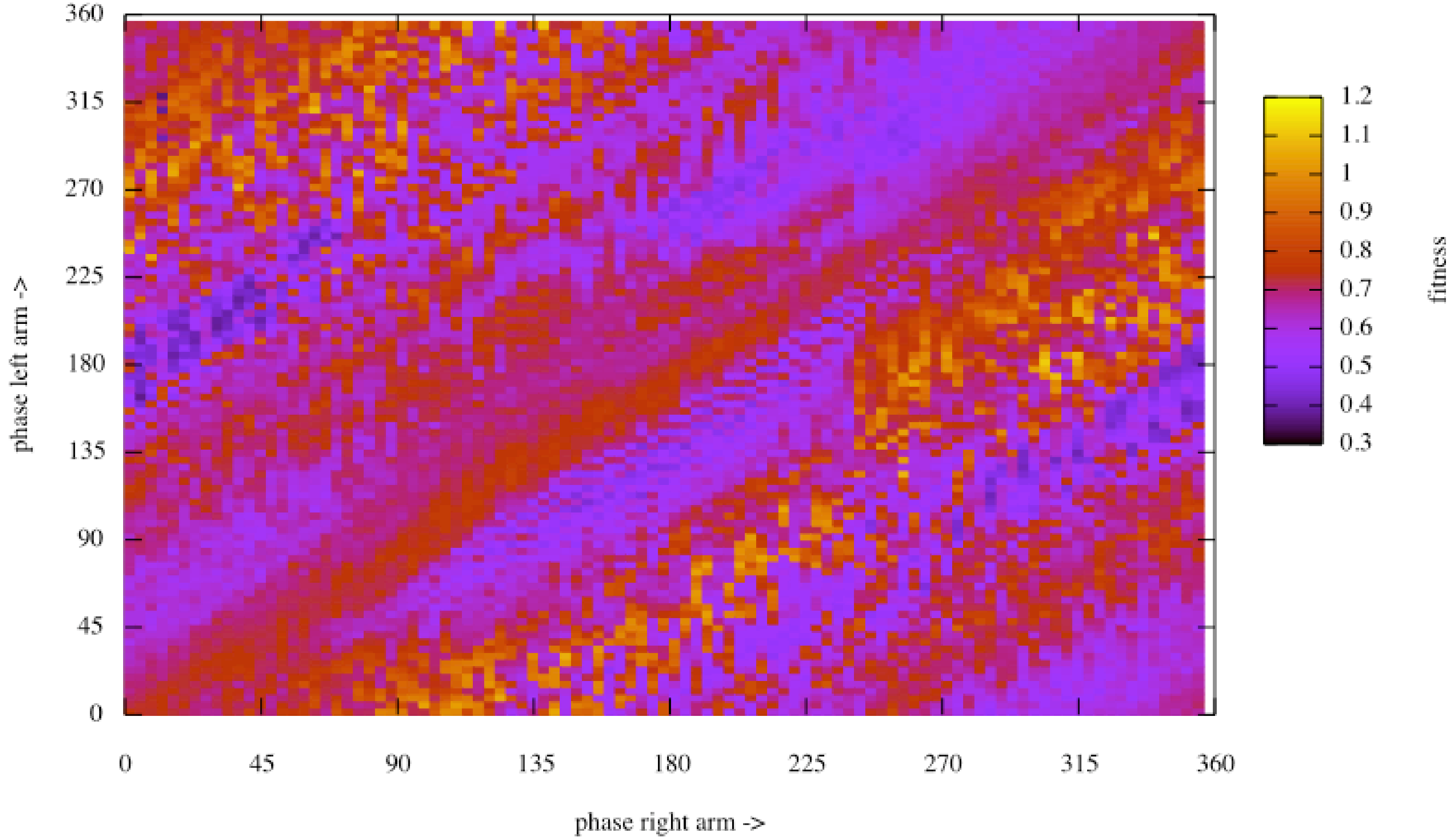
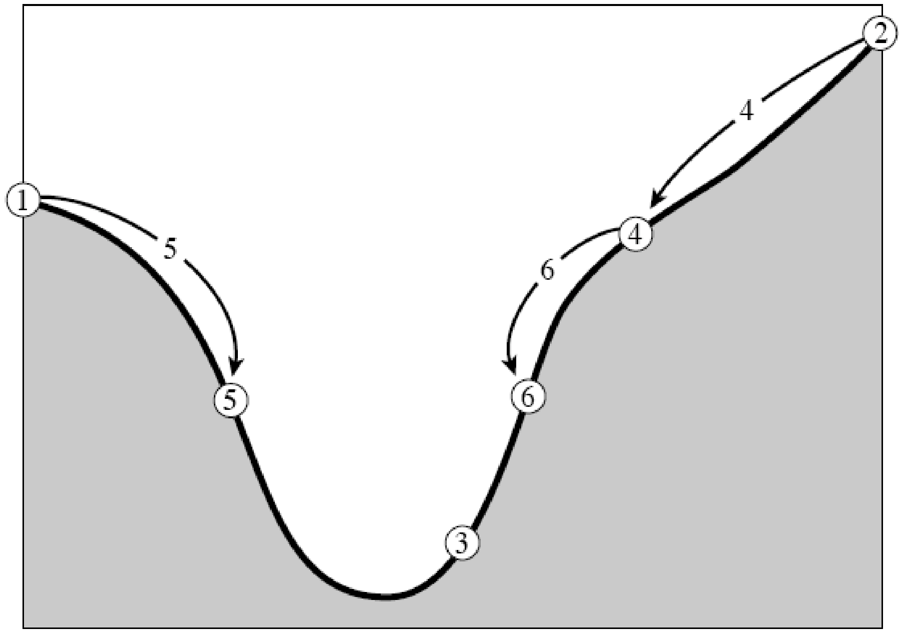
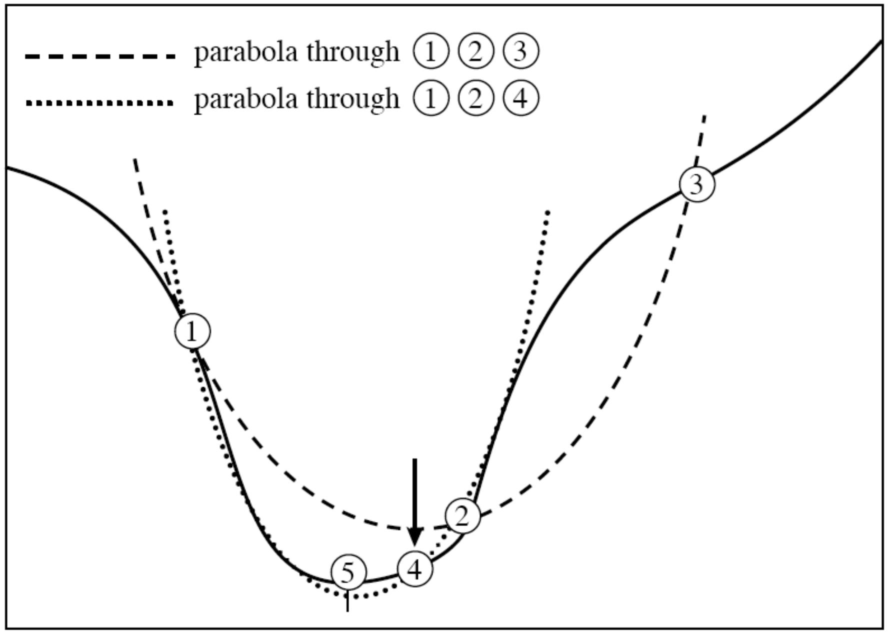


QOOL

- Brent's method for one-dimensional optimization
  - Golden section search + parabolic interpolation
  - Quadratic convergence





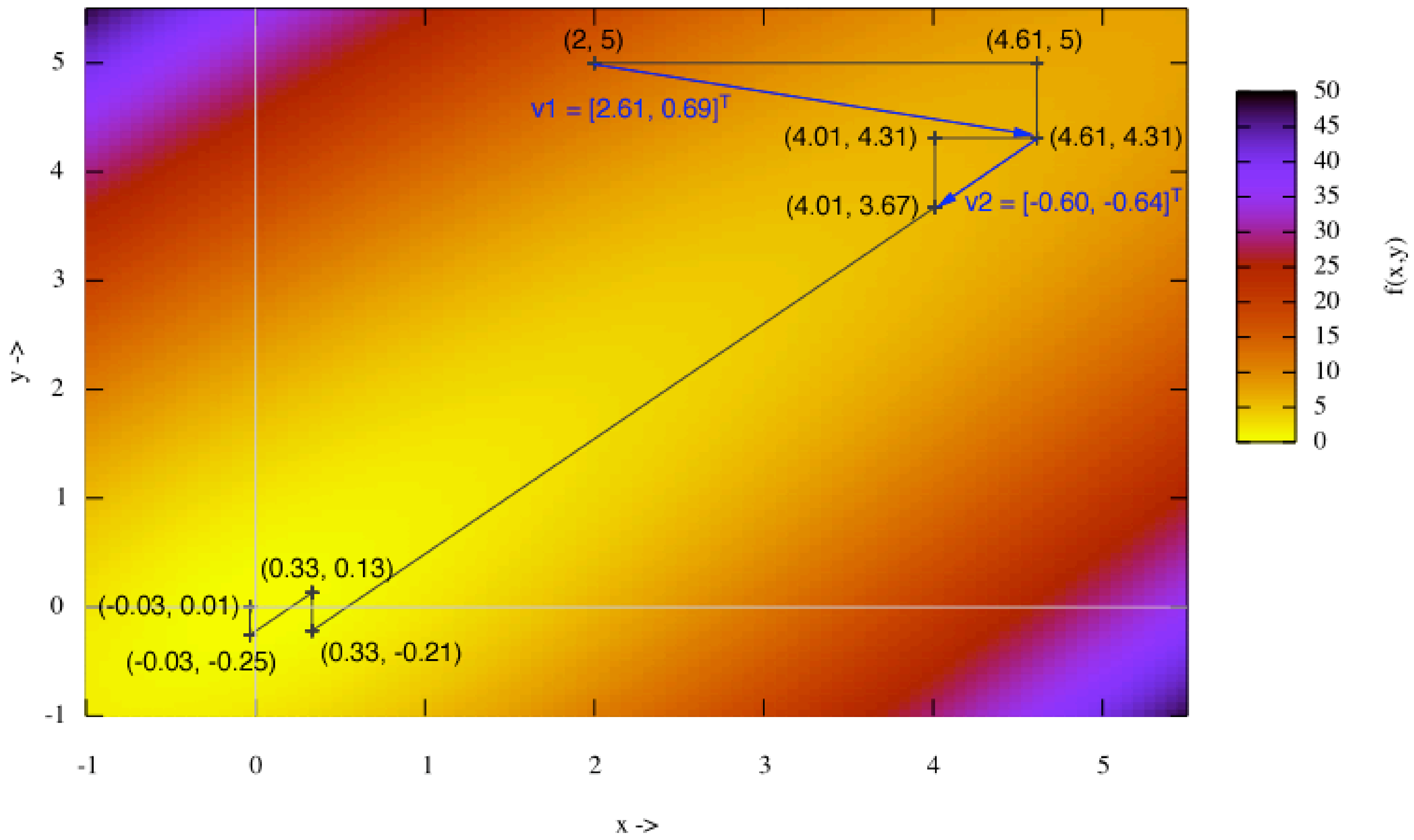
QOOL

- Powell’s method for multidimensions
  - Direction-set method
  - Succeeding line minimizations through **P** in direction **n**
  - Line minimization: Optimize the g with Brent’s method

    g(λ) = f(**P**+λ**n**)
  - Example: Minimization of

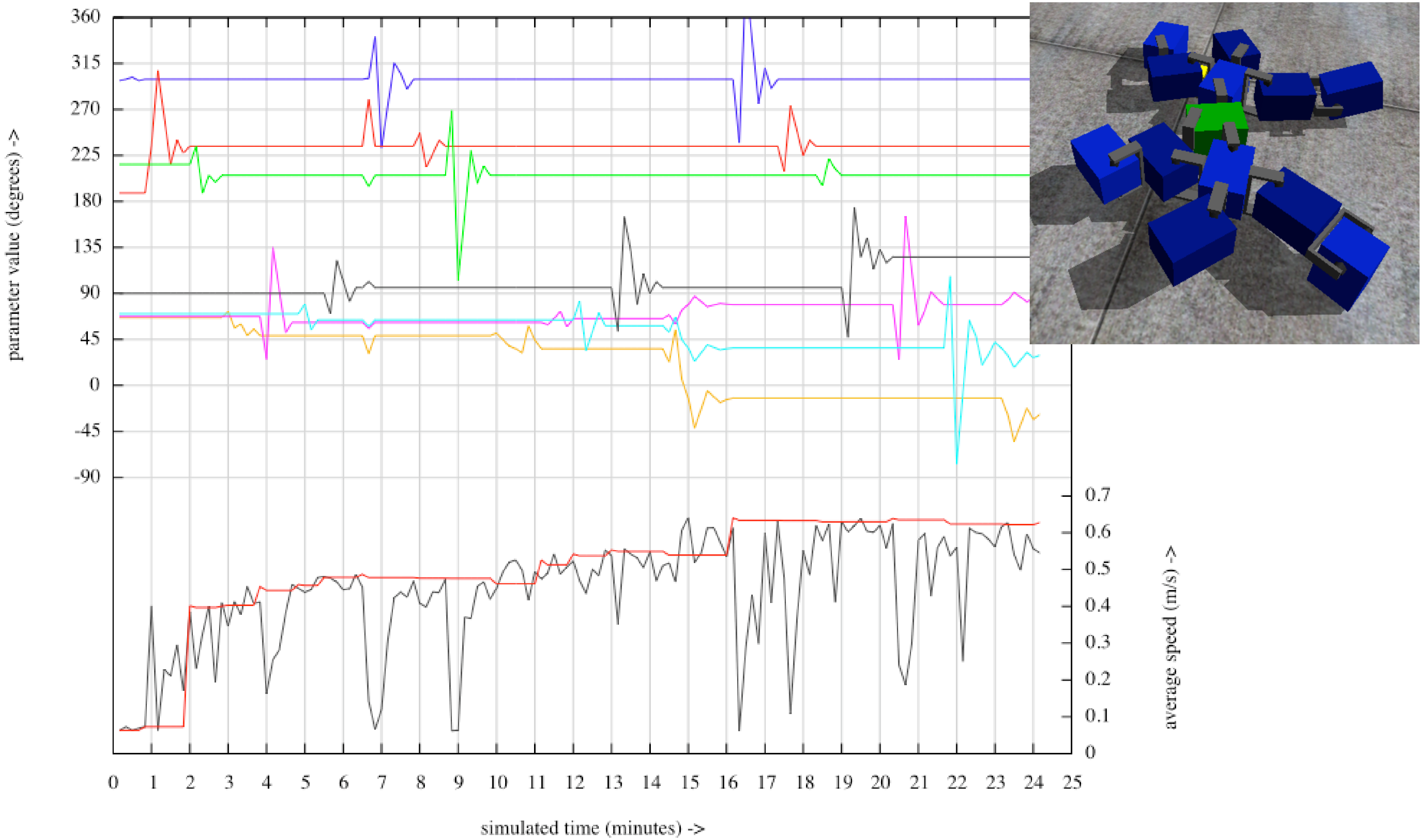
$$f(\mathbf{x}) = |\mathbf{x}| + \sum_{i=1}^{N} \left(x_i - x_{i-1}\right)^2$$

QOOL

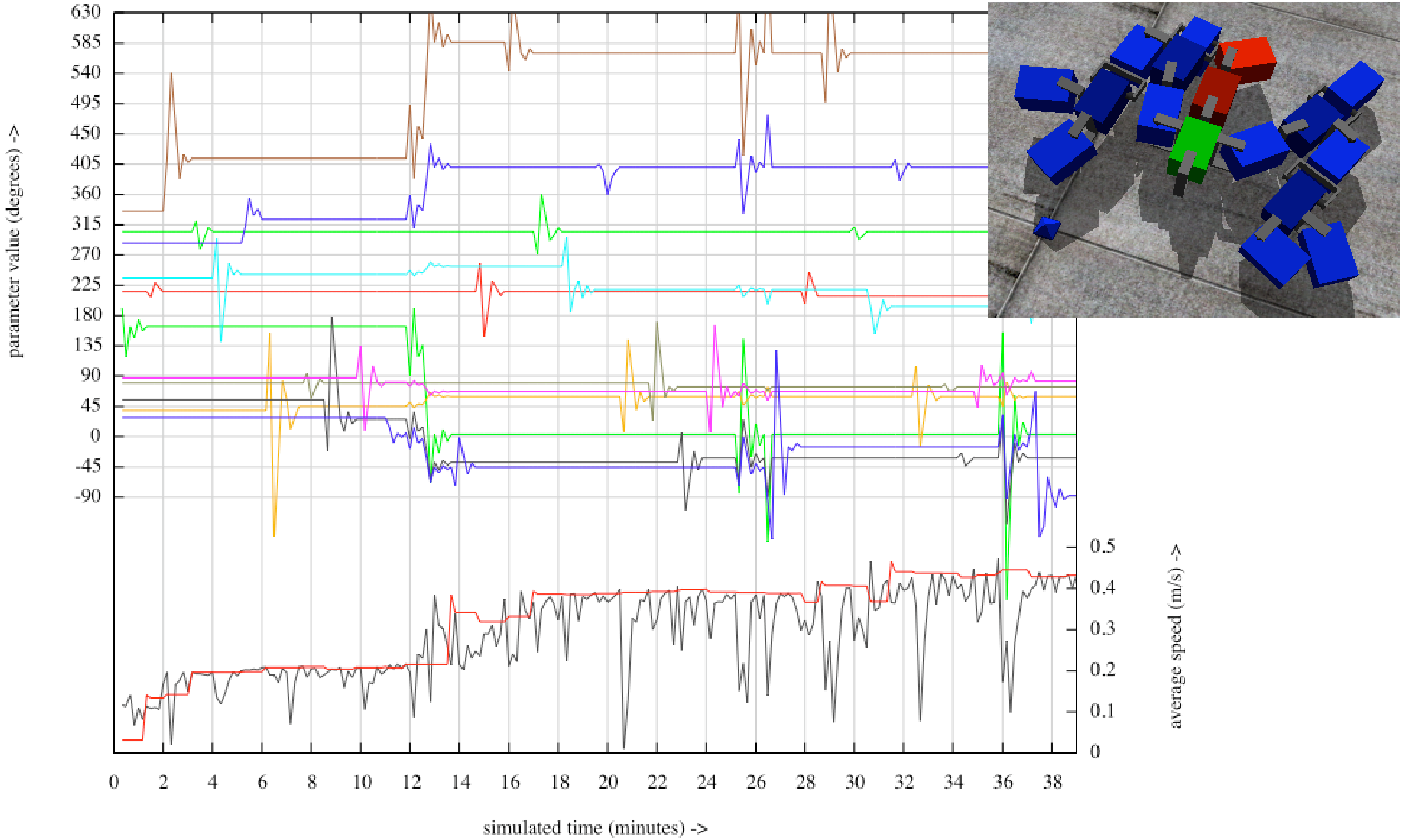


(2, 5)
(4.61, 5)
v1 = [2.61, 0.69]^T
(4.01, 4.31)
(4.61, 4.31)
(4.01, 3.67)
v2 = [-0.60, -0.64]^T
(0.33, 0.13)
(-0.03, 0.01)
(-0.03, -0.25)
(0.33, -0.21)
5
4
3
2
1
0
-1
y ->
-1
0
1
2
3
4
5
x ->
50
45
40
35
30
25
20
15
10
5
0
f(x,y)

QOOL


parameter value (degrees) ->
360
315
270
225
180
135
90
45
0
-45
-90
average speed (m/s) ->
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
simulated time (minutes) ->

QOOL


630
585
540
495
450
405
360
315
270
225
180
135
90
45
0
-45
-90
parameter value (degrees) ->
0.5
0.4
0.3
0.2
0.1
0
average speed (m/s) ->
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38
simulated time (minutes) ->

Conclusions

- Phase prediction and energy balanced couplings
  - Significant reduction of the parameter space
  - Distributed asynchronous and reliable control algorithm for MR
- Co-evolutionary algorithm
  - Symmetric encoding outperforms the general encoding
  - Robots are more complex than those of previous research
  - The locomotion gaits are more elegant and sophisticated than those of other chain-type robots in previous research
- QOOL online optimization
  - New approach to online optimization or adaptation of locomotion
  - Extremely fast

Future work

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- Co-evolution
  - Use L-systems for a generative encoding
- QOOL
  - Test online adaptation with changing environmental constraints
  - Include initial angles in the optimization
- Transfer to the YaMoR hardware…
- Modular robot control
  - Include sensory feedback
  - Design a higher level controller

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Master Thesis

Swiss Federal Institute of Technology Lausanne

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http://birg.epfl.ch/page32031.html