NISE Snake Robot Challenge

Kunal Aggarwal, Katja Frey, Alexandra Samoylova,
Oscar Soto Rivera, Maria Zeller

Elite Master Program Neuroengineering
Technical University of Munich

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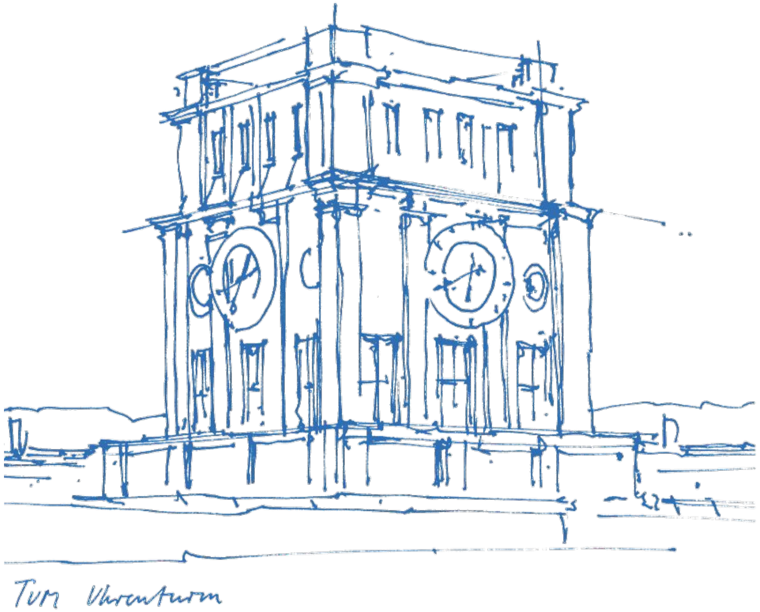


Building the Network and Working Out Coordinated Locomotion:

- **Matsuoka oscillator model**: several parameters influence CPG output

  ⇨ robot’s control becomes complicated and difficult

- **Phase Oscillator Model** (Nor & Ma, 2013, Nor & Ma, 2014)

  The paper describes: ✅ turning behavior
  ✅ change in # of S-shapes (motion pattern change)

  ⇨ a promising approach!

Phase Oscillator Model

Mathematical model of Phase Oscillator:

$$\boxed{\tau}\boxed{\dot{\theta}_i} = 2\pi\boxed{\nu_i} + \sum \boxed{w_{ij}}\sin(\boxed{\theta_j} - \boxed{\theta_i} - \boxed{\phi_{ij}})$$

Output of each oscillator:

$$x_i = \boxed{A}\cos(\theta_i)$$

$$goal\_position = x_i + \boxed{offset}$$

→ *solved with Euler Method*

Time evolution of the phase $\boldsymbol{\theta}_i$

Intrinsic frequency

Coupling oscillator *j* to oscillator *i*

Phase of the *j*th oscillator

Phase of the *i*th oscillator

Phase bias

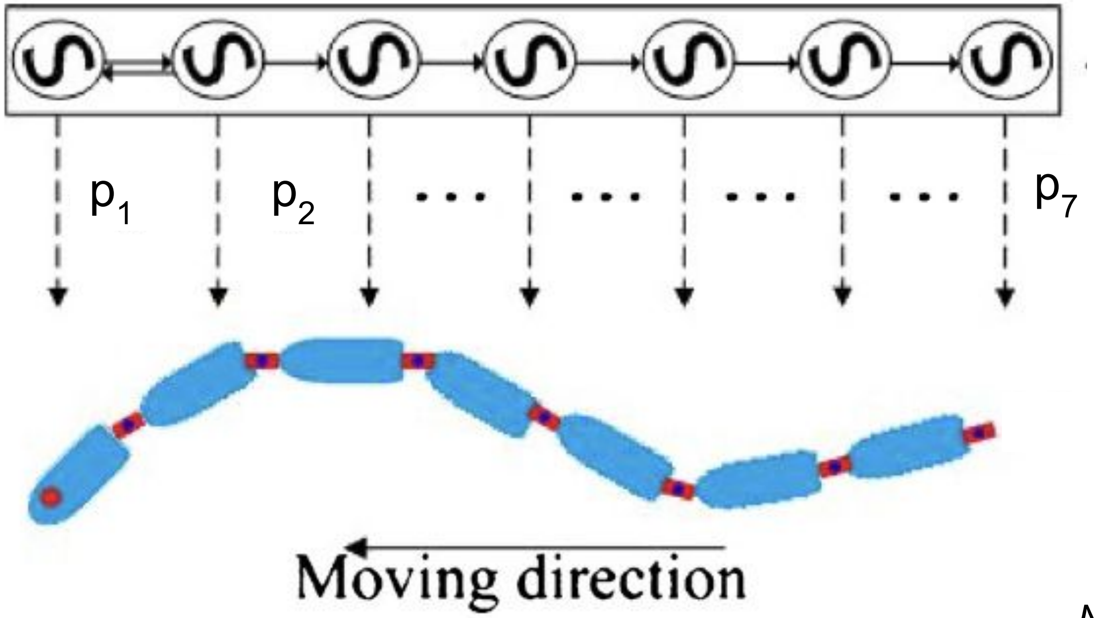
Time constant

Amplitude

Trajectory offset

Phase Oscillator Model

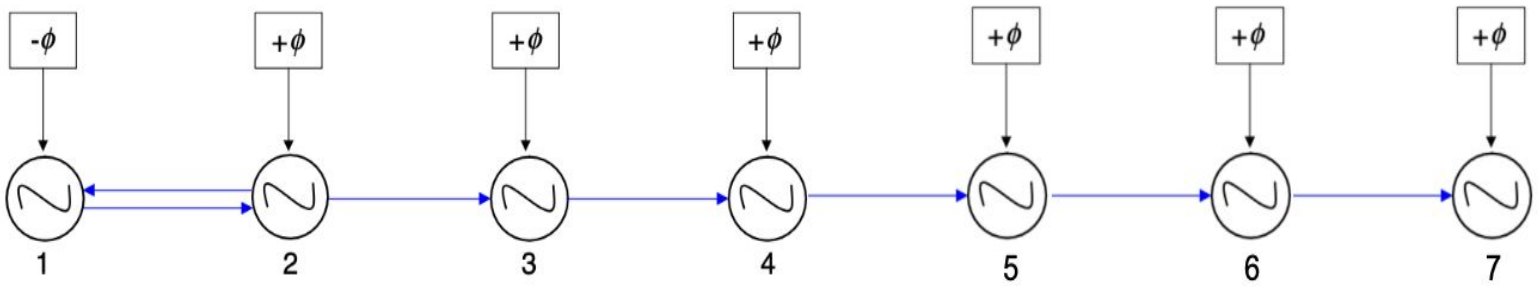
Unidirectional coupling:



Nor & Ma, 2013

Phase Bias Parameter

- $\phi_{ij} = \phi$ for all oscillators
- the sign (±) for ϕ for oscillator 1 → opposite to the other oscillators



Straight Movement Parameters

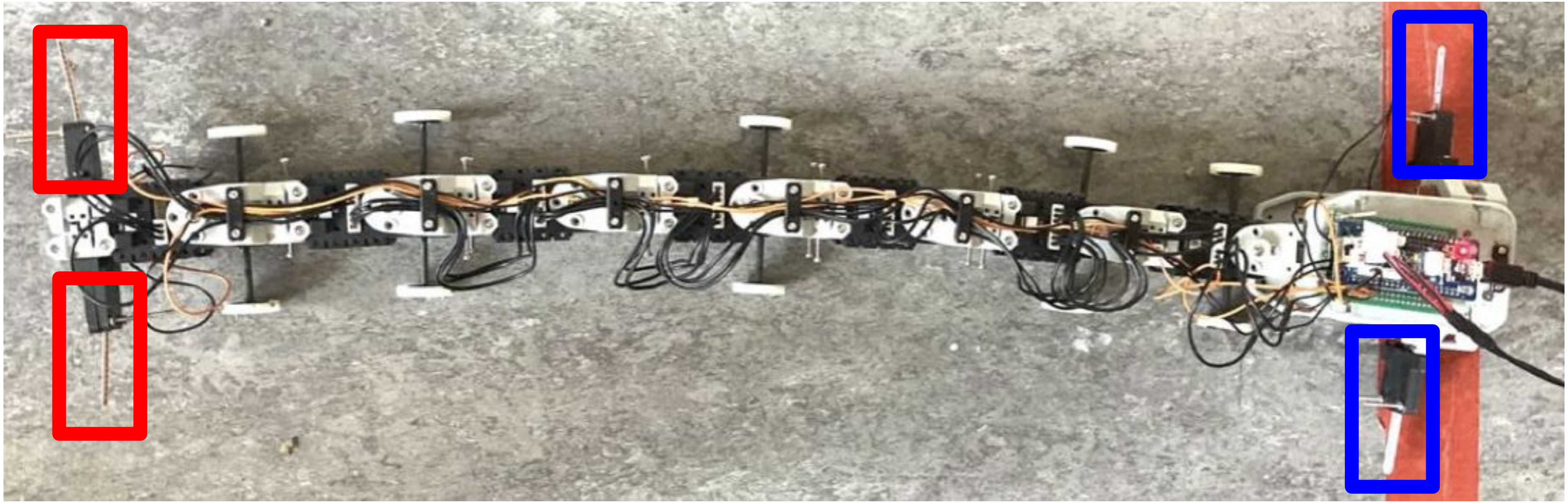
Parameter	***W***	$\boldsymbol{\phi}$	***A***	***trajectory offset***	$\boldsymbol{\tau}$	***v***
Value	10	2π/7	120	511	0.2	0.8

→ same for all oscillators

Changing Behaviour

Back sensors:
Amplitude adjustment

Front sensors:
Left & right movement



- Behavioural change achieved with just 4 sensors
- Sensors at the head & at the tail for better internal representation of environment

Changing Behaviour

***Phase transition-based turning** is not robust in practice (slides 23,24).*
*So, we developed our own approach, based on **offset parameter:***

Left turn: decrease trajectory offset

Parameter	W	ϕ	A	***trajectory offset***	τ	v
Value	10	2π/7	120	max 500 min 451	0.2	0.8

Right turn: increase trajectory offset

Parameter	W	ϕ	A	***trajectory offset***	τ	v
Value	10	2π/7	120	min 522 max 571	0.2	0.8

→ duration: 2 seconds

Changing Behaviour

Phase transition-based approach *is not robust in practice (slides 23,25).*
So, we used an approach based on ***Amplitude and Time-constant parameters:***

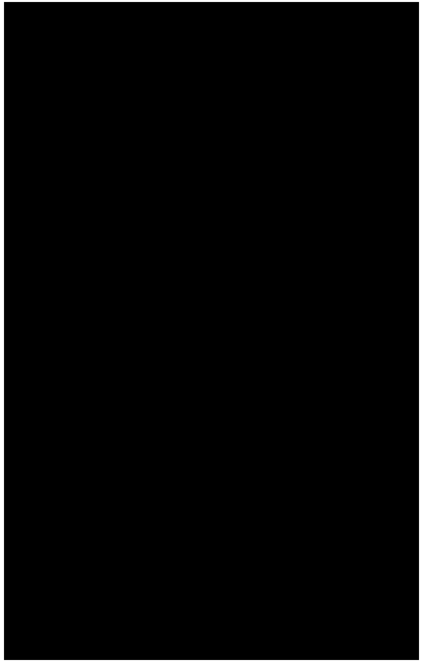
Amplitude adjustment when entering a narrow section:

- Decrease parameter A → decreases speed
- Decrease parameter τ → increases speed

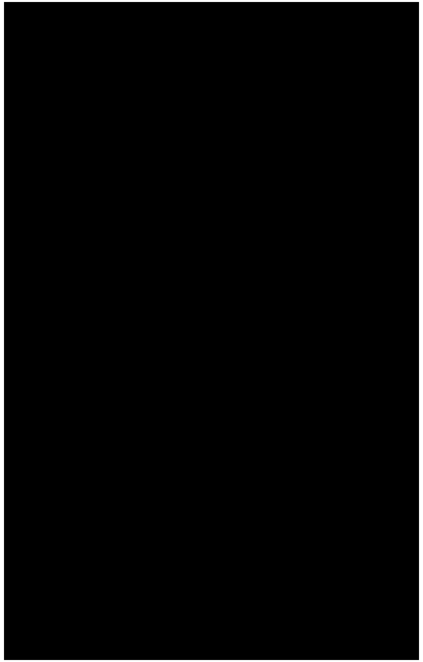
Parameter	***W***	***ϕ***	***A***	***trajectory offset***	$\boldsymbol{\tau}$	***v***
Value	10	2π/7	60	511	0.08	0.8

→ duration: 5 seconds

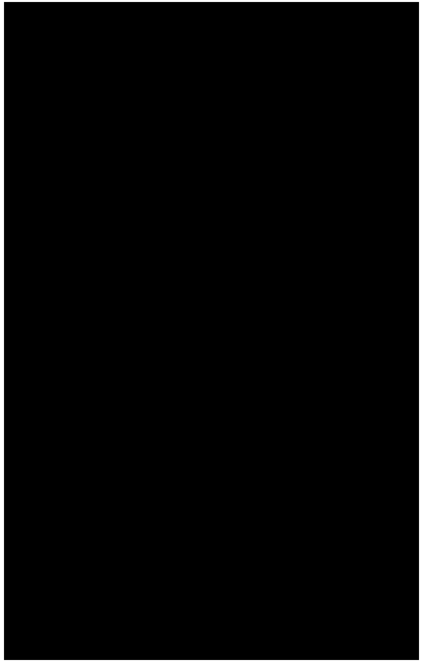
Changing Behaviour



Right turning



Left turning

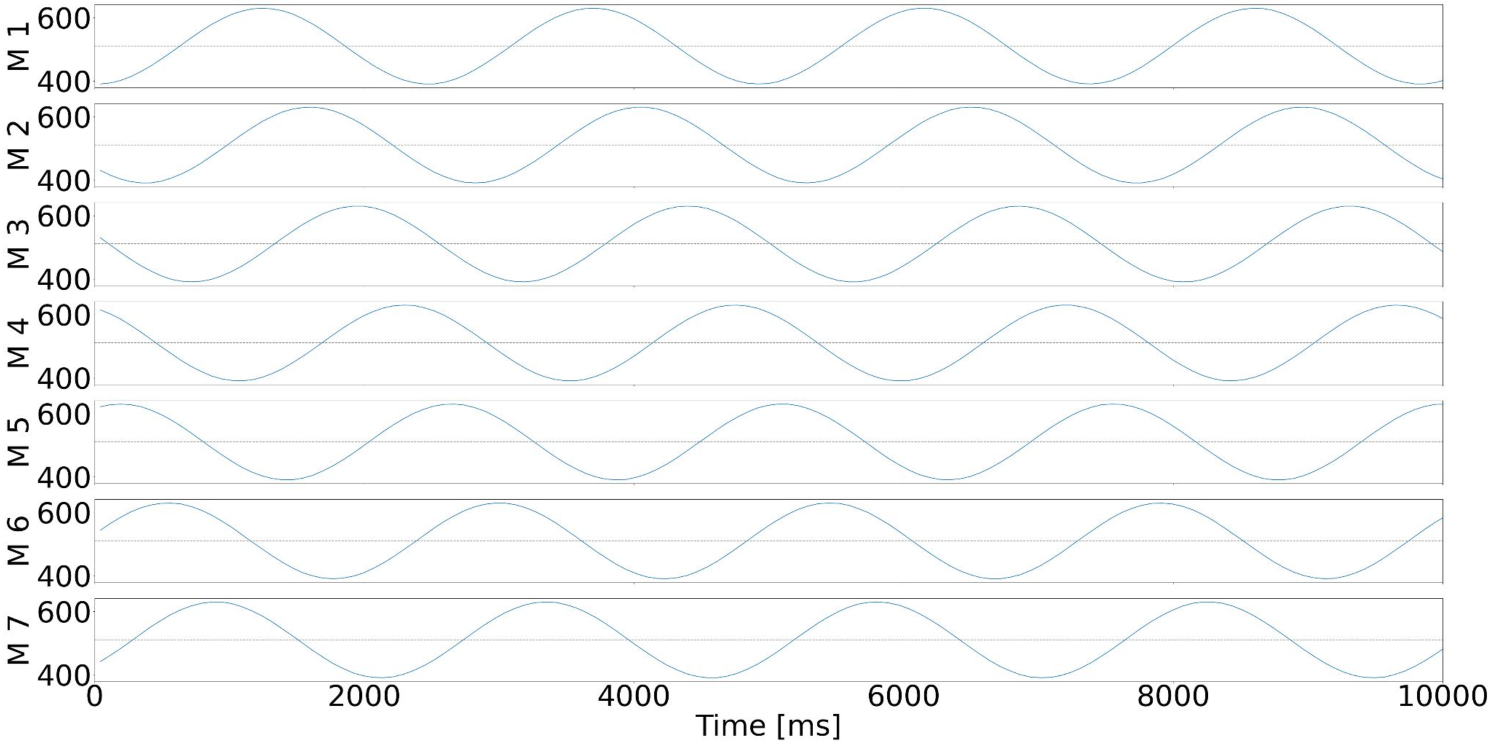


Amplitude change

Evaluations

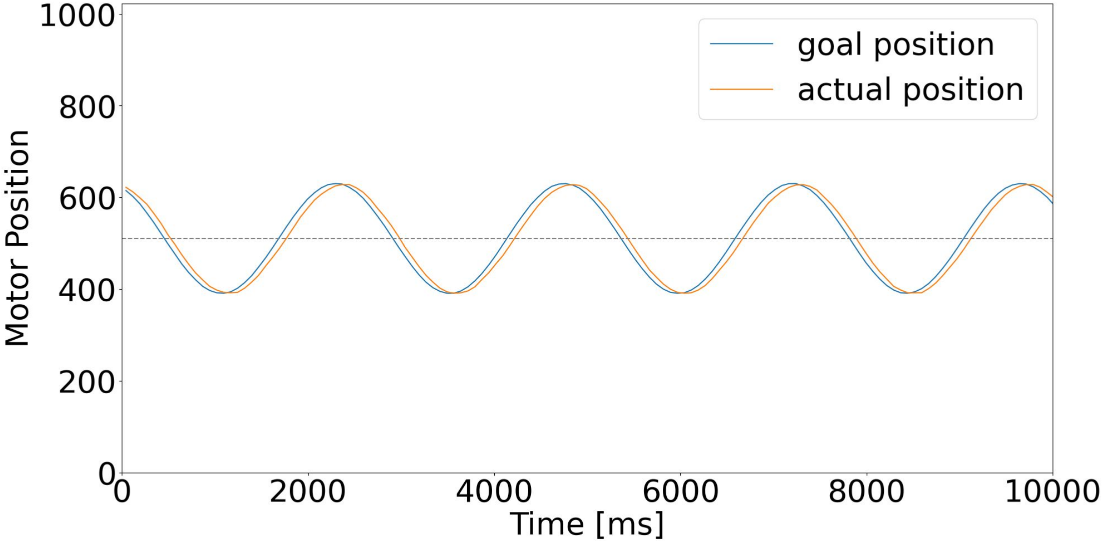
Phase Shift between CPGs

Param.	W	ϕ	A	*offset*	τ	v
Value	10	2π/7	120	511	0.2	0.8



Default Straight Movement

Param.	W	ϕ	A	*offset*	τ	v
Value	10	2π/7	120	511	0.2	0.8



Speed:

0.113 m/s

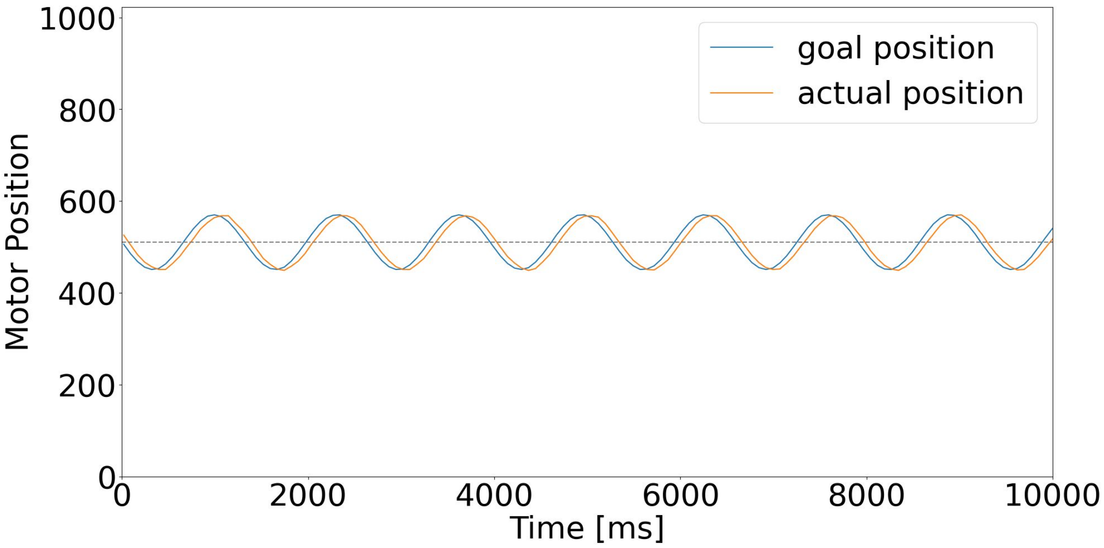
Range of Motion:

Goal Position: 391 - 630

Actual Position: 388 - 629

Narrow Straight Movement

Param.	*W*	*ϕ*	*A*	*offset*	*τ*	*v*
Value	10	2π/7	60	511	0.08	0.8



Speed:

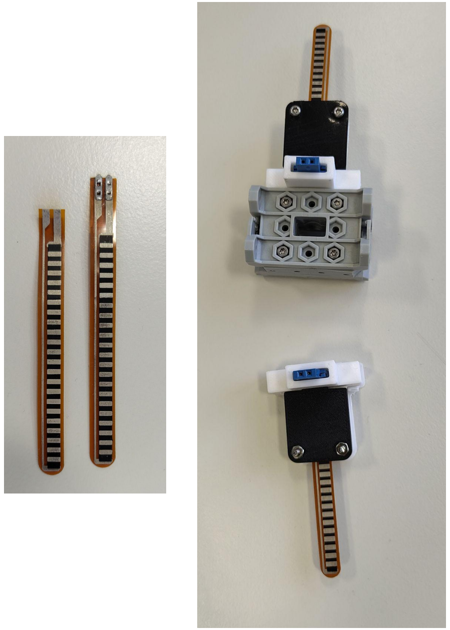
0.124 m/s

Range of Motion:

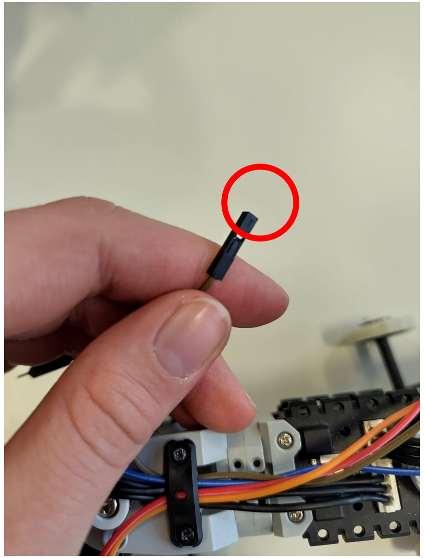
Goal Position: 451 - 570

Actual Position: 448 - 570

Hardware Fixing during the Project

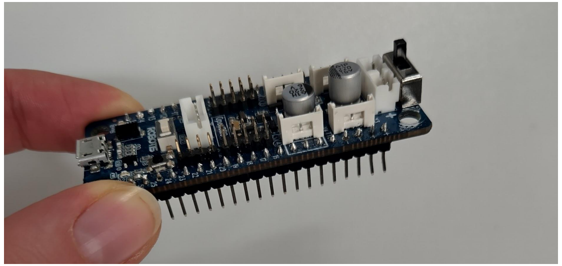


Sensor and sensor holder replacement



Wire replacement

Motor replacement



Sharing a microcontroller

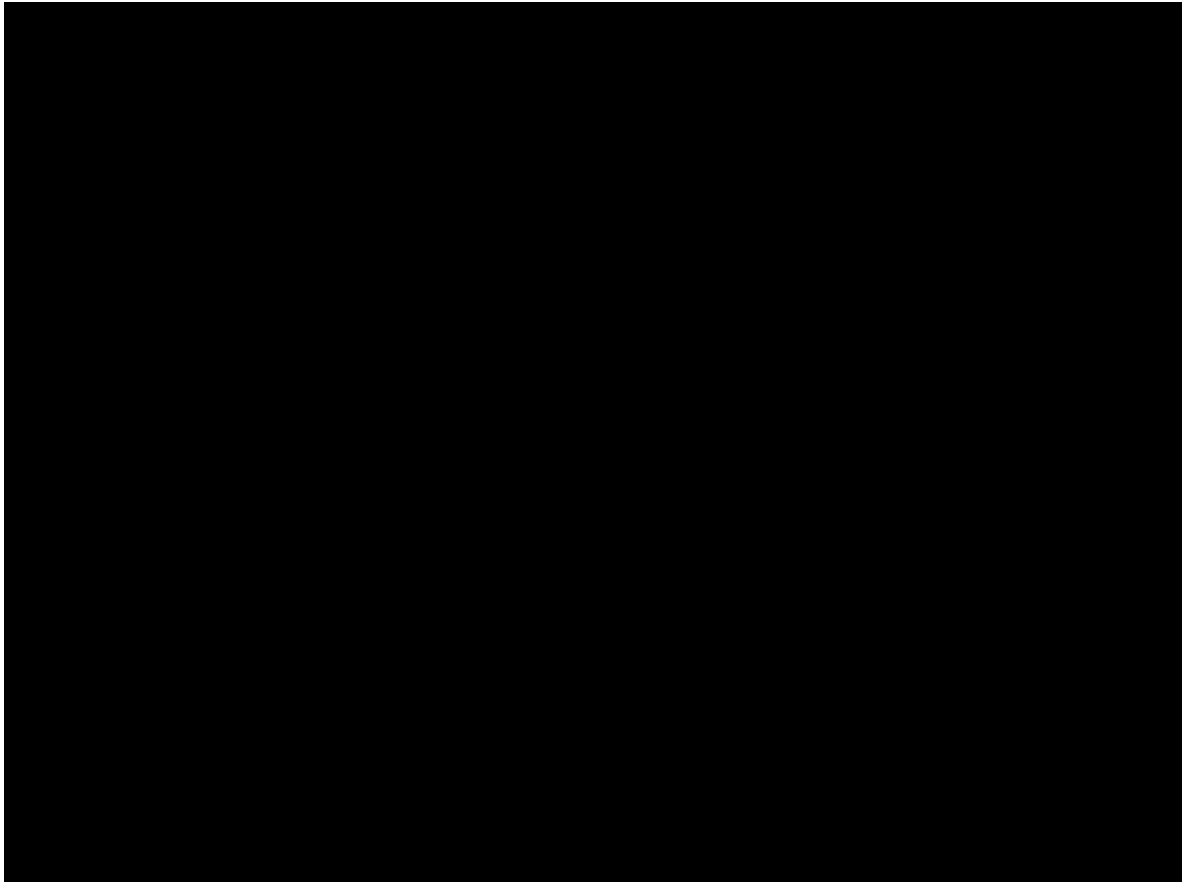
Limitations of Implemented Changing Behaviour

- **Jerky turning** behaviour & **amplitude** change might damage the hardware
  → need for **smoother transitions**

- **A larger number of sensors** would make the robot more robust
  → sooner wide-to-narrow path transition with **sensors in the middle**

- No **parameter tuning** of the phase bias $\boldsymbol{\phi}$
  → might impact the **speed**

Thank you!



References

- Nor, N. M., & Ma, S. (2013). A Simplified CPGs Network with Phase Oscillator Model for Locomotion Control of a Snake-like Robot. *Journal of Intelligent and Robotic Systems*, *75*(1), 71–86. https://doi.org/10.1007/s10846-013-9868-9

- Nor, N. M., & Ma, S. (2014). CPG-based locomotion control of a snake-like robot for obstacle avoidance. *IEEE International Conference on Robotics & Automation (ICRA)*. https://doi.org/10.1109/icra.2014.6906634

Backup Slides

Constraints on Intrinsic Frequency (v) and Coupling Strength (w)

Exemplary for one oscillator θ :

$$\dot{\theta}_3 = 2\pi v + w \sin(\theta_2 - \theta_3 + \phi)$$

Setting the ODE to 0 we obtain:

$$2\pi v + w \sin(\theta_2 - \theta_3 + \phi) = 0$$

Solving for θ_3 we get:

$$\theta_3^{\infty} = \theta_2 + \phi + \sin^{-1}(2\pi v / w)$$

θ_3 will always evolve at constant phase difference of:

$$\theta_2 + \phi + \epsilon, \text{ where } \epsilon = \sin^{-1}(2\pi v / w)$$

for the output of oscillator, to converge to oscillations that are phase locked with a phase difference of ϕ, we need:

$$v << w$$

for ε to become so small that it can be neglected

➔ introduction of parameter τ to control both v and w while keeping the system dynamics

Nor & Ma, 2013

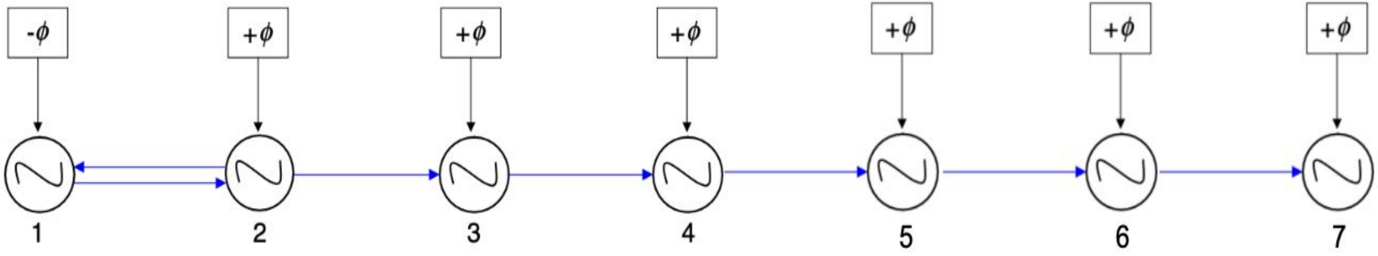
Phase Bias Parameter

- $\phi_{ij} = \phi$ for all oscillators with:

$$\phi = 2\pi N/n$$

N = # of S-shapes ,
n = # of actuated joints from head to tail

- The sign (±) for ϕ for oscillator 1 → opposite to the other oscillators



Modification of Number of S-Shapes (N) via Phase Transition

In order to change number of S-shapes N in robot's locomotion from *N1* to *N2*, phase bias should be changed from ϕ1 to ϕ2. This happens during phase transition time (*t2-t1*), by continuously adjusting bias term as follows :

$$\phi = \phi_1 - \alpha(t_1 - t)$$

$$\alpha = \phi_1(N_2/N_1)(1 - (N_1/N_2))/(t_2 - t_1)$$

Where:

ϕ1 - old phase bias term

ϕ2 - new phase bias term

N1 - old # of S-shapes

N2 - new # of S-shapes

t1 - phase transition start time

t2 - phase transition end time

t - current time

Attempted Implementation of Behaviour Change via Modification of Number of S-Shapes (N) via Phase Transition

We implemented **phase transition via modification of phase bias parameter** as described in *Nor & Ma, 2013*. We applied phase transition strategy to implement:

1. **Turning behavior** by transitioning from N1→N2, where N1>N2
2. **Oscillation amplitude/frequency change in narrow/wide path behavior**, with N1→N2

   where N1>N2 for wide->narrow change

   where N1<N2 for narrow->wide change

For both behaviors, we observed the expected result: change in number of S shapes
However, these **changes were not robust enough** for real-world use *(see next slides)*.

Attempted Implementation of Behaviour Change via Modification of Number of S-Shapes (N) via Phase Transition

Turning behavior:

For turning behavior, N2 must be smaller than N1.
We observed desired pattern change for N2=2 and N1=1 as well as N2=1.5 and N2=1.

Next we needed to find a (t2-t1) parameter which would guarantee that snake makes **less than 0.5 of motion cycle** (otherwise it continues straight motion, with the new number of S-shapes N2).

We used (t2-t1) parameters ranging from 0.1 to 10 seconds:

- For (t2-t1)<2sec, we observed no pattern change
- For (t2-t1)>=2sec, snake makes one movement cycle or more, moving straight (not turning).

One possible reason: the method is not robust enough.
In *Nor & Ma, 2013,* turning behavior via phase transition was simulated,
but no exhaustive experimental results proving robustness of the method were provided.

Attempted Implementation of Behaviour Change via Modification of Number of S-Shapes (N) via Phase Transition

Oscillation amplitude/frequency change in narrow/wide path behavior:

For the above mentioned behavior, depending on environment change, the number of S-shapes should either increase (wide->narrow path) or decrease (narrow->wide path). After this change, straight movement should proceed.

We observed expected pattern changes for N1=1 and N2=2, N1=1 and N2=3, N1=1 and N2=1.5, N1=2 and N=1, N2=1 and N2=1, N1=1.5 and N2=1.

However, we observed, that during transitions N1->N2 **where N2>N1**, the snake develops N2>4 some time after phase transition. The number of S-shapes is too large for effective straight movement, so the **snake does not move effectively** (even though motors are turning).

One possible reason: flaws in our implementation.

Even though the approach worked well for N1>N2, it failed for N1<N2, so we could not use it.

Parameter Tuning

Parameter	*W*	*ϕ*	*A*	*offset*	*τ*	*v*	*speed*
Nor & Ma, 2013	10	2π/7	1	511*	0.2*	0.1	0 m/s
Measurement 2	10	2π/7	120	511	0.2	0.1	0.013 m/s
Measurement 3	10	2π/7	120	511	0.08	0.1	0.026 m/s
Measurement 4	10	2π/7	120	511	0.08	0.8	0.232 m/s
Chosen Default	10	2π/7	120	511	0.2	0.8	0.113 m/s
Measurement 6	10	2π/7	60	511	0.2	0.8	0.054 m/s
Chosen Narrow	10	2π/7	60	511	0.08	0.8	0.124 m/s

no movement
→ increase A

very slow
→ decrease τ **

still slow
→ increase v

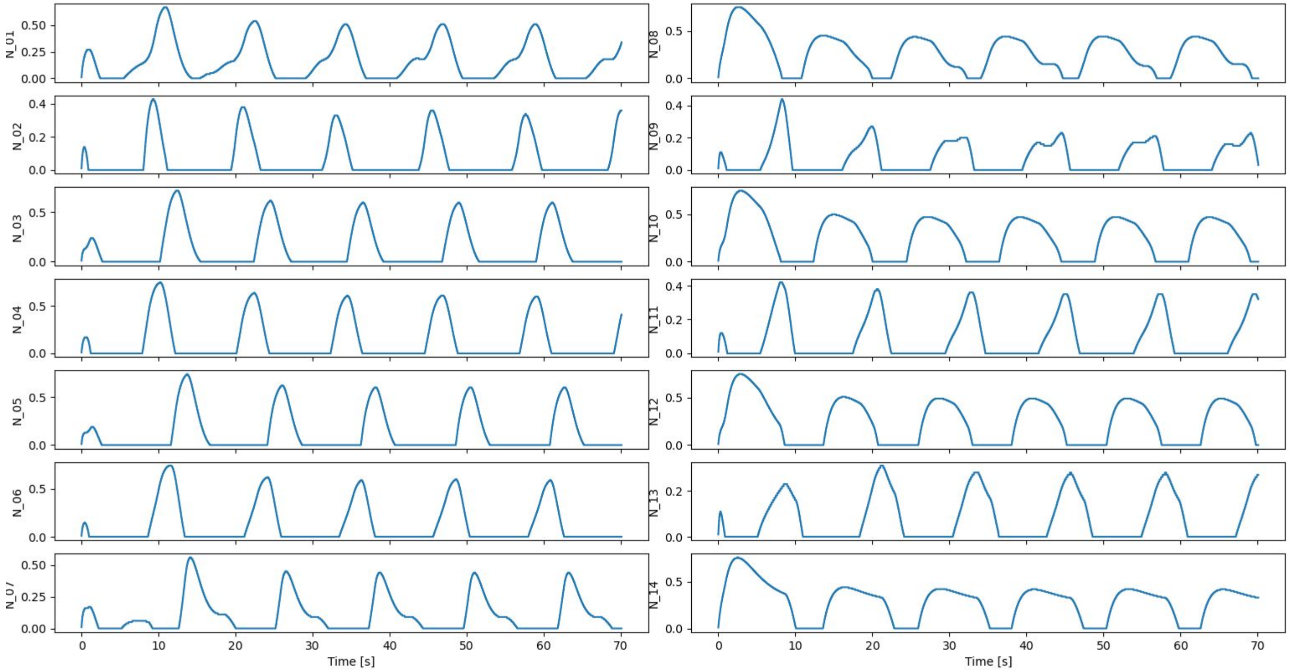
violent speeding
→ decrease τ

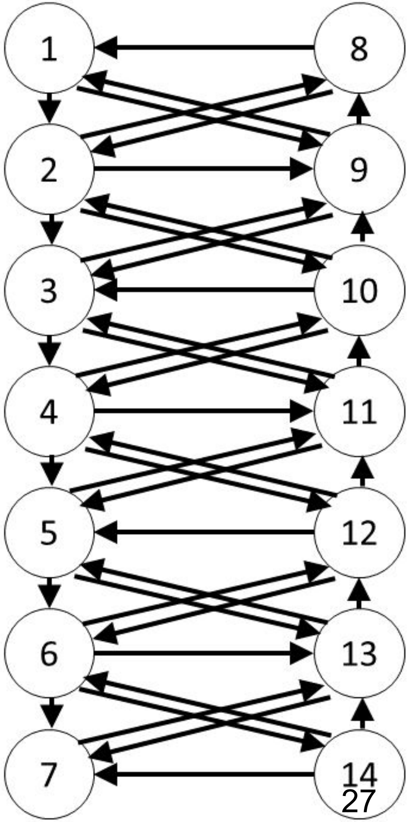
explore narrow movement
→ decrease A

too slow
→ decrease τ

* not specified in paper, 1/20 ≥ τ ≤ 1, ** for relationship v, w, τ see slide 20

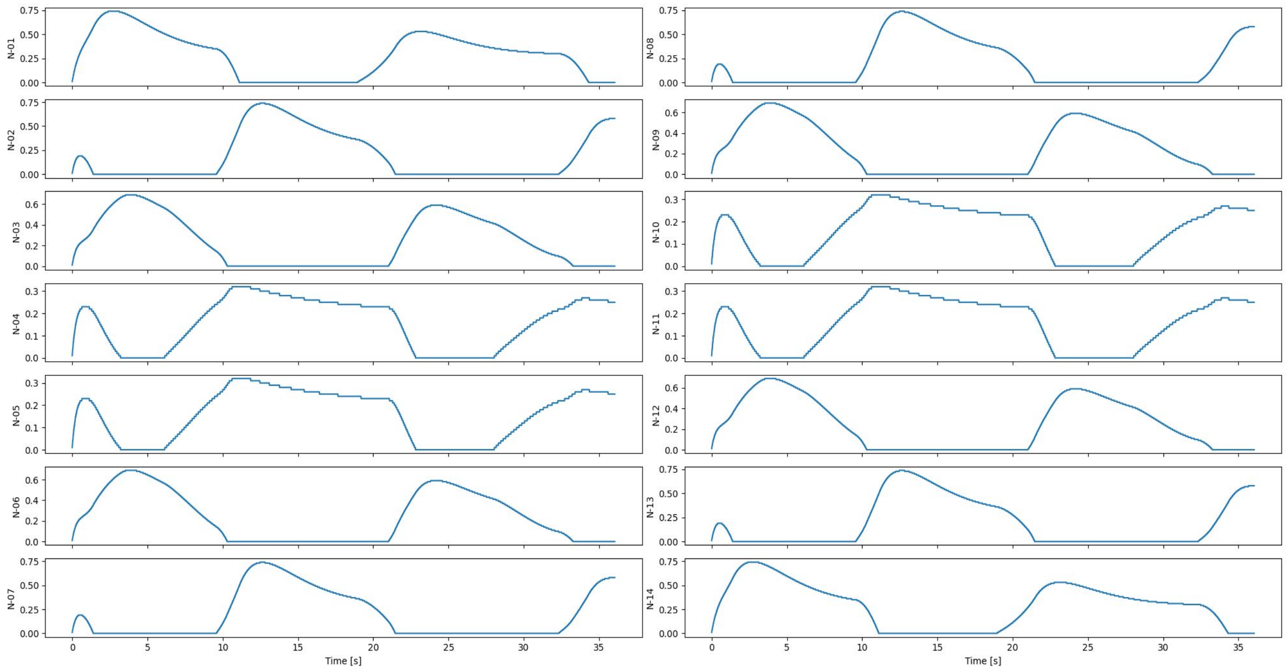
Matsuoka Model Configurations Testing

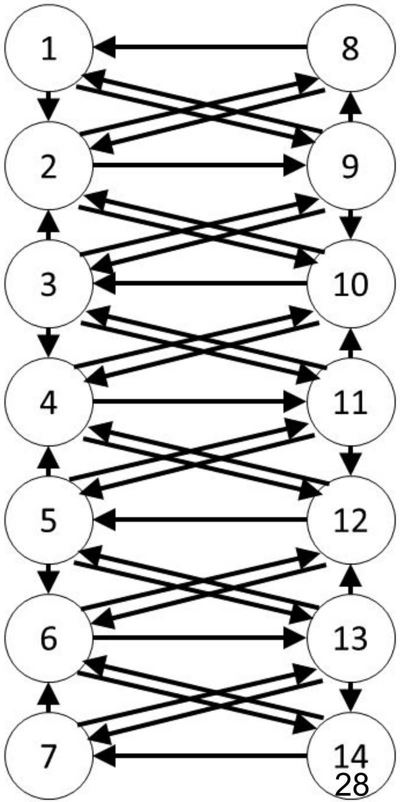




→ no horizontal mutual inhibition, phase difference too large, varying shapes

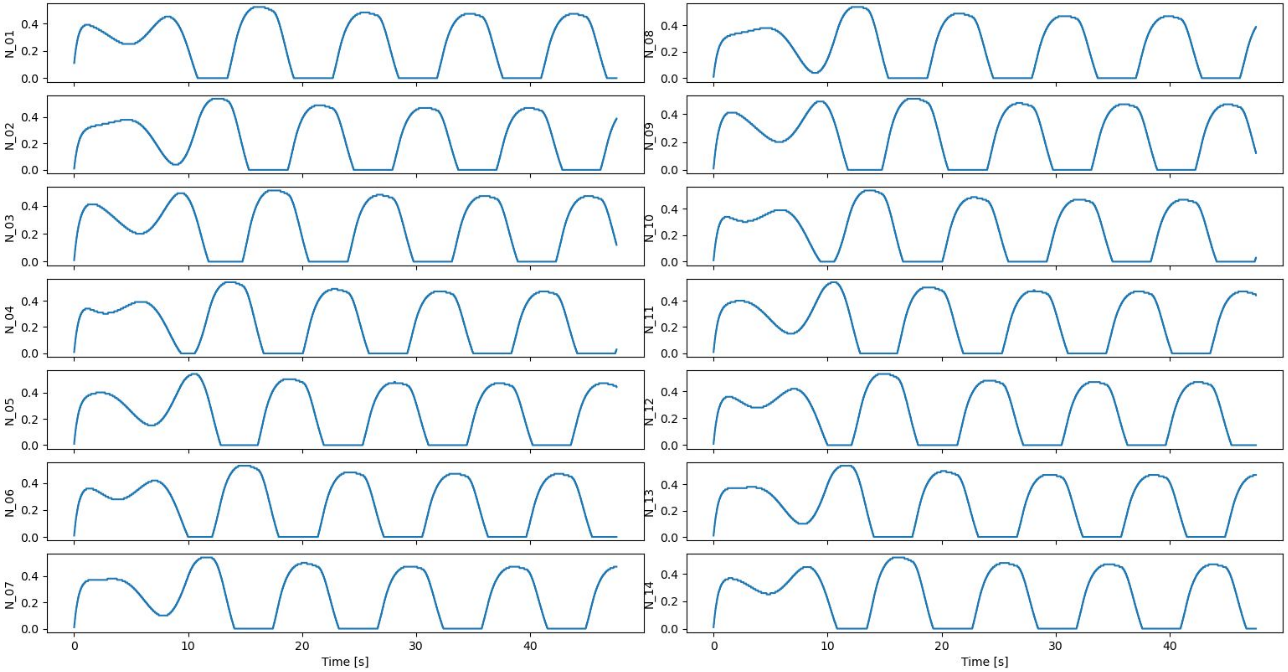
Matsuoka Model Configurations Testing

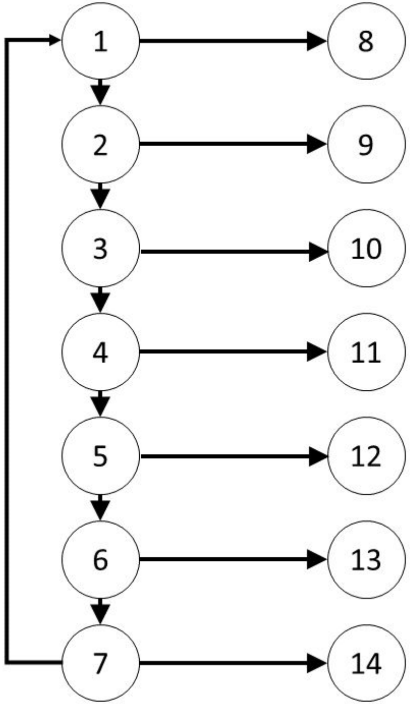




→ period and phase difference too large, varying shapes

Matsuoka Model Configurations Testing





→ phase difference too large