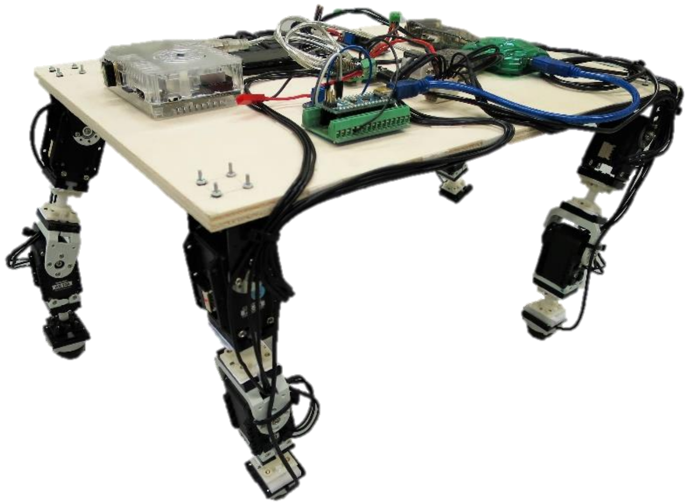
Final Presentation

CPG and Tegotae based Locomotion Control of Quadrupedal Modular Robots



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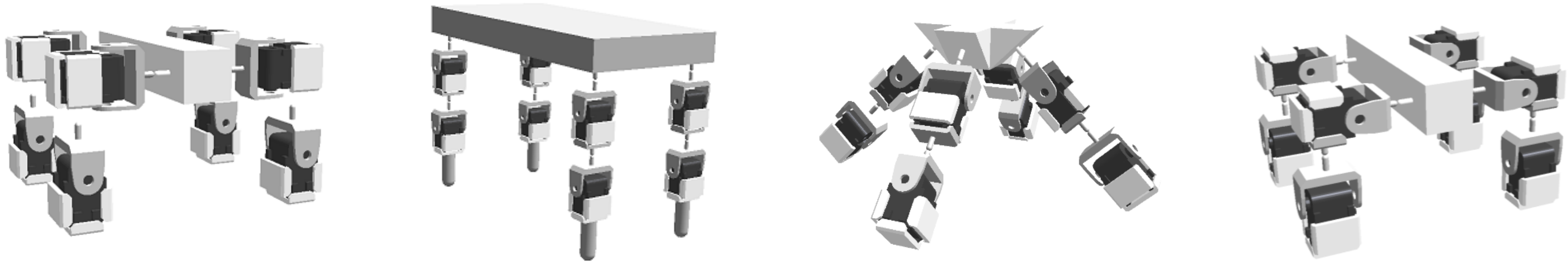
Florin Dzeladini
Prof. Auke Ijspeert
Prof. Paulo Oliveira

Control Problem

Is there a general approach to control ~~arbitrary~~ modular robots?

Control Problem

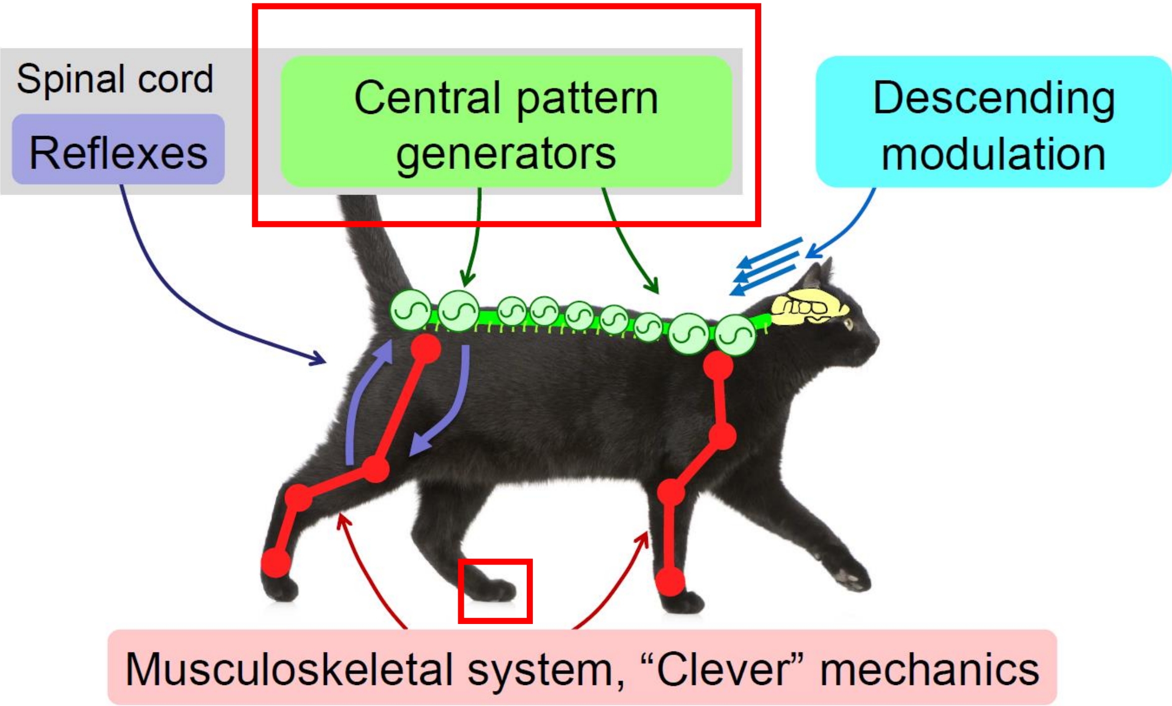
Is there a general approach to control $\boxed{\text{quadrupedal}}$ modular robots?



Simplifications:

1. 8 degrees of freedom
2. Symmetric configuration
3. Central body

Bioinspiration

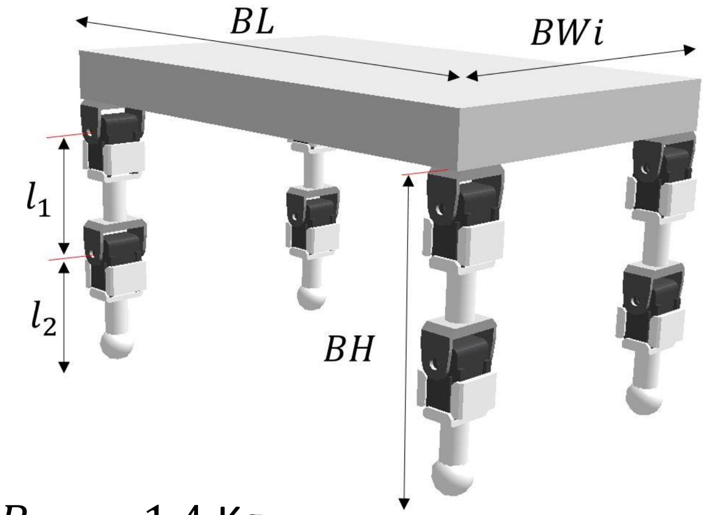


[Ijspeert A.]

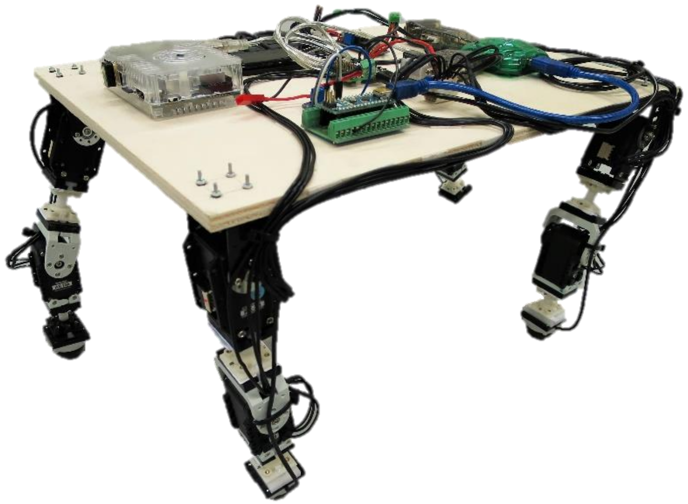
Methods

Base Morphology

Simulation	Hardware



$B_{wg} = 1.4$ Kg



$B_{wg} = 2$ Kg

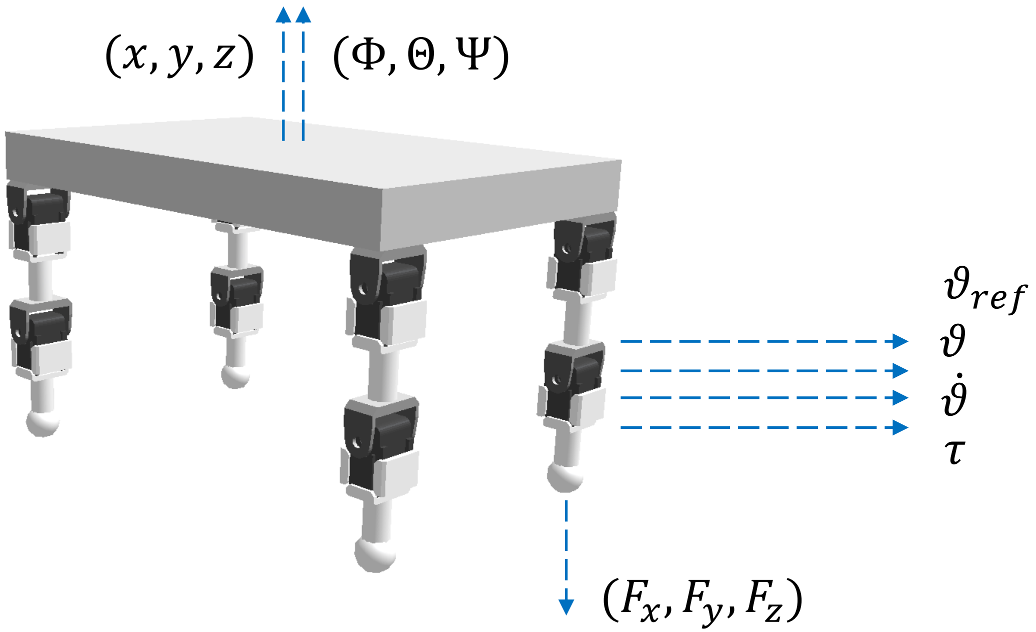
Simplifications:

1. Planar Limbs
2. Specialized foot

Base Morphology

Simulation

Webots
robot simulation



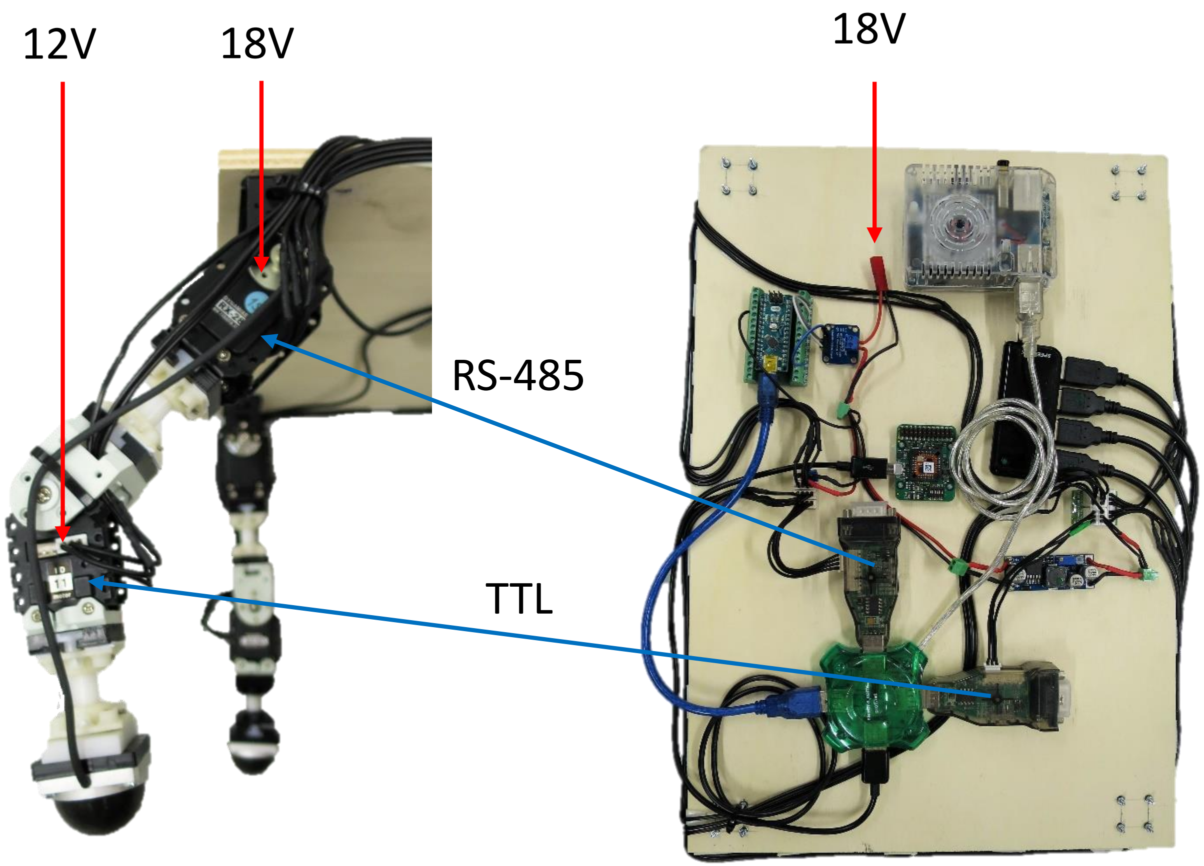
$$P_m(kT) = \sum_{i=1}^{n} \sum_{j=0}^{m} \dot{\vartheta}_{j,i}(kT) \cdot \tau_{j,i}(kT)$$

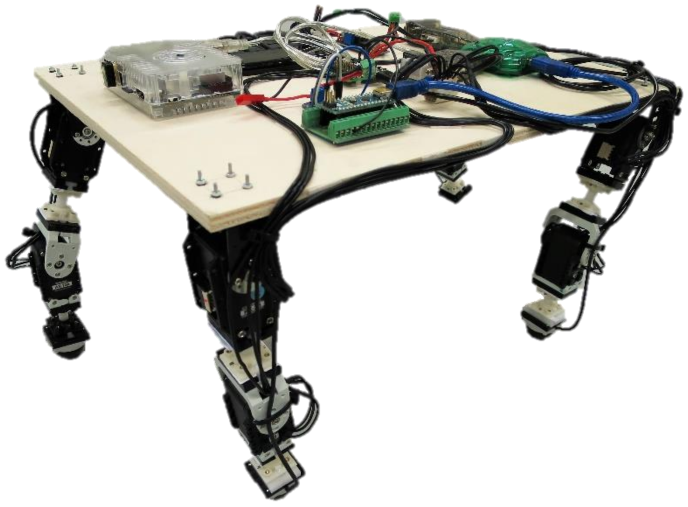
$$E_t = \sum_{k=k_m}^{k_e} P_m(kT)$$

$$\epsilon_t = COT^{-1} = D_t / E_t$$

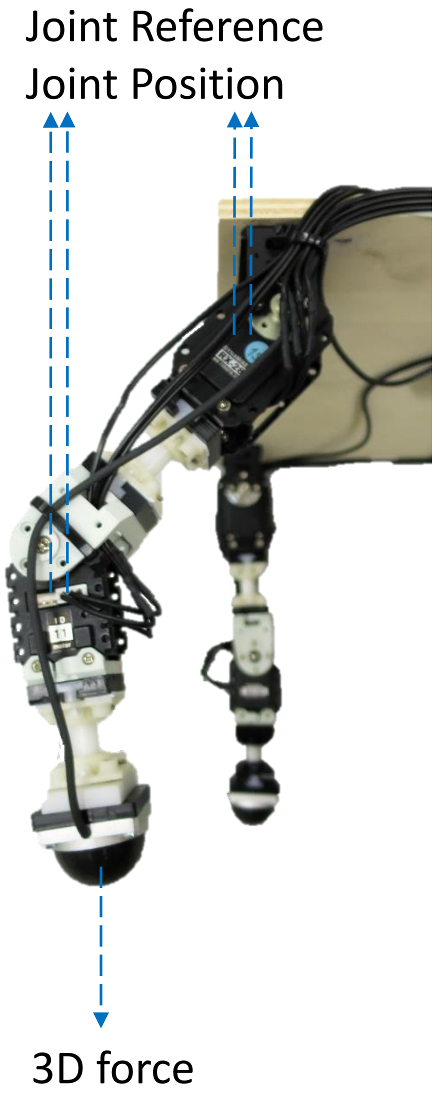
Base Morphology

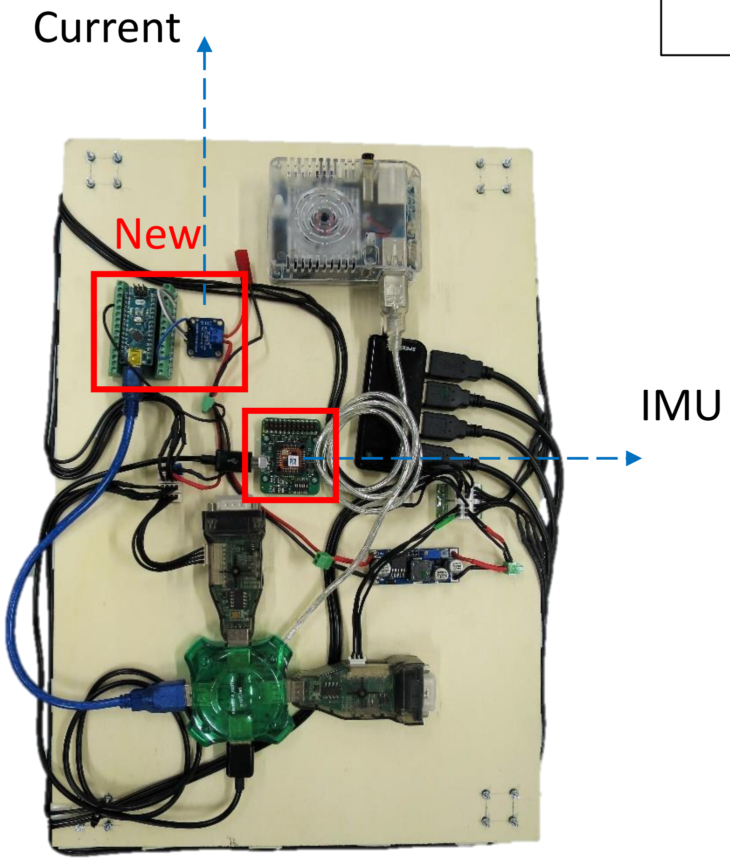
Hardware





Base Morphology





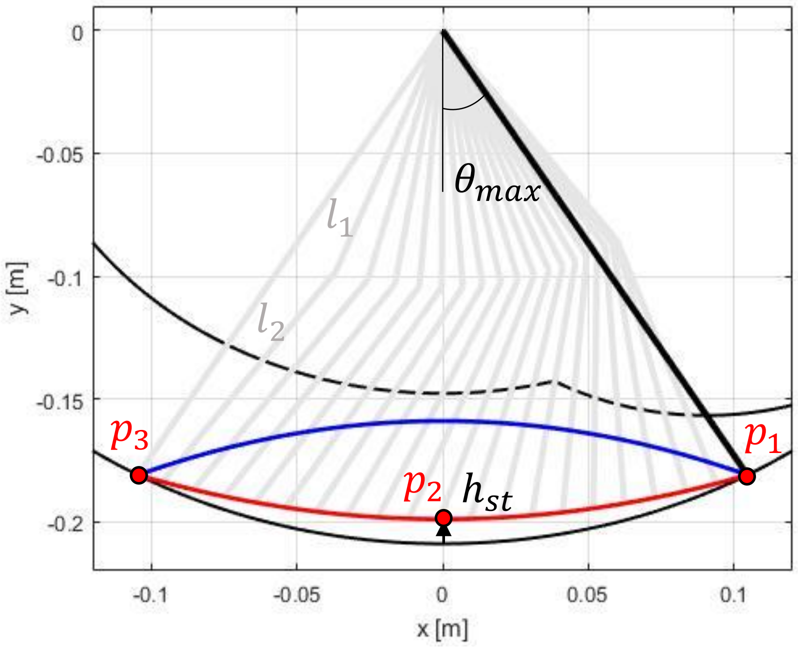
Hardware

$$E_t = \sum_{k=k_m}^{k_e} V_{in} \cdot I_{in}(kT)$$

$$\epsilon_t = COT^{-1} = D_t/E_t$$

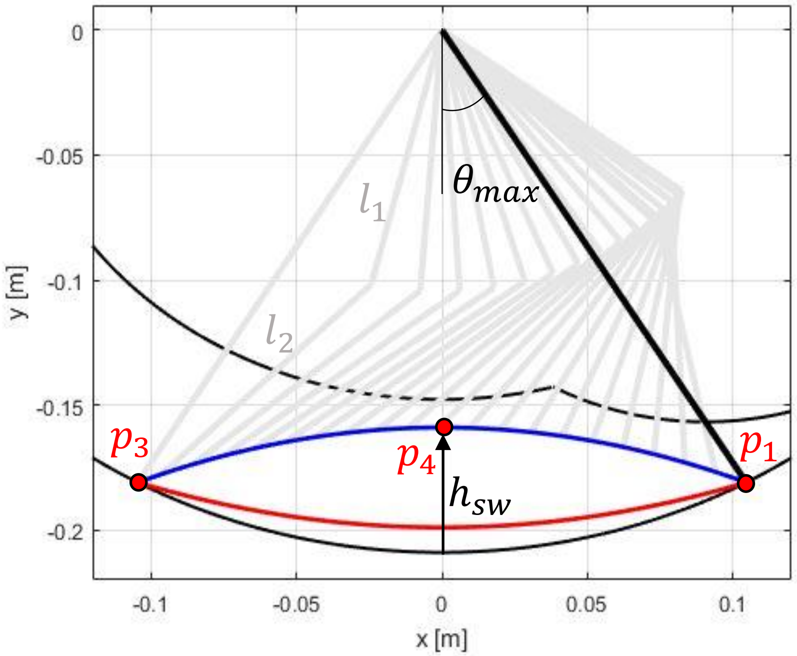
Step Trajectory

Stance phase	Swing phase



Parameters:

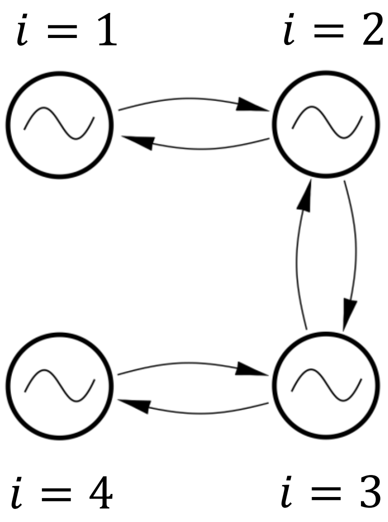
1. θ_{max}
2. h_{st}
3. h_{sw}

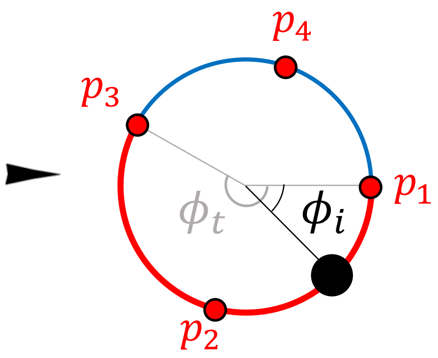


Control Approaches

Open Loop CPG

$$\dot{\phi}_i = 2\pi f + \sum_j w_{ij} \sin(\phi_j - \phi_i - \psi_{ij})$$



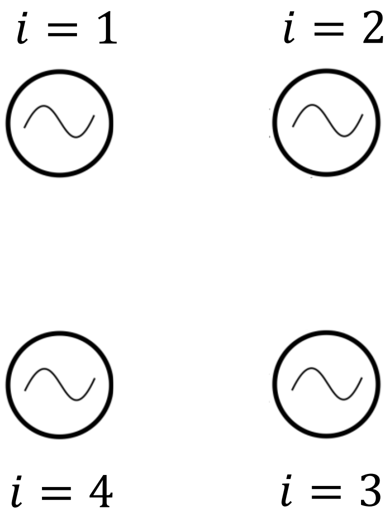


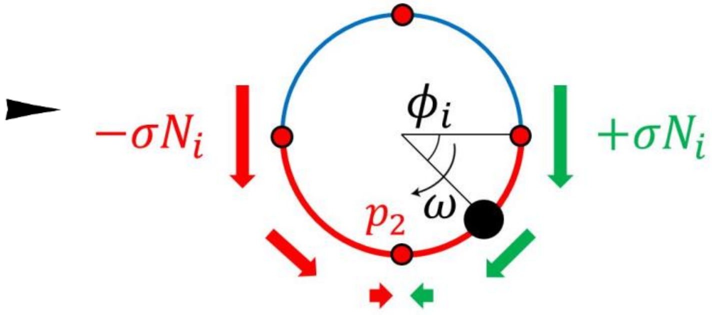
Parameters:

1. f
2. df
3. $\psi_{ij} = -\psi_{ji}$

Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma\, N_i \cos(\phi_i)$$





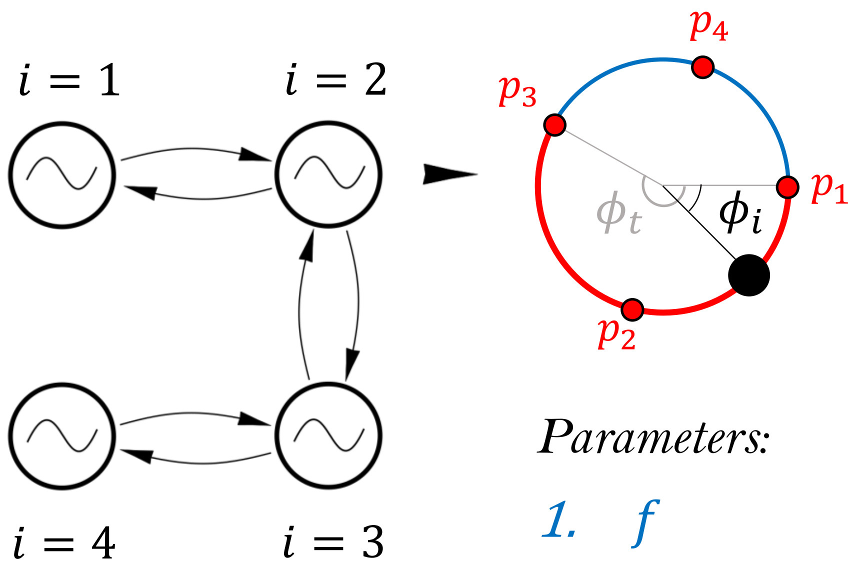
Parameters
:

1. f
2. σ

Control Approaches

Open Loop CPG

$$\dot{\phi}_i = 2\pi f + \sum_j w_{ij}\ \sin(\phi_j - \phi_i - \psi_{ij})$$



Parameters:

1. f
2. df
3. $\psi_{ij} = -\psi_{ji}$

Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma\ N_i\ \cos(\phi_i)$$

Binary Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma_b\ B_i\ \cos(\phi_i)$$

$$B_i = \begin{cases} 1 & \text{if } N_i > 0.2\ \text{N} \\ 0 & \text{if } N_i < 0.2\ \text{N} \end{cases}$$

Goals

Thesis Goals

Open Loop CPG

$$\dot{\phi}_i = 2\pi f + \sum_j w_{ij}\ \sin(\phi_j - \phi_i - \psi_{ij})$$

1. Trajectory
2. Duty factor

Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma\ N_i\ \cos(\phi_i)$$

1. Trajectory
2. Effect of σ
3. Scaled by frequency?
4. Binary Tegotae?

Convergence

Steady State

Energy

Speed

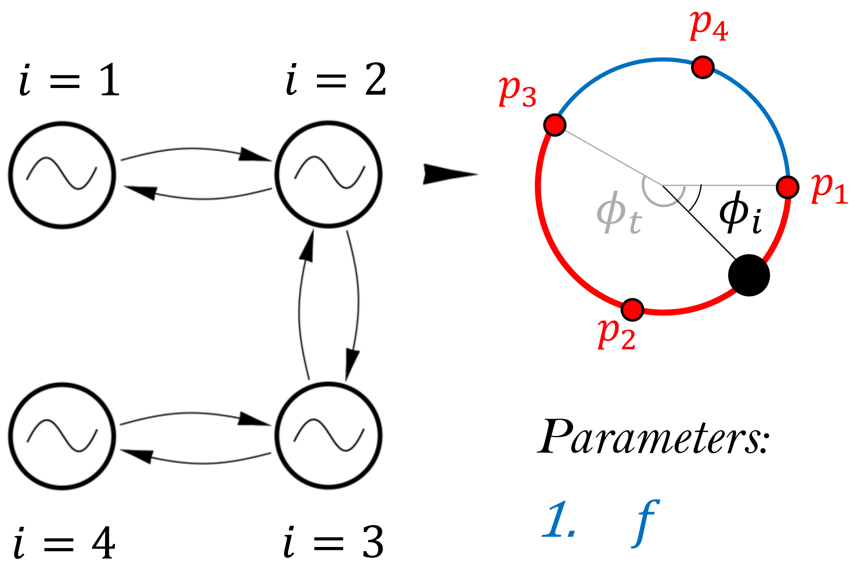
Stability

Results

Control Approaches

Open Loop CPG

$$\dot{\phi}_i = 2\pi f + \sum_j w_{ij}\ \sin(\phi_j - \phi_i - \psi_{ij})$$



Parameters:

1. f
2. df
3. $\psi_{ij} = -\psi_{ji}$

Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma\ N_i\ \cos(\phi_i)$$

Binary Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma\ B_i\ \cos(\phi_i)$$

$$B_i = \begin{cases} N_i & \text{if } N_i > 0.2\ \mathrm{N} \\ 0 & \text{if } N_i < 0.2\ \mathrm{N} \end{cases}$$

Particle Swarm Optimization

Open Loop CPG

Maximize

:

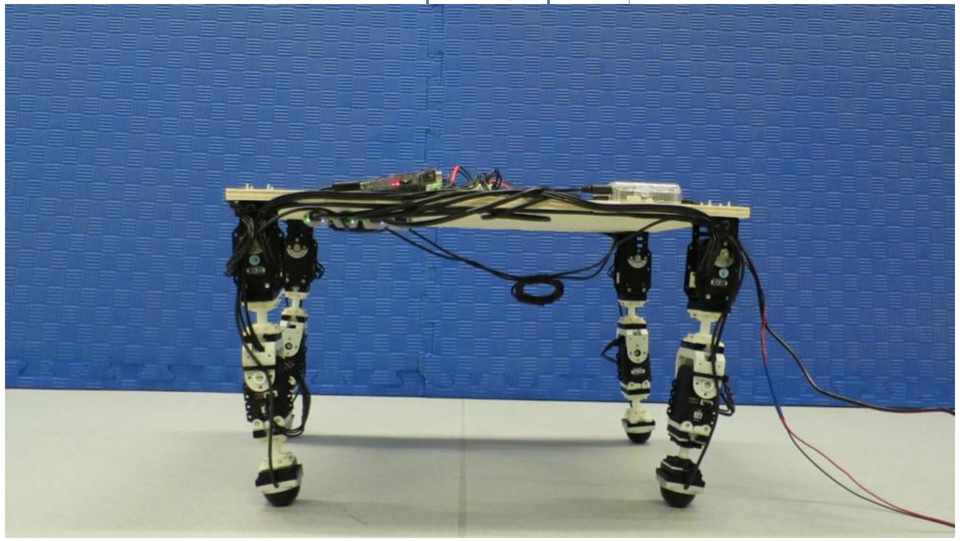
$$Z(\theta_{max}, h_{st}, \boxed{h_{sw}}, df, \psi_{12}, \psi_{23}, \psi_{34}) = \sum_{kT=30}^{90} \frac{v_{CM}(kT)}{P_m(kT)} = \epsilon_t$$

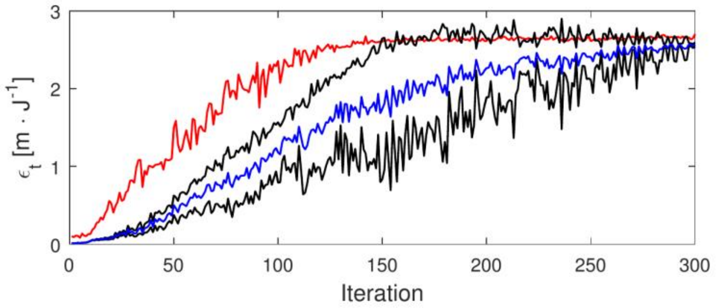
$> h_{min}$

Subject to:

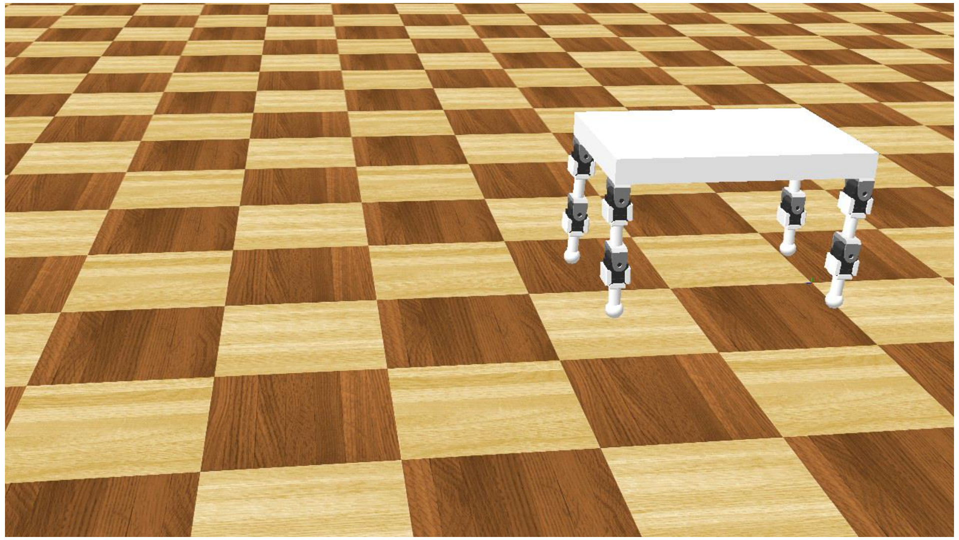
Validation on hardware

$f = f_d$





$h_{st} \to 0$, $h_{sw} \to 0$, $\theta_{max} \to \approx 0.07$ rad



Particle Swarm Optimization

Open Loop CPG

Maximize

:
$$Z(f, \theta_{max}, h_{st}, h_{sw}, df, \psi_{12}, \psi_{23}, \psi_{34}) = \sum_{kT=30}^{90} \frac{1}{P_m(kT)} = \frac{1}{E_t}$$

Subject to:

$$\boxed{\overline{v_{CM}} \geq v_d}$$

$$0 \leq \theta_{max} \leq \pi/3$$

$$0 \leq h_{st} \leq 0.06$$

$$0 \leq h_{sw} \leq 0.06$$

$$h_{sw} > h_{st}$$

$$0 \leq df \leq 1$$

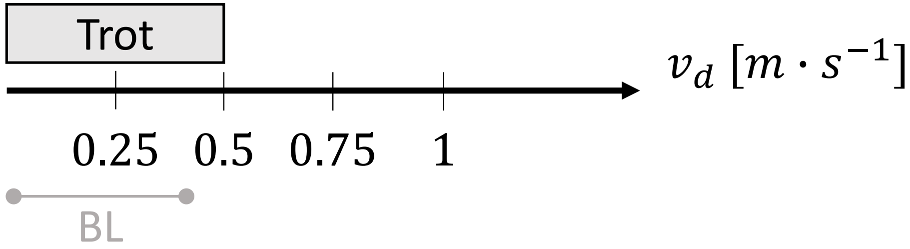
$$-\pi \leq \psi_{ij} \leq \pi$$

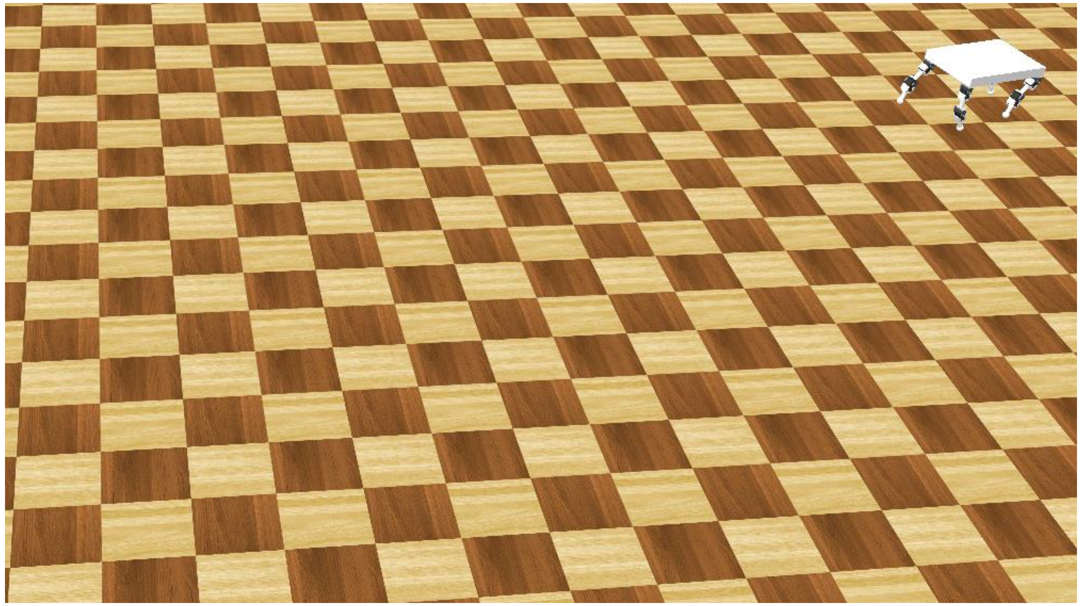
Particle Swarm Optimization

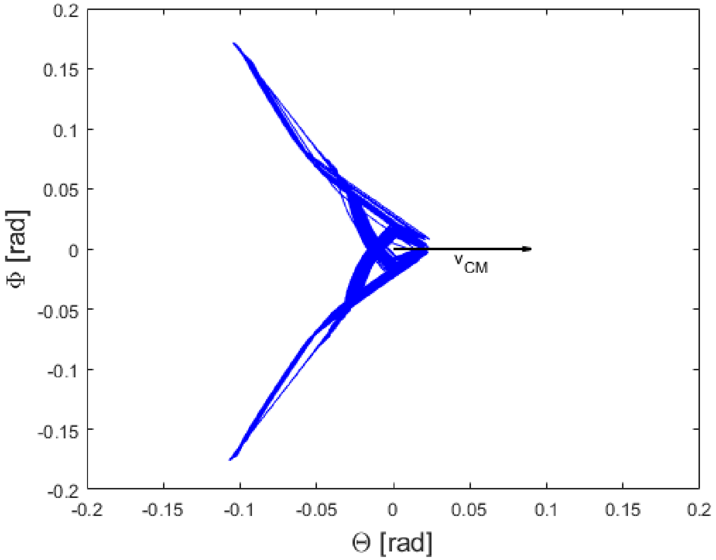
Open Loop CPG

Maximize :

$$Z(f, \theta_{max}, h_{st}, h_{sw}, df, \psi_{12}, \psi_{23}, \psi_{34}) = \sum_{kT=30}^{90} \frac{1}{P_m(kT)} = \frac{1}{E_t}$$





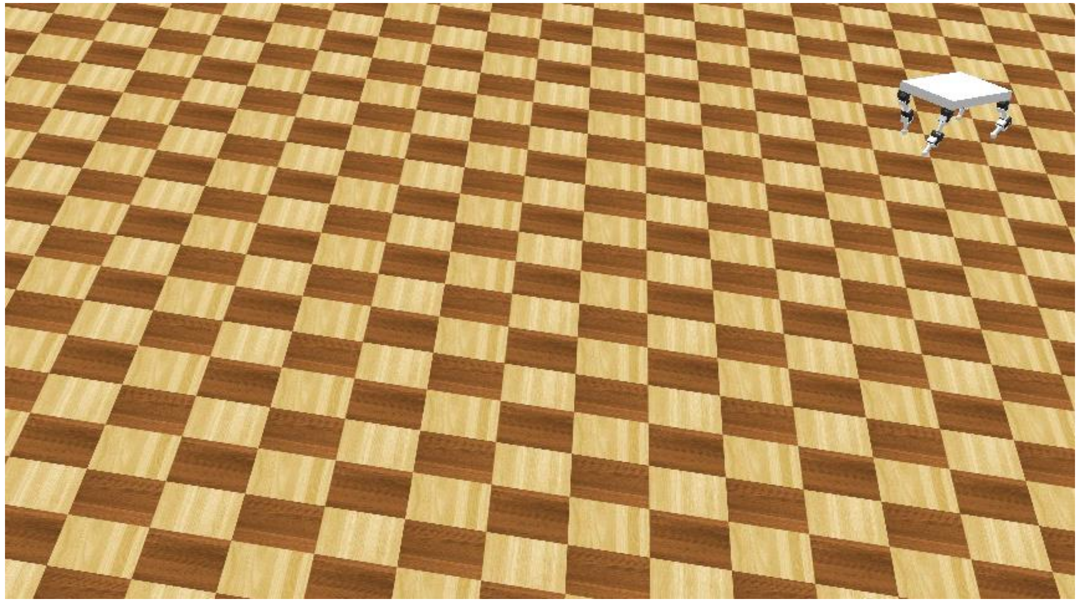


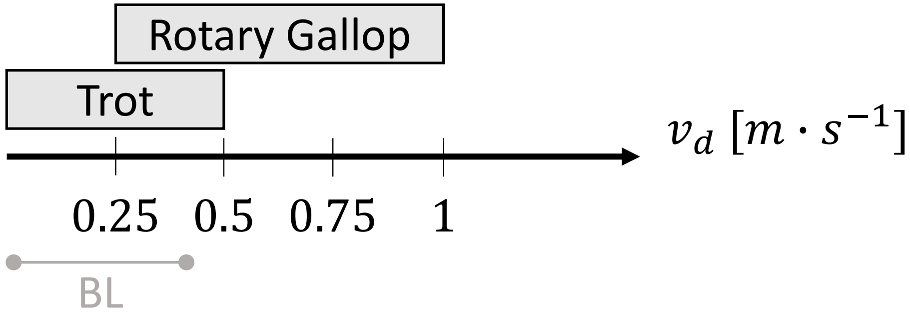
Particle Swarm Optimization

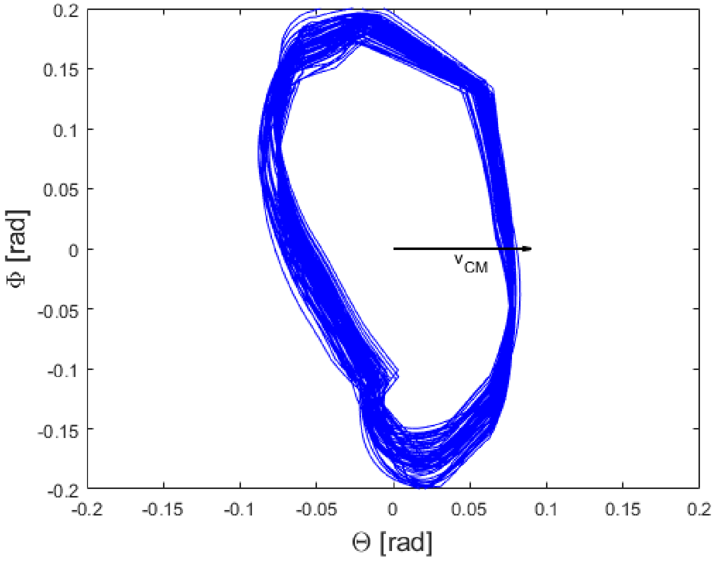
Open Loop CPG

Maximize

$$:Z(f,\theta_{max},h_{st},h_{sw},df,\psi_{12},\psi_{23},\psi_{34}) = \sum_{kT=30}^{90}\frac{1}{P_m(kT)} = \frac{1}{E_t}$$





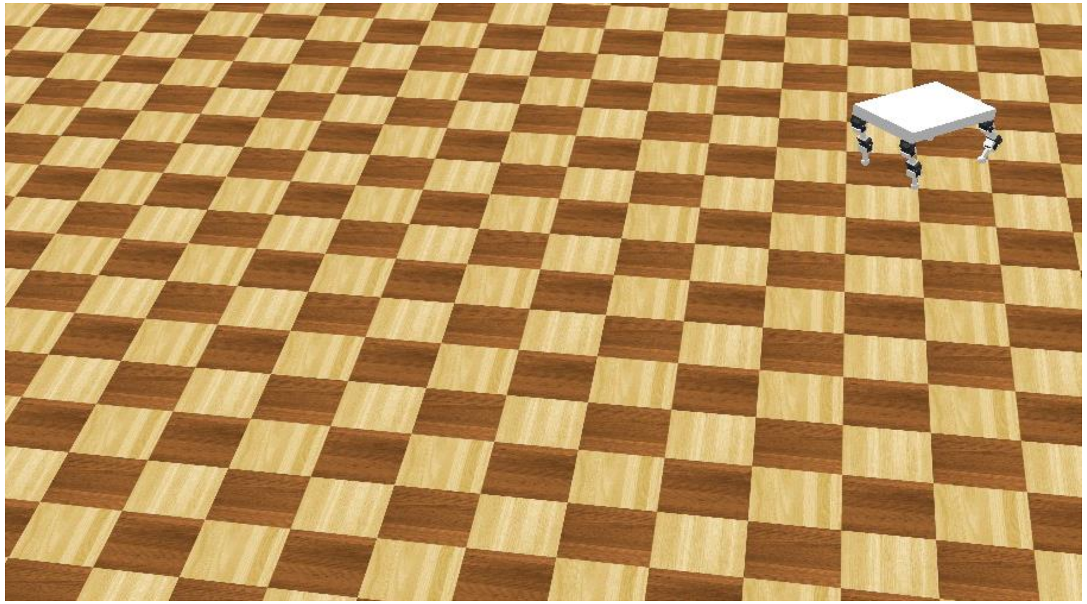


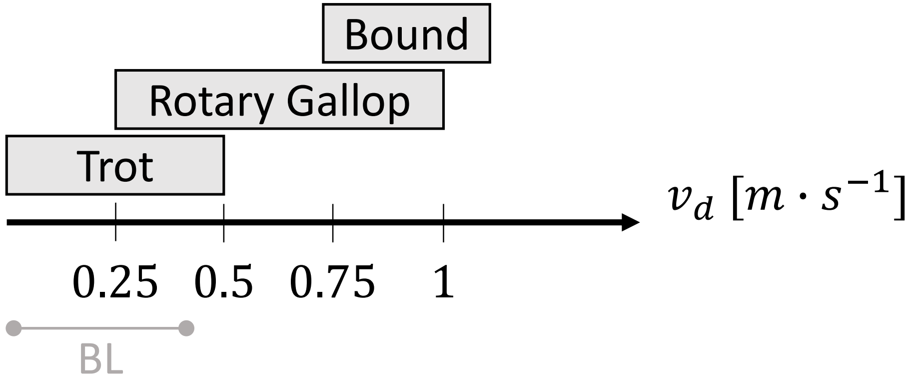
Particle Swarm Optimization

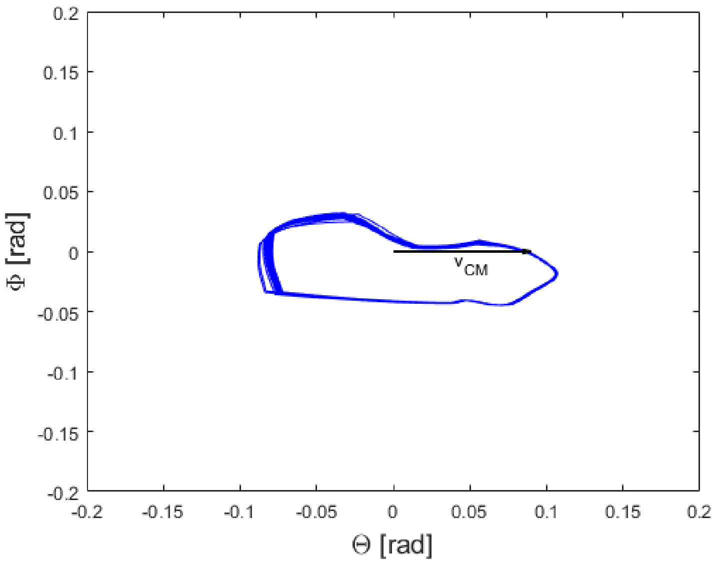
Open Loop CPG

Maximize

$$Z(f, \theta_{max}, h_{st}, h_{sw}, df, \psi_{12}, \psi_{23}, \psi_{34}) = \sum_{kT=30}^{90} \frac{1}{P_m(kT)} = \frac{1}{E_t}$$







Particle Swarm Optimization

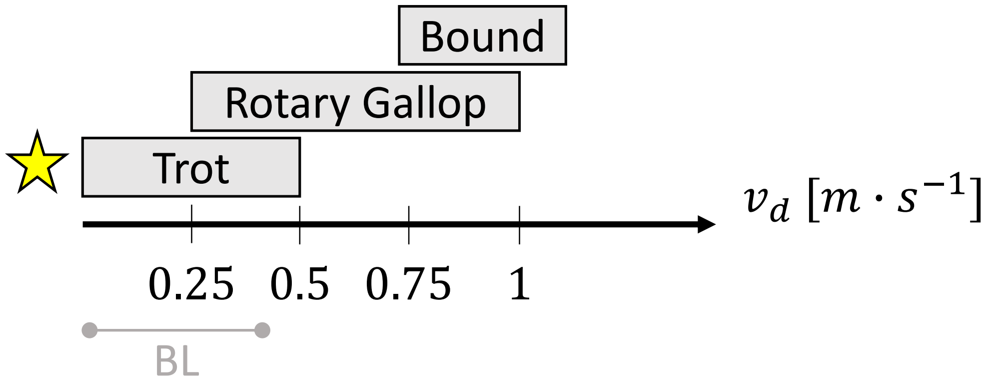
Open Loop CPG

Maximize : Validated on hardware

0 Trot

$$Z(f, \theta_{max}, \cancel{h_{st}}, h_{sw}, \boxed{df}, \cancel{\psi_{12}, \psi_{23}, \psi_{34}}) = \sum_{kT=30}^{90} \frac{1}{P_m(kT)} = \frac{1}{E_t}$$

≥ 0.5

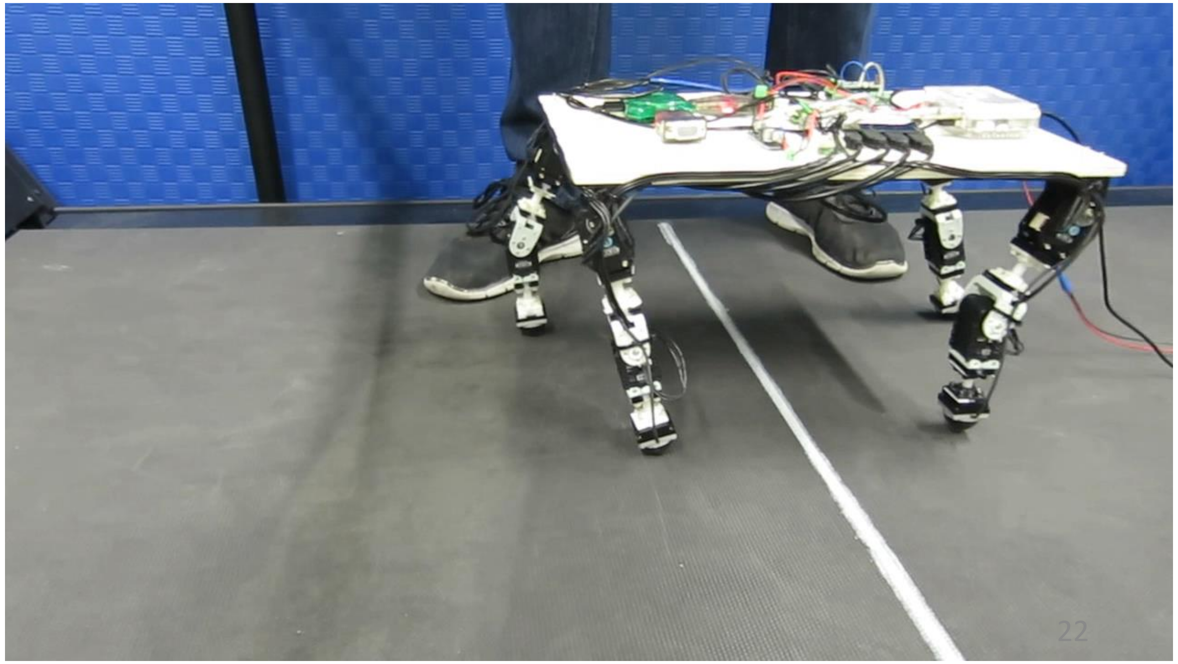


Validation on hardware

Imposed Gait	$\overline{v_{CM}}\ [m \cdot s^{-1}]$	$\epsilon_t\ [m \cdot kJ^{-1}]$
Trot	0.059	$\boxed{4.042}$
D-S walk	0.035	1.583
L-S walk	0.032	1.87

$f = 0.25\ Hz,\ \theta_{max} = 0.3\ rad,\ h_{sw} = 15\ mm,\ h_{st} = 0\ mm$

Imposed Trot

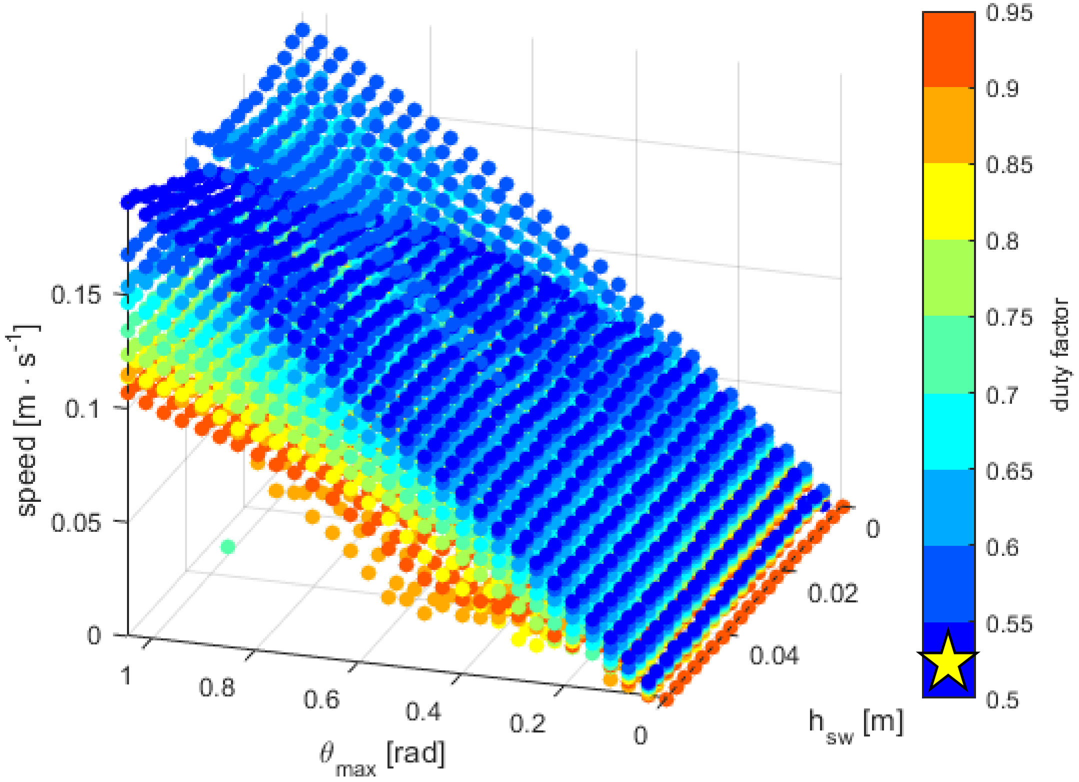


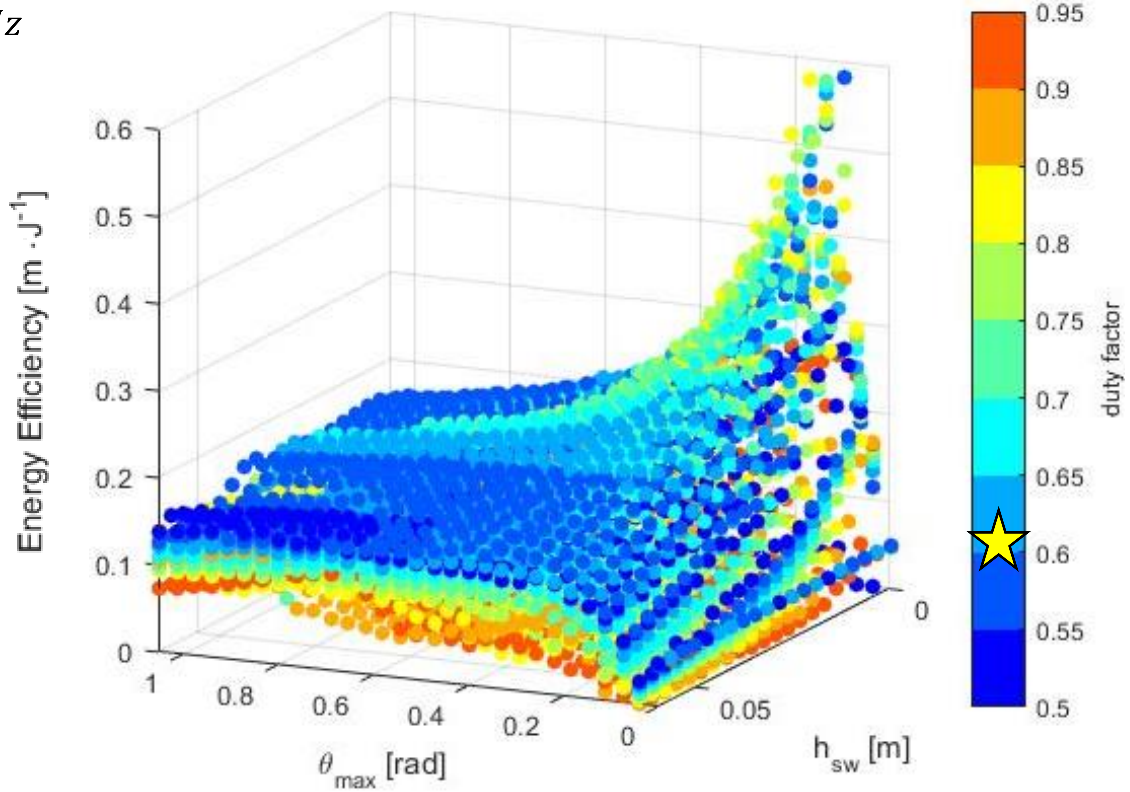
Steady State Systematic Search: Trajectories

Open Loop CPG

Simulation

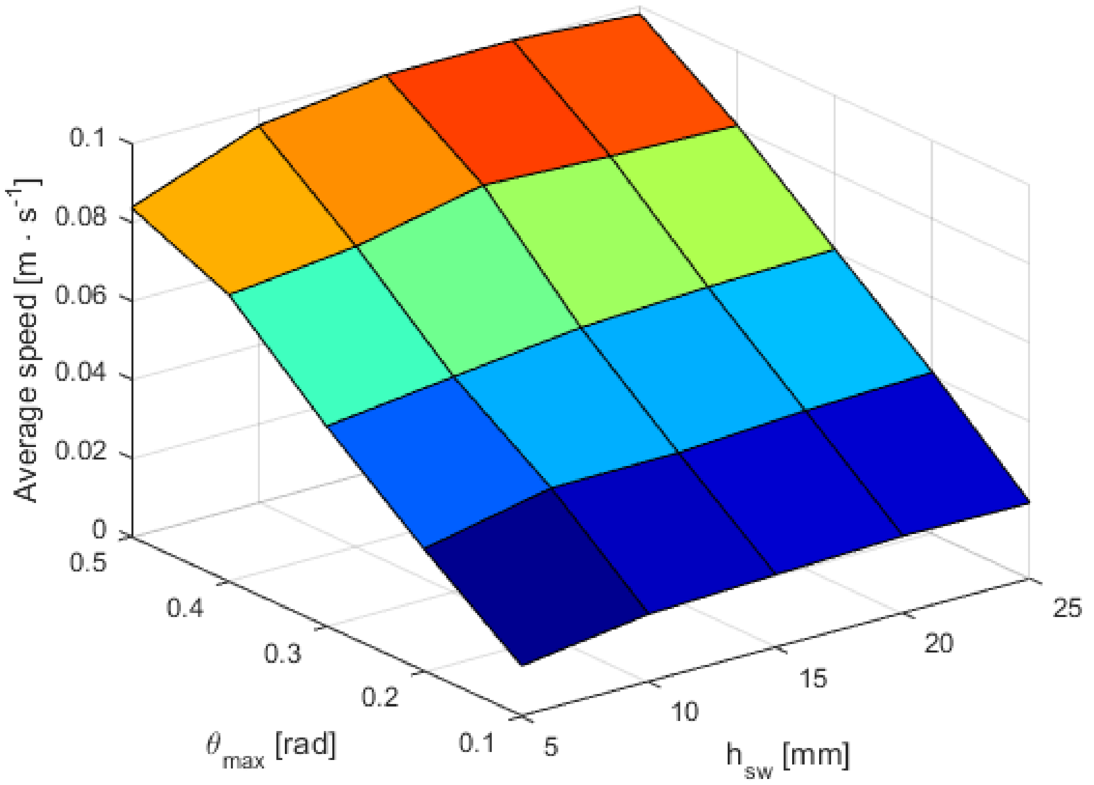
$f = 0.25\ Hz$





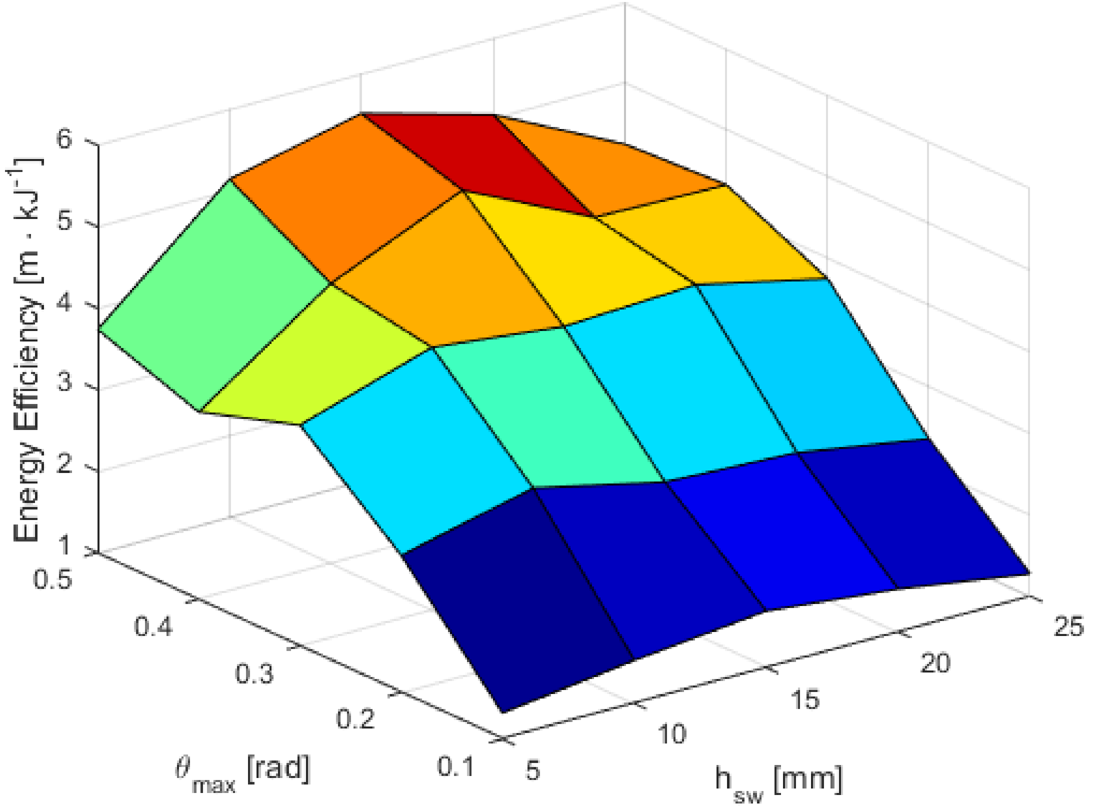
Steady State Systematic Search: Trajectories

Open Loop CPG



Hardware

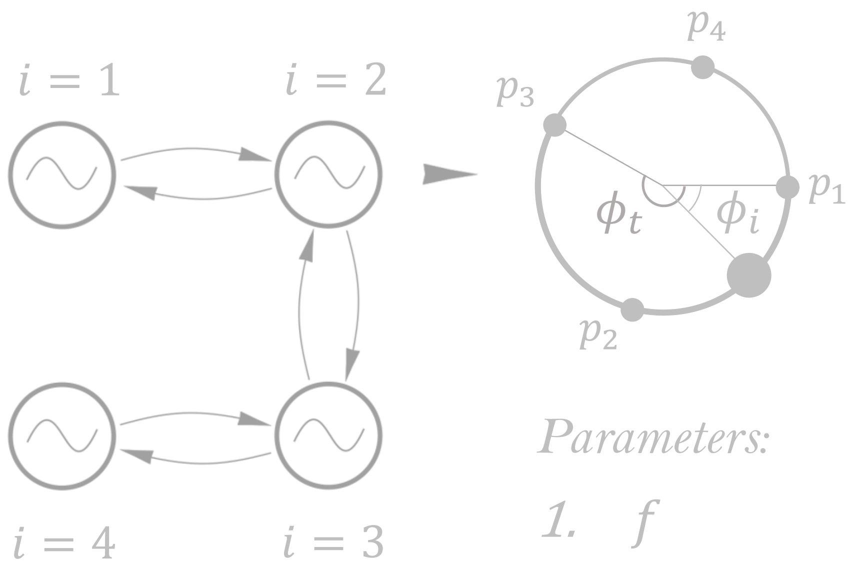
$f = 0.25\ Hz$
$df = 0.5$



Control Approaches

Open Loop CPG

$$\dot{\phi}_i = 2\pi f + \sum_j w_{ij}\ \sin(\phi_j - \phi_i - \psi_{ij})$$



Parameters:

1. f
2. df
3. $\psi_{ij} = -\psi_{ji}$

Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma\ N_i\ \cos(\phi_i)$$

Binary Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma_b\ B_i\ \cos(\phi_i)$$

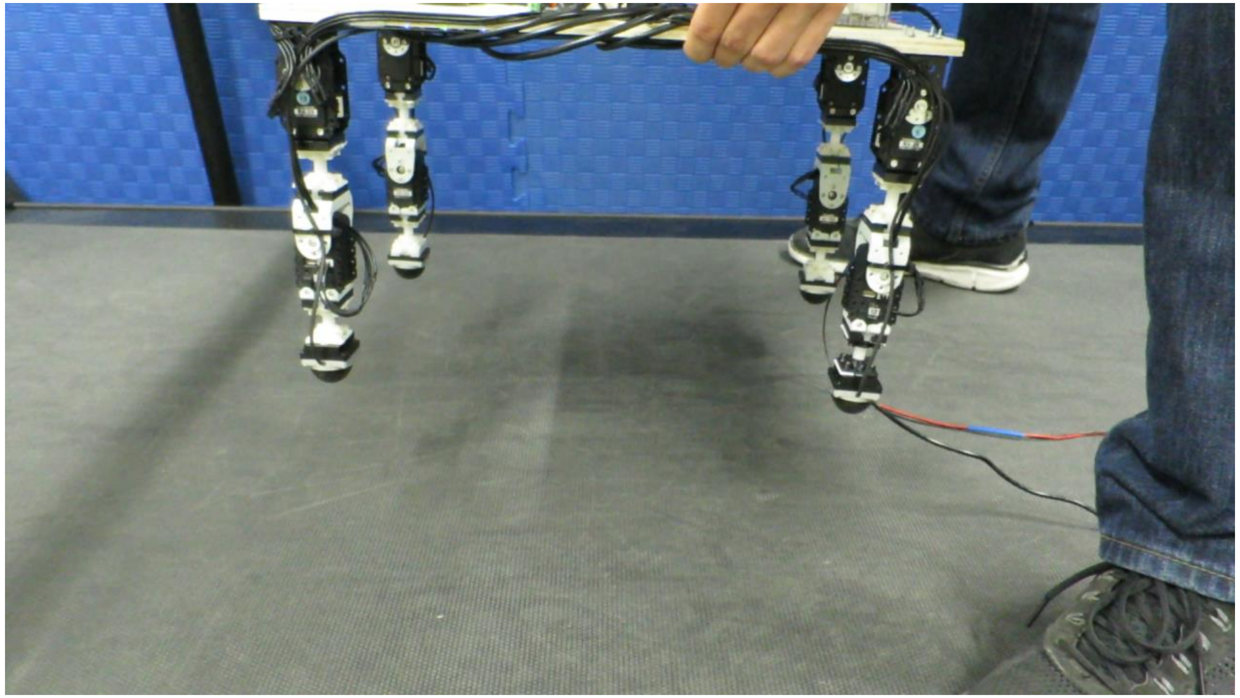
$$B_i = \begin{cases} 1 & \text{if } N_i > 0.2\ \mathrm{N} \\ 0 & \text{if } N_i < 0.2\ \mathrm{N} \end{cases}$$

1. Convergence
2. Steady State

1. Convergence

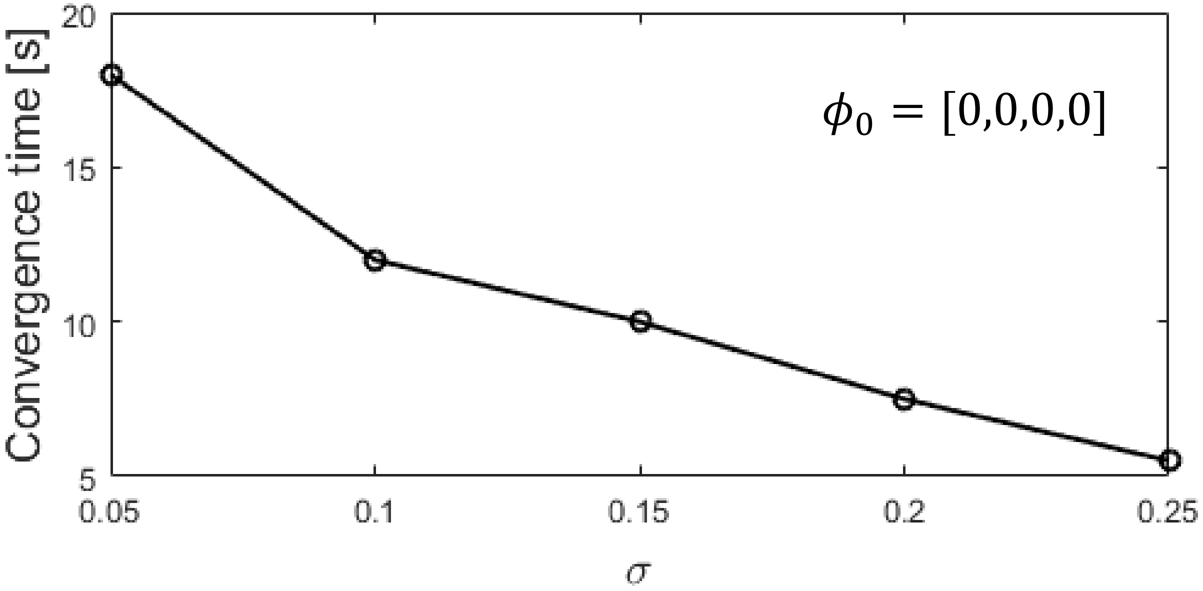
Trot ← Tegotae

$\boldsymbol{\sigma = 0.25}$



$$\dot{\phi}_i = 2\pi f + \sigma\, N_i\, \cos(\phi_i)$$

Hardware



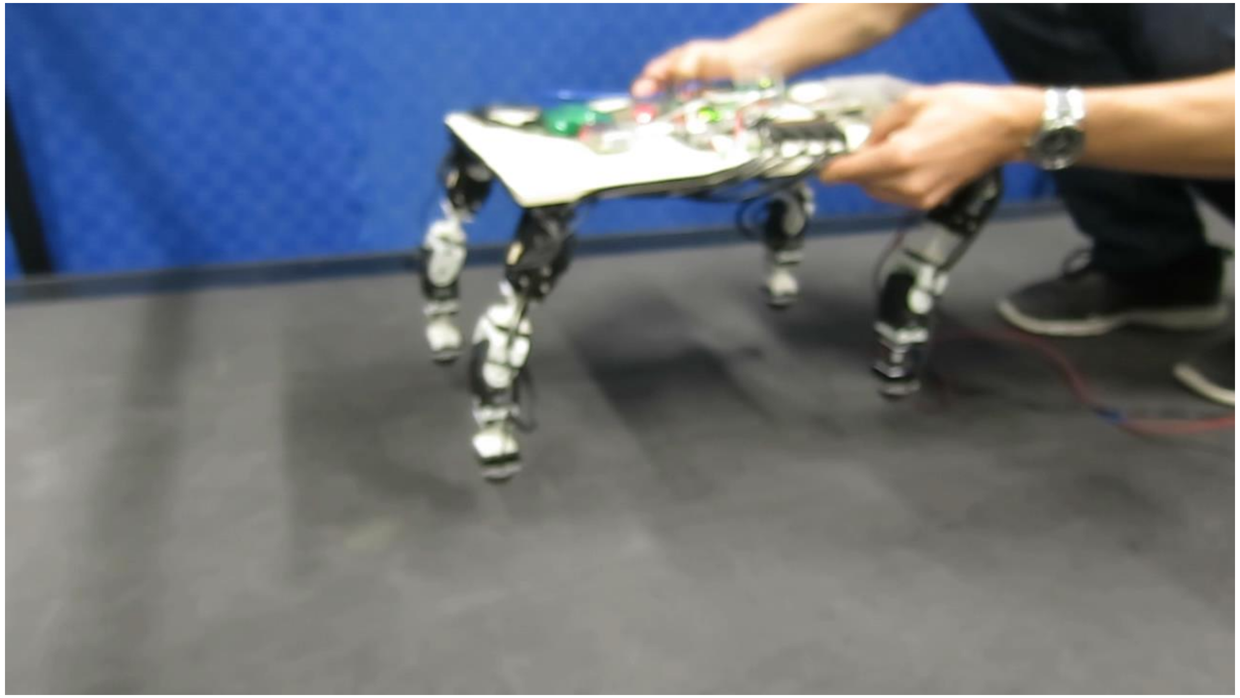
$f = 0.25\ Hz,\ \theta_{max} = 0.3\ rad,\ h_{sw} = 15\ mm, h_{st} = 0\ mm$

1. Convergence

$\boxed{\sigma_b = 6\,\sigma}$

Binary Tegotae

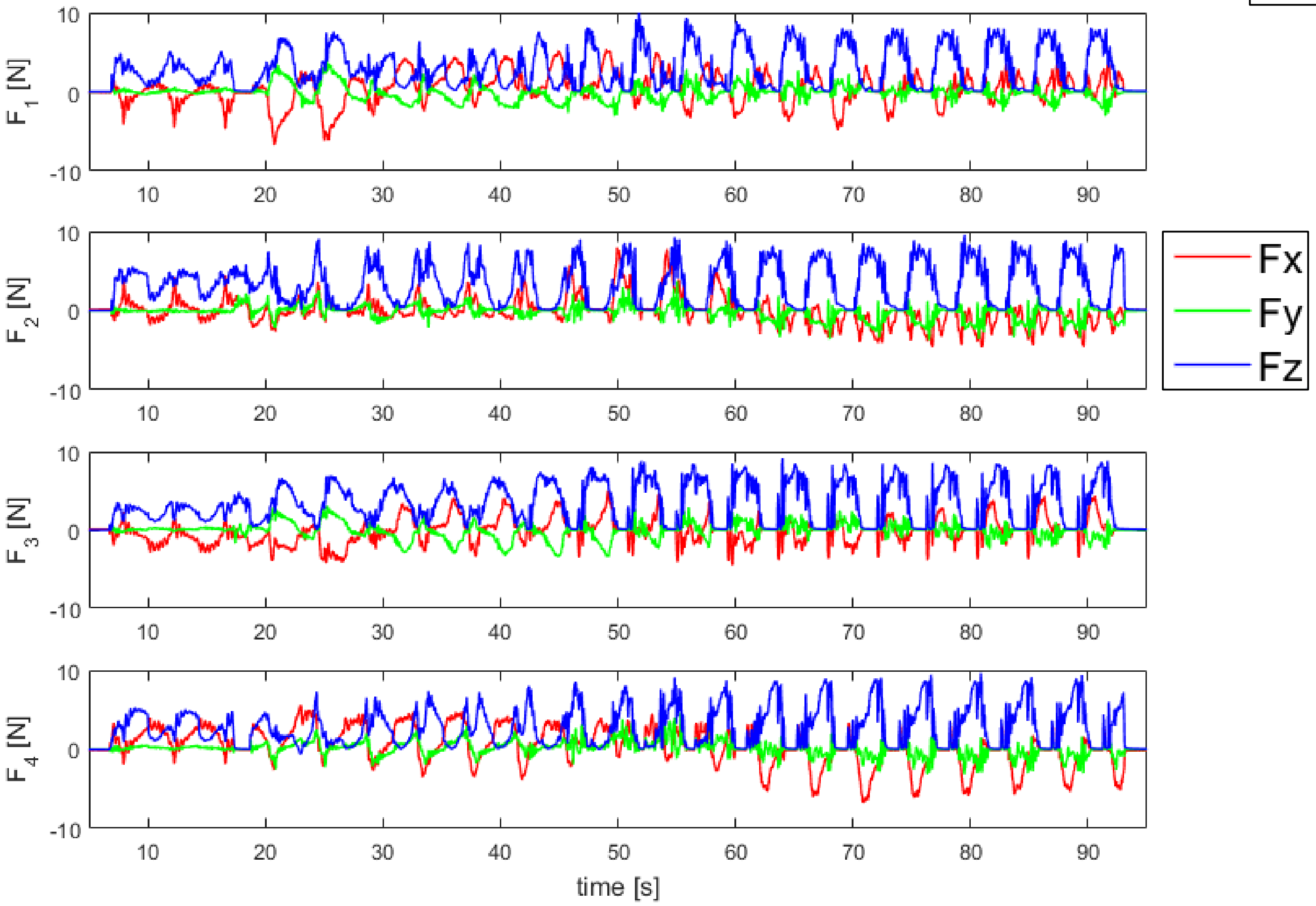
$\boldsymbol{\sigma_b = 0.6}$



$$\dot{\phi}_i = 2\pi f + \sigma_b\, B_i\ \cos(\phi_i)$$

$$B_i = \begin{cases} 1 & \text{if } N_i > 0.2\ \mathrm{N} \\ 0 & \text{if } N_i < 0.2\ \mathrm{N} \end{cases}$$

1. Convergence



Binary Tegotae

$$\dot{\phi}_i = 2\pi f + \sigma_b \, B_i \, \cos(\phi_i)$$

$$B_i = \begin{cases} 1 & \text{if } N_i > 0.2 \text{ N} \\ 0 & \text{if } N_i < 0.2 \text{ N} \end{cases}$$

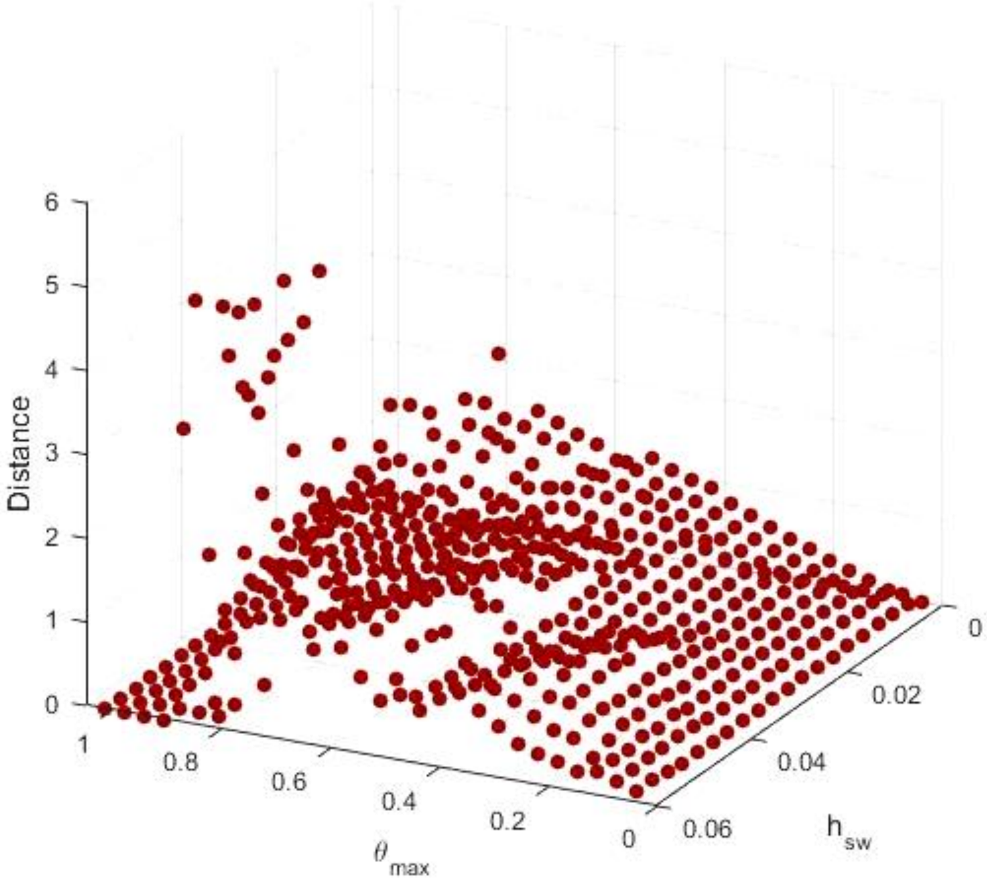
Frequency [Hz]	Convergence time [s]
0.25	43
0.5	41
0.75	≈ 20

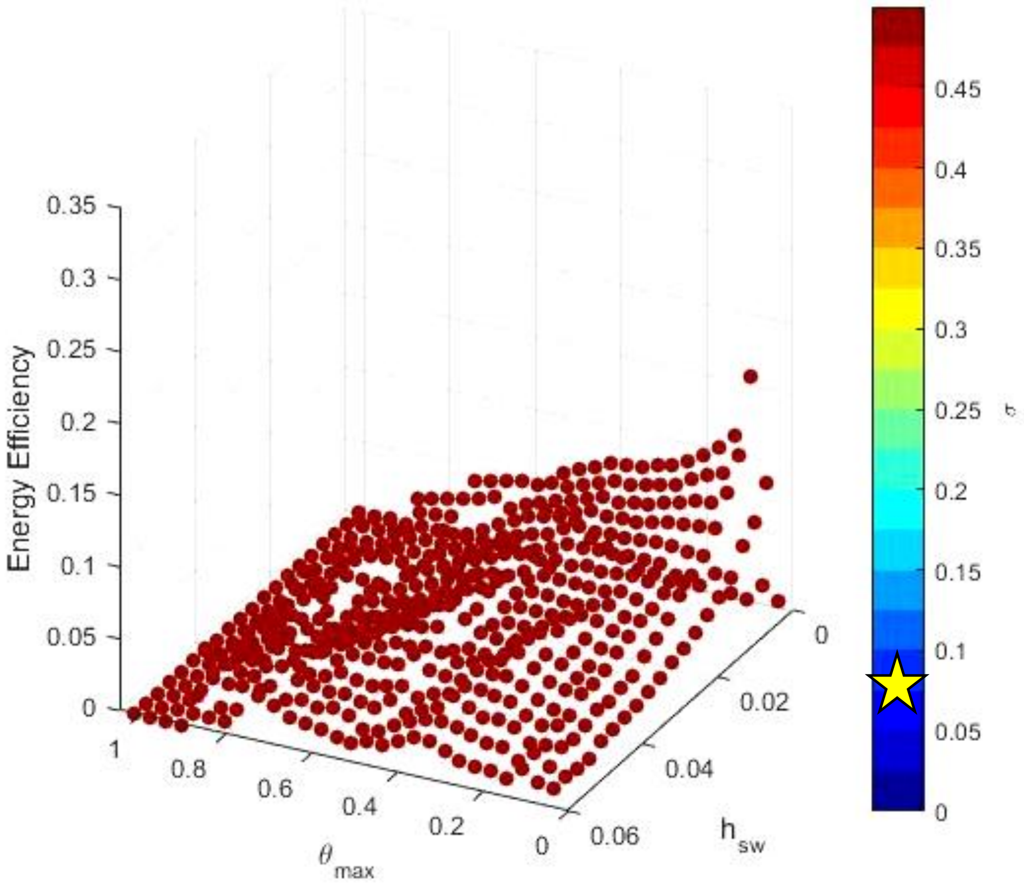
2. Steady State

Simulation

1. Trajectory
2. Effect of σ

Tegotae



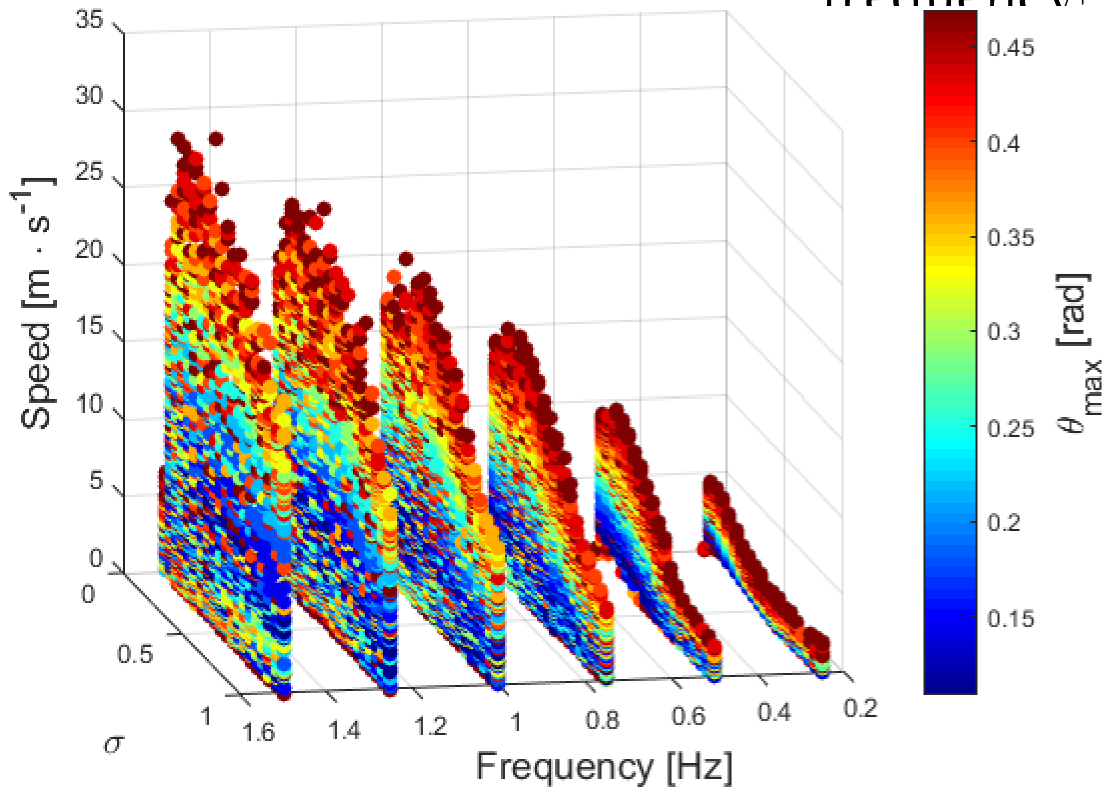


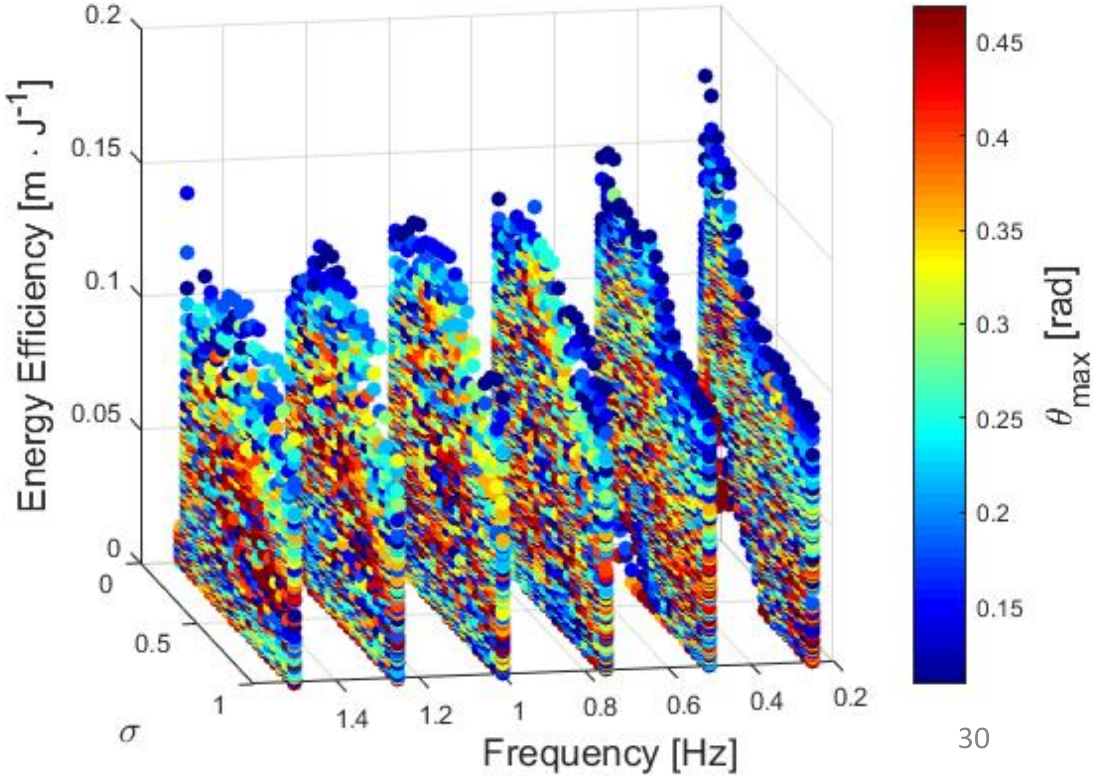
2. Steady State

Simulation

1. Trajectory
2. Effect of σ
3. Scaled by frequency?

Tegotae



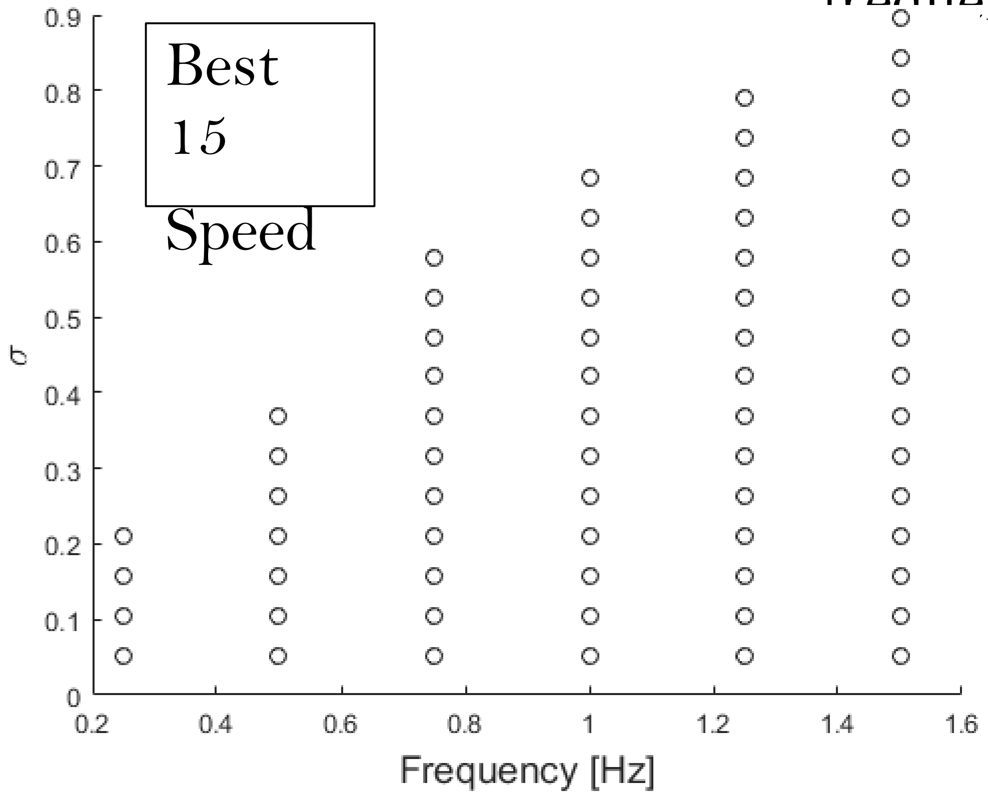


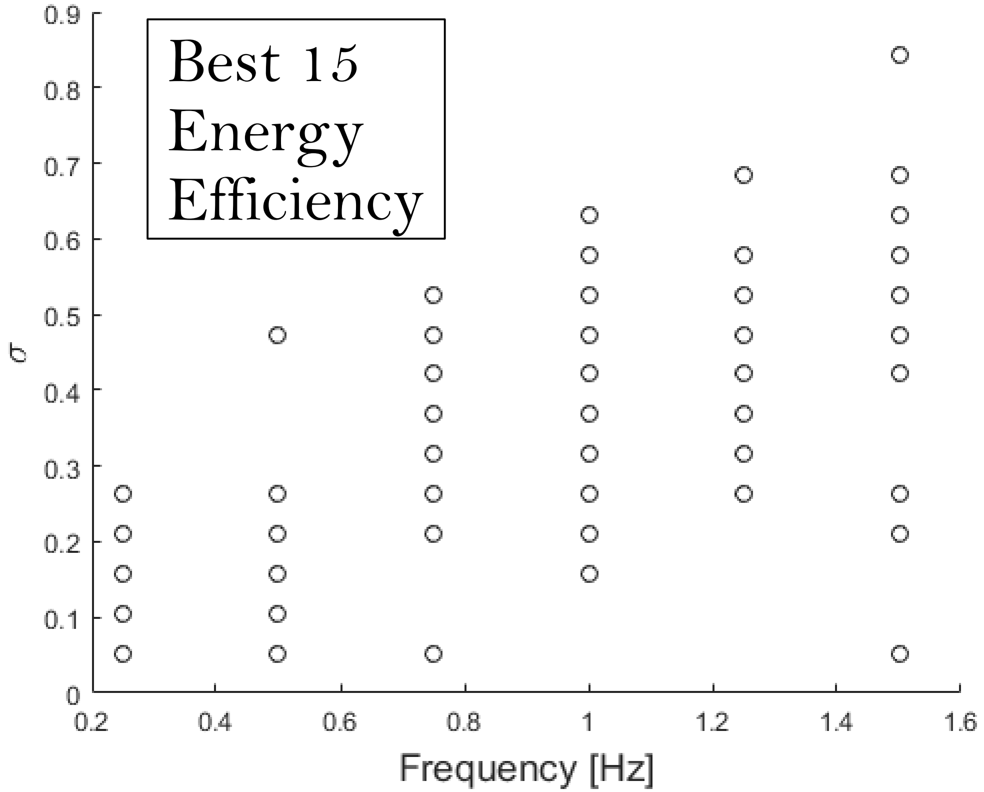
2. Steady State

Simulation

1. Trajectory
2. Effect of σ
3. Scaled by frequency?

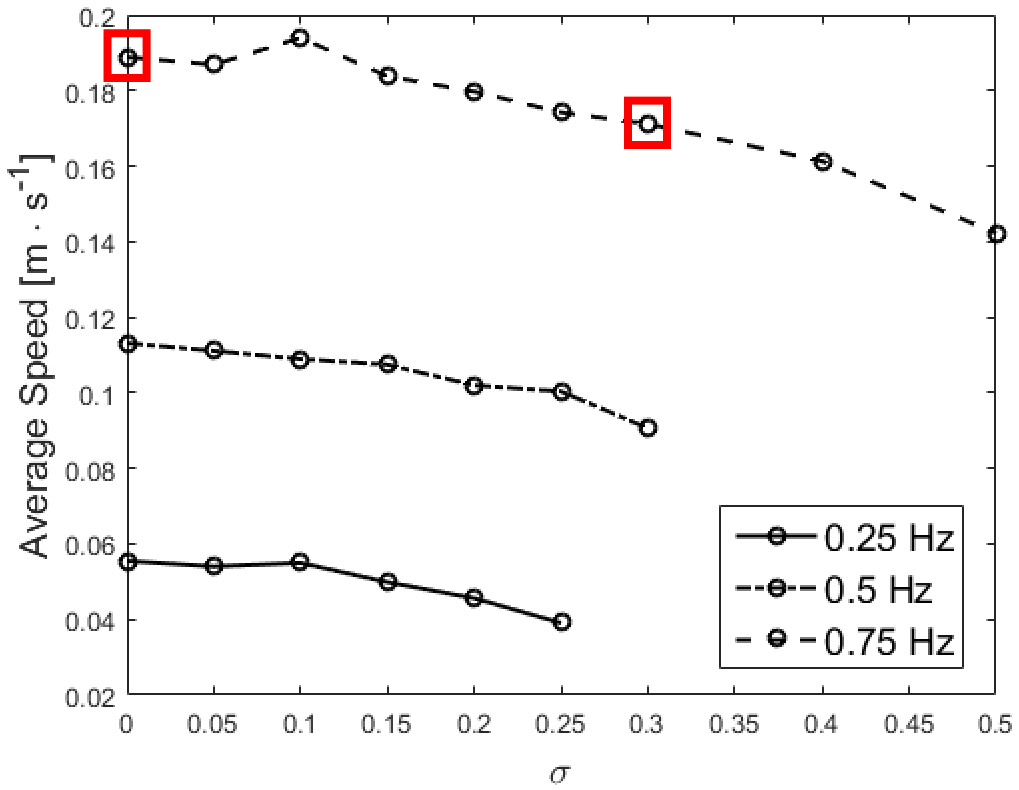
Tegotae



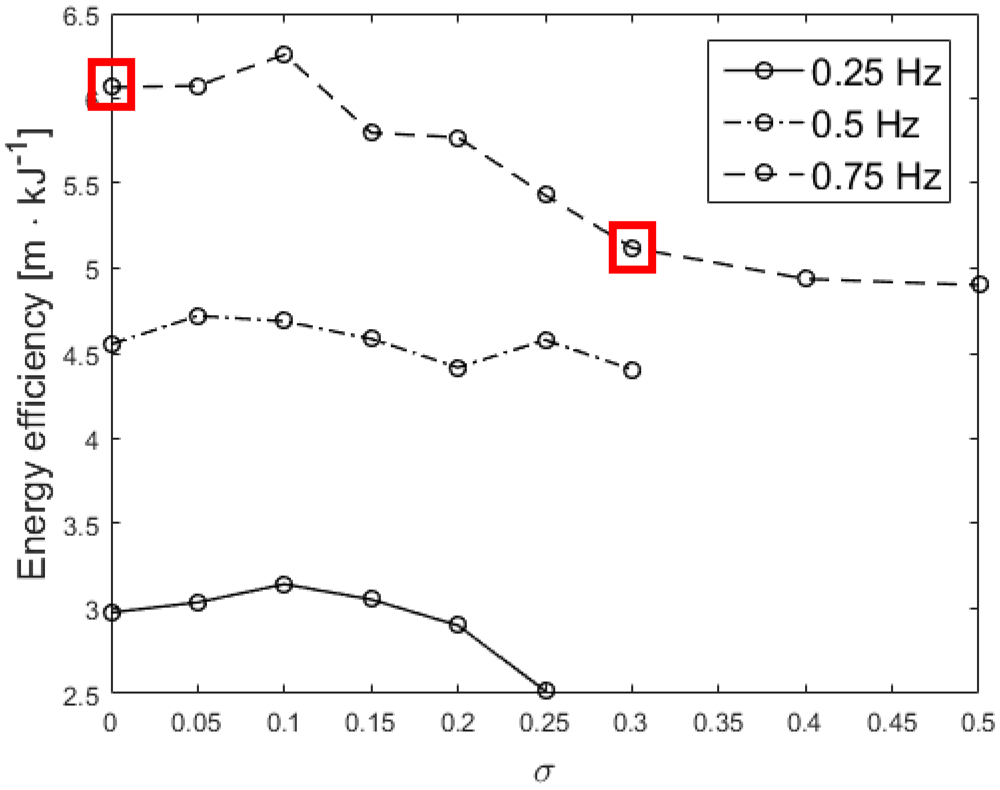


2. Steady State

Hardware



Tegotae



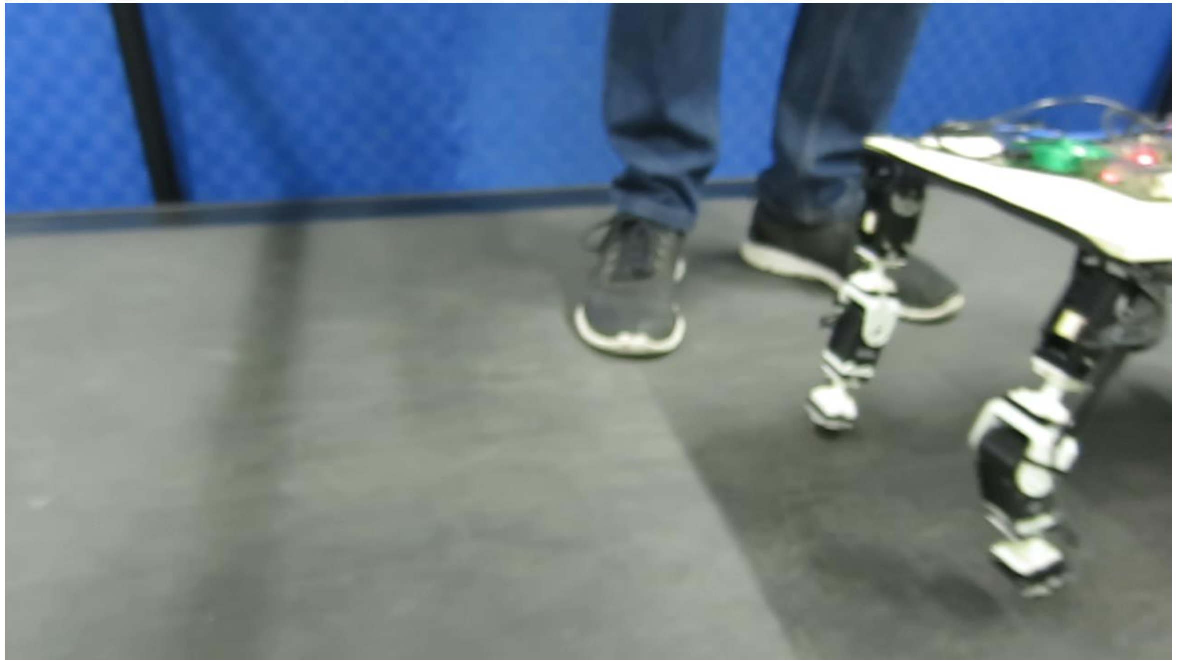
$f = 0.25\,Hz\,, \theta_{max} = 0.3\,rad\,, h_{sw} = 15\,mm, h_{st} = 0\,mm$

2. Steady State

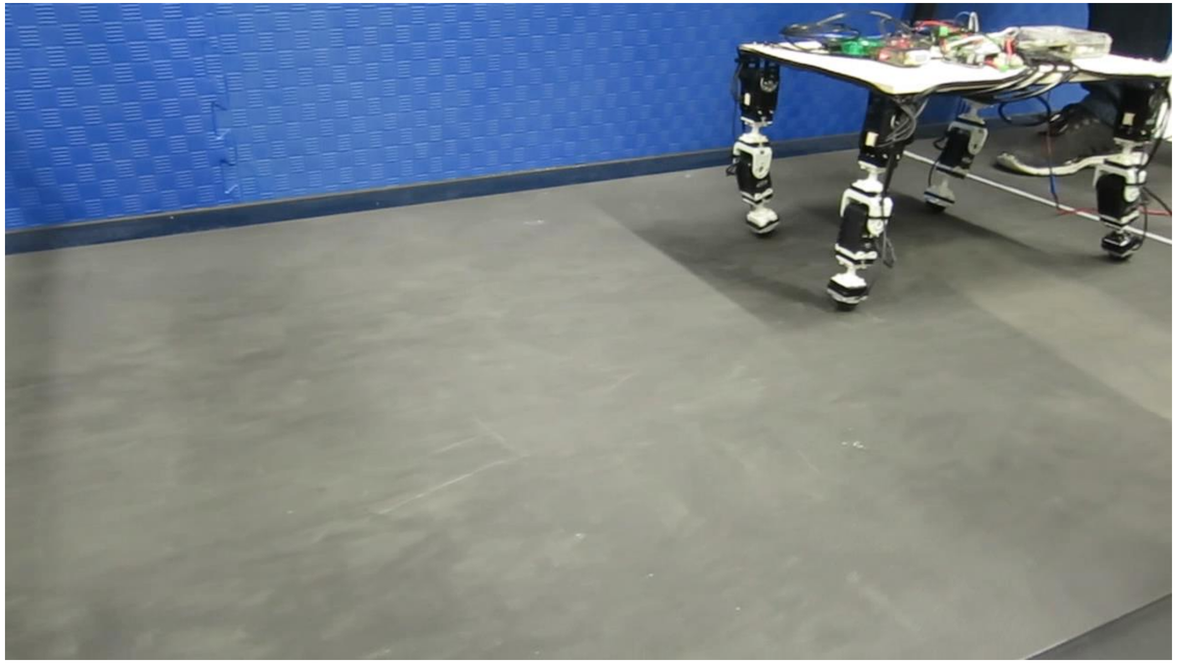
Hardware

Tegotae

$\boldsymbol{\sigma = 0}$



$\boldsymbol{\sigma = 0.3}$

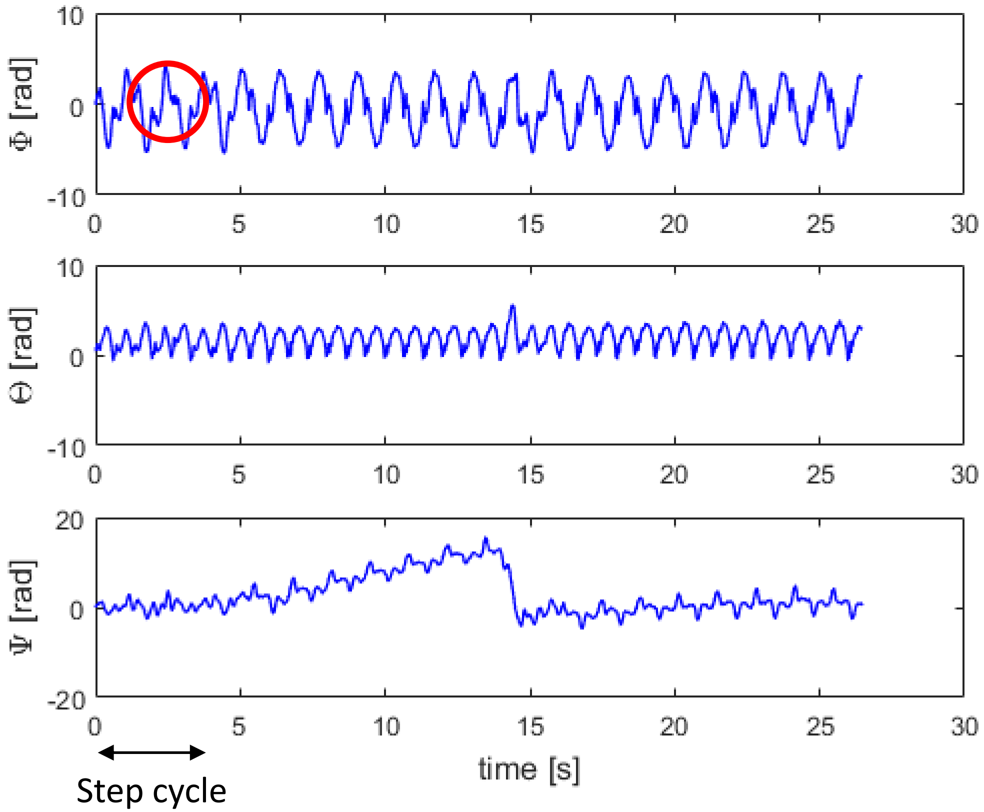


2. Steady State

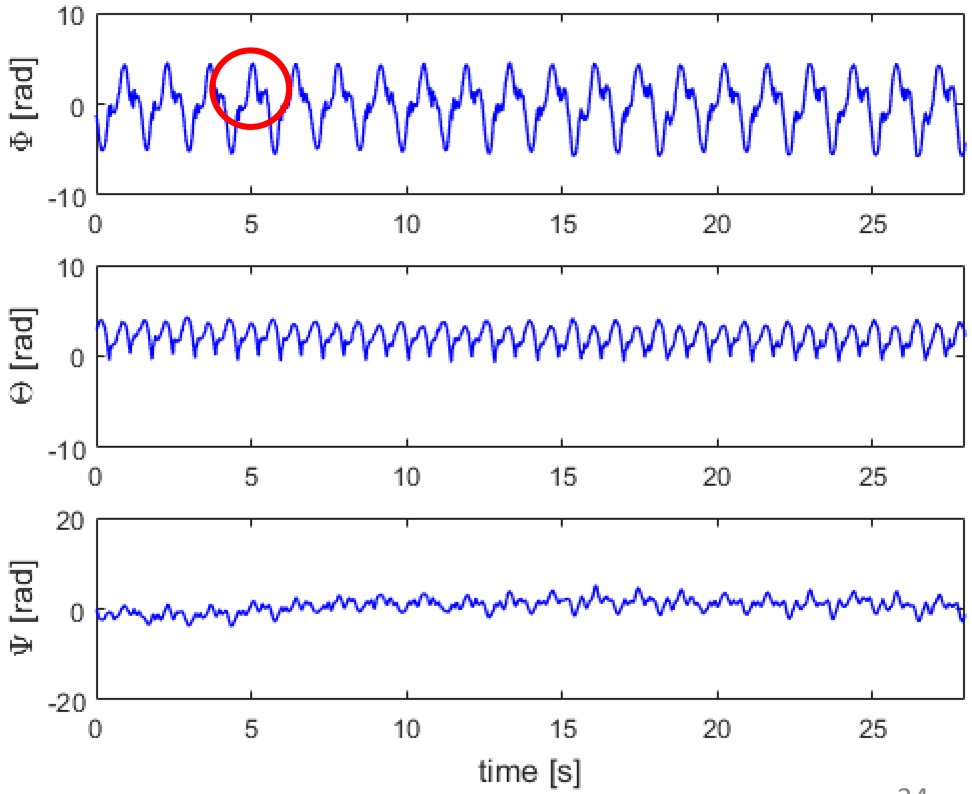
Hardware

Tegotae

$\boldsymbol{\sigma = 0}$



$\boldsymbol{\sigma = 0.3}$



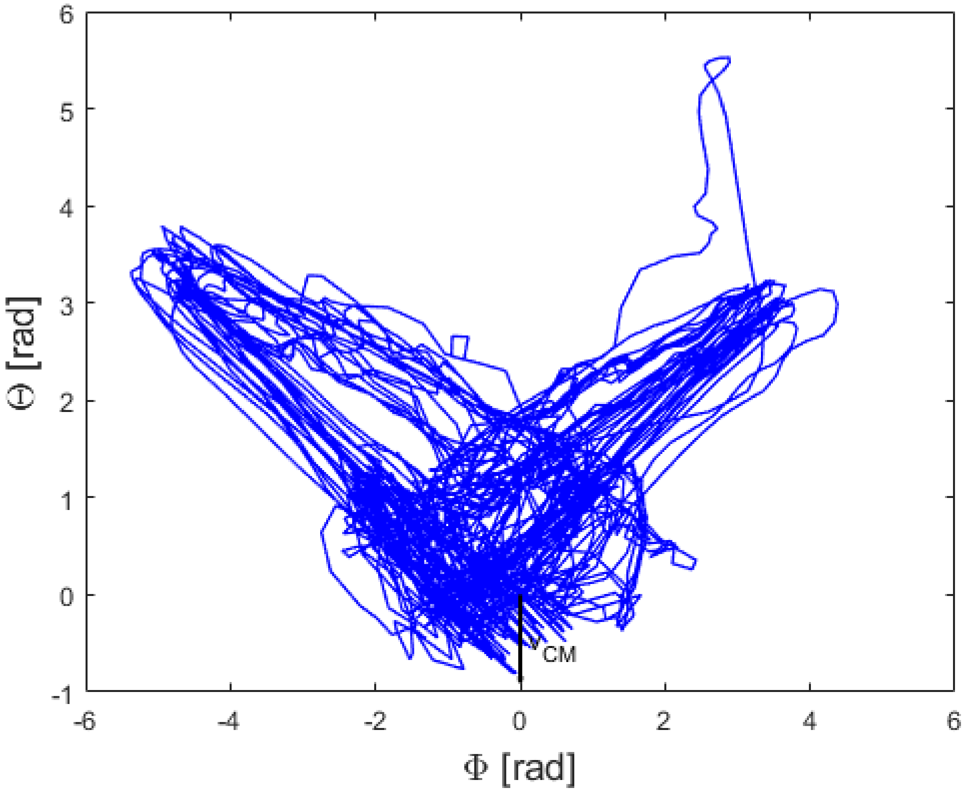
2. Steady State

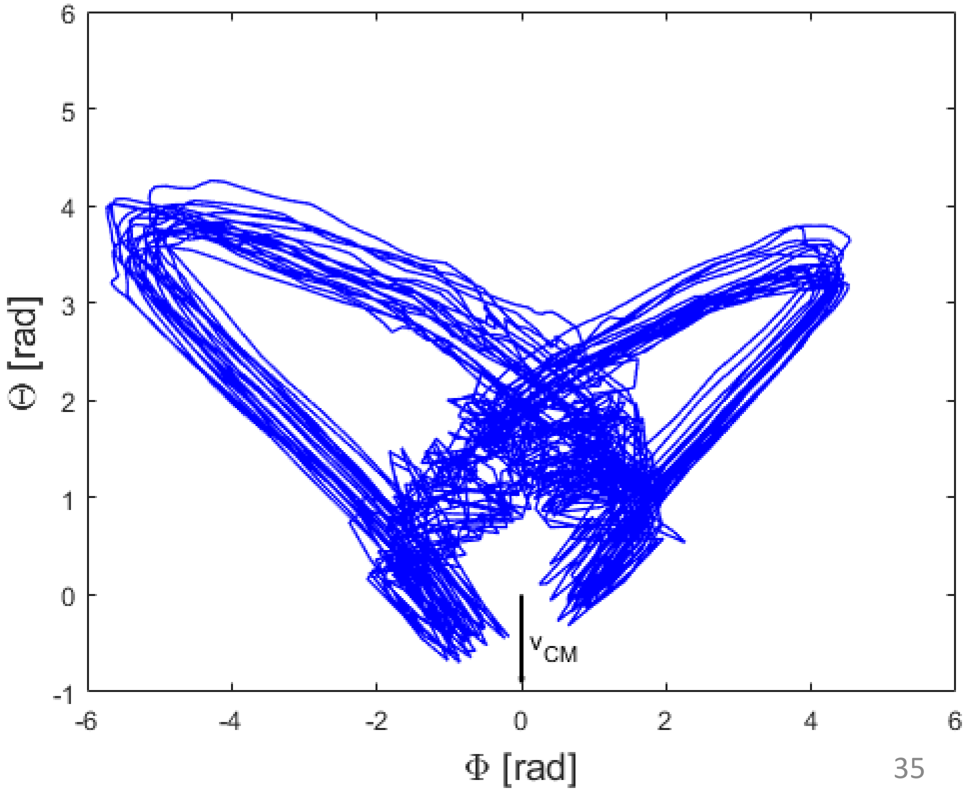
Hardware

Tegotae

$\boldsymbol{\sigma = 0}$

$\boldsymbol{\sigma = 0.3}$



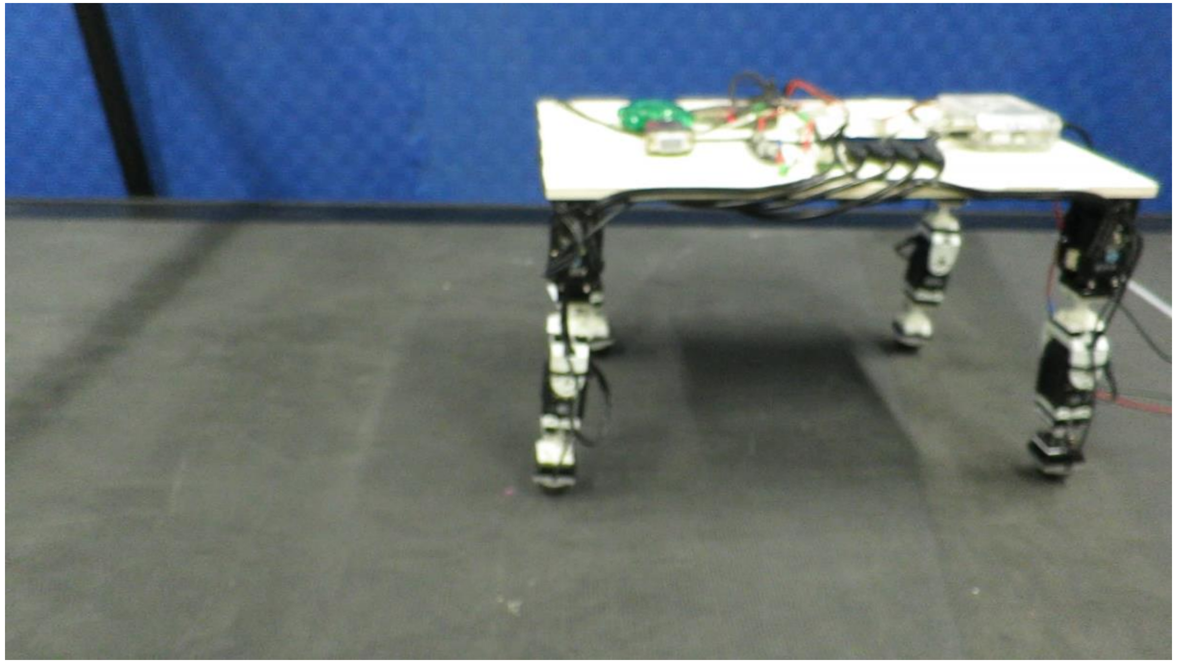


2. Steady State

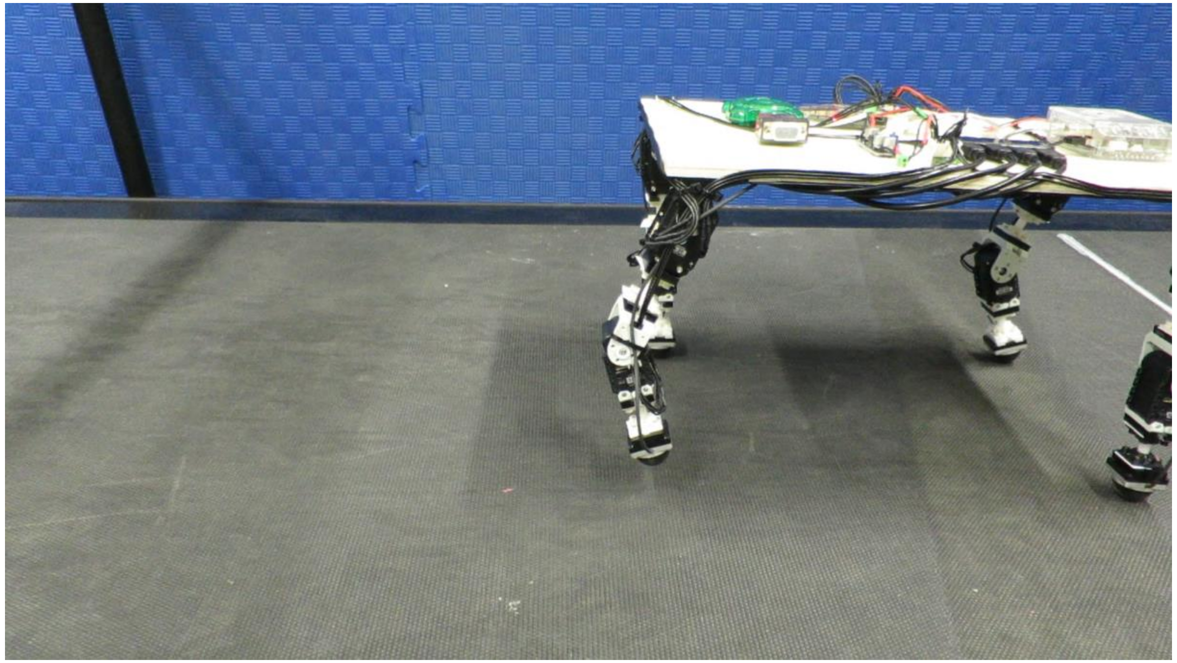
Hardware

Tegotae

$\boldsymbol{\sigma = 0.5}$



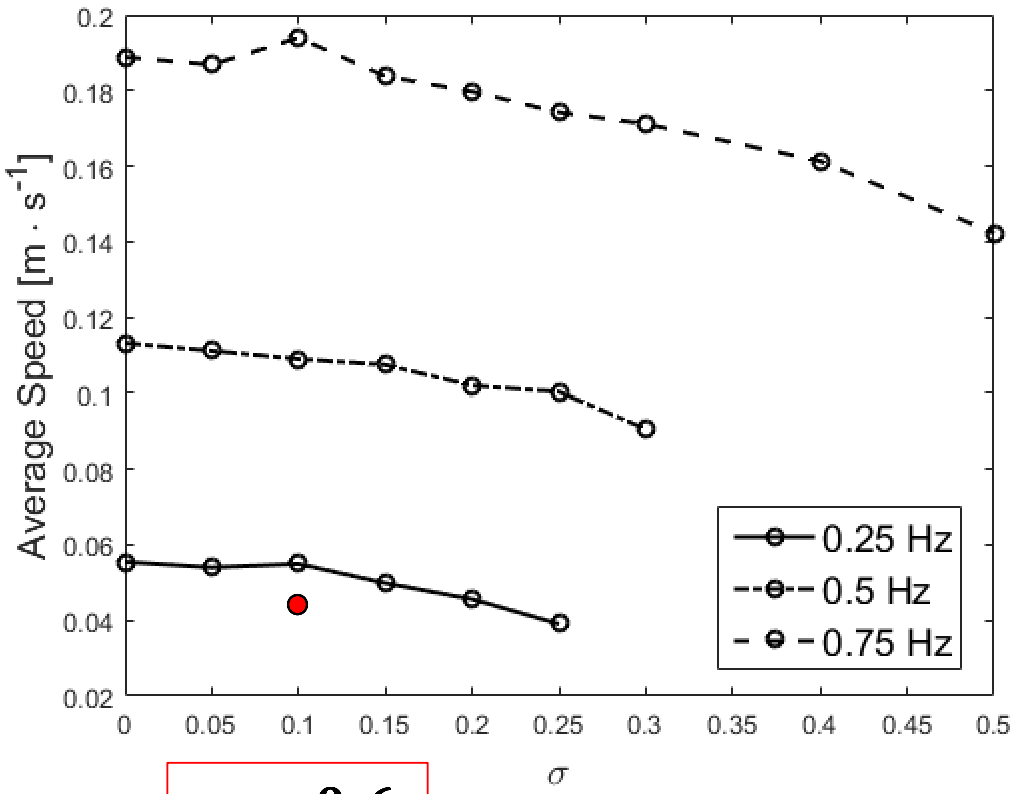
$\boldsymbol{\sigma = 1}$



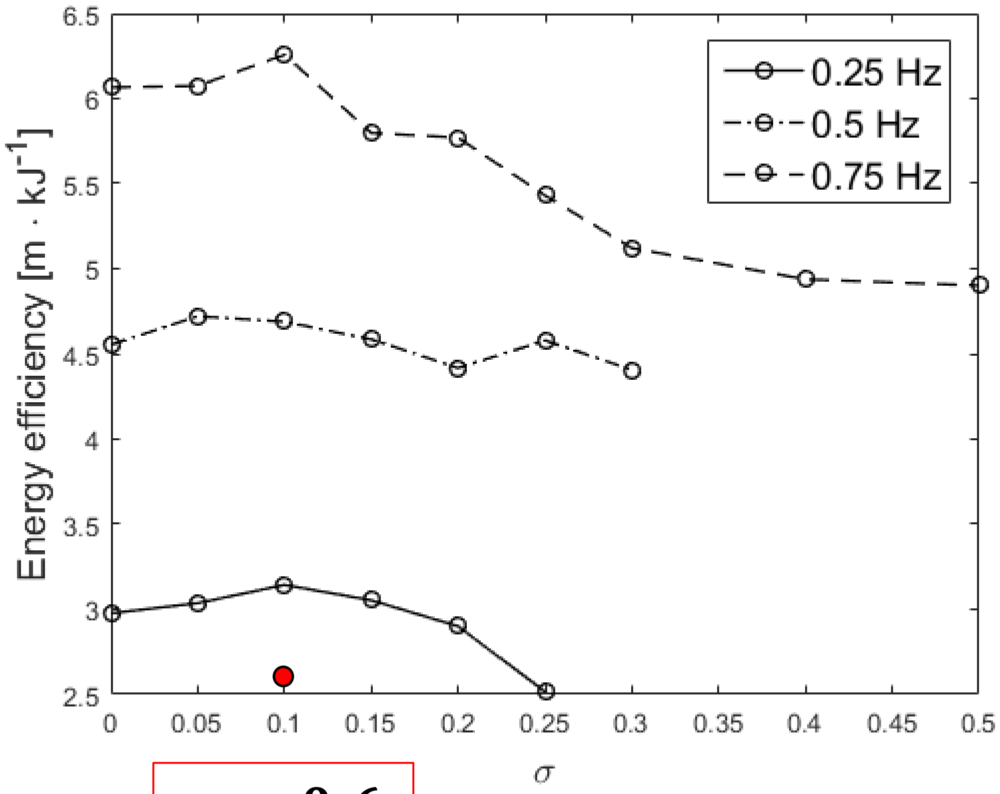
2. Steady State

$\sigma_b = 6\ \sigma$

Binary Tegotae



$\boldsymbol{\sigma_b = 0.6}$



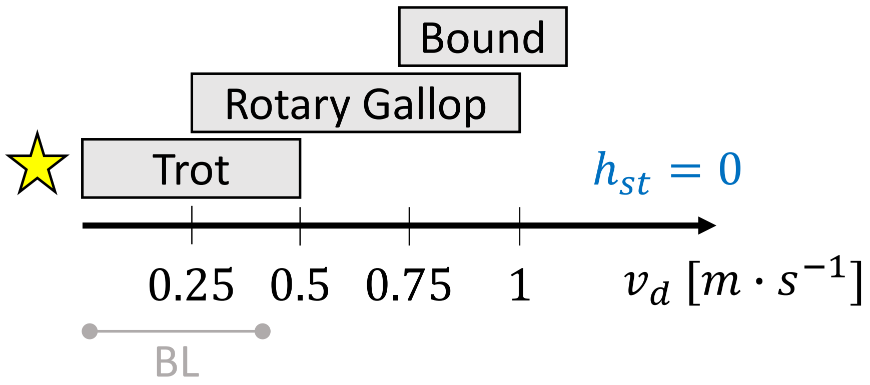
$\boldsymbol{\sigma_b = 0.6}$

Conclusions

Conclusions

Open Loop CPG

Particle Swarm Optimizations:



Systematic Search:

$h_{sw} \in [10,20]\ mm$

H: θ_{max} $\Longrightarrow$ Fast + Efficient

S: θ_{max} $\Longrightarrow$ Slow + Efficient

Tegotae $\boxed{\sigma(t)}$

Convergence: σ ⟶ Trot ☆

Steady state:
σ $\Longrightarrow$ Fast + Efficient
σ ⟶ Stable

$$\dot{\phi}_i = \omega + \sigma_c\, \omega\, N_i\, \cos(\phi_i)$$

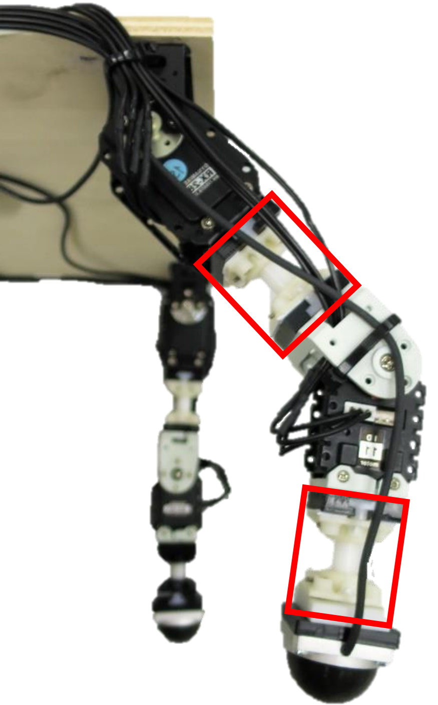
Binary Tegotae ✗

1. Slower convergence
2. Less efficient steady state

Simulation VS Hardware

Future Work

1. More experiments!
2. Rough Terrain
3. Compliance
4. Mophology changes



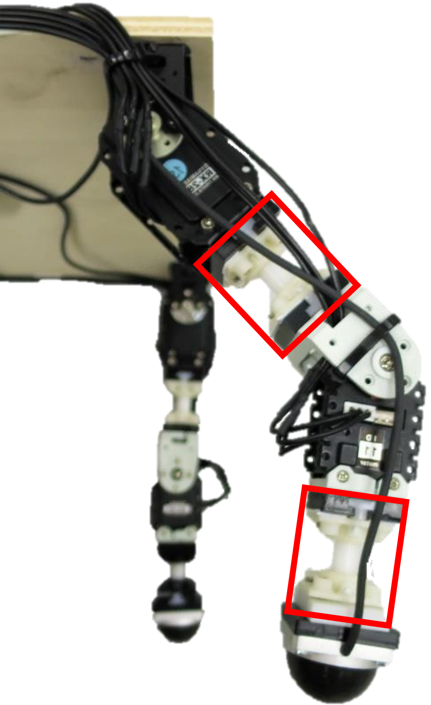
Tegotae

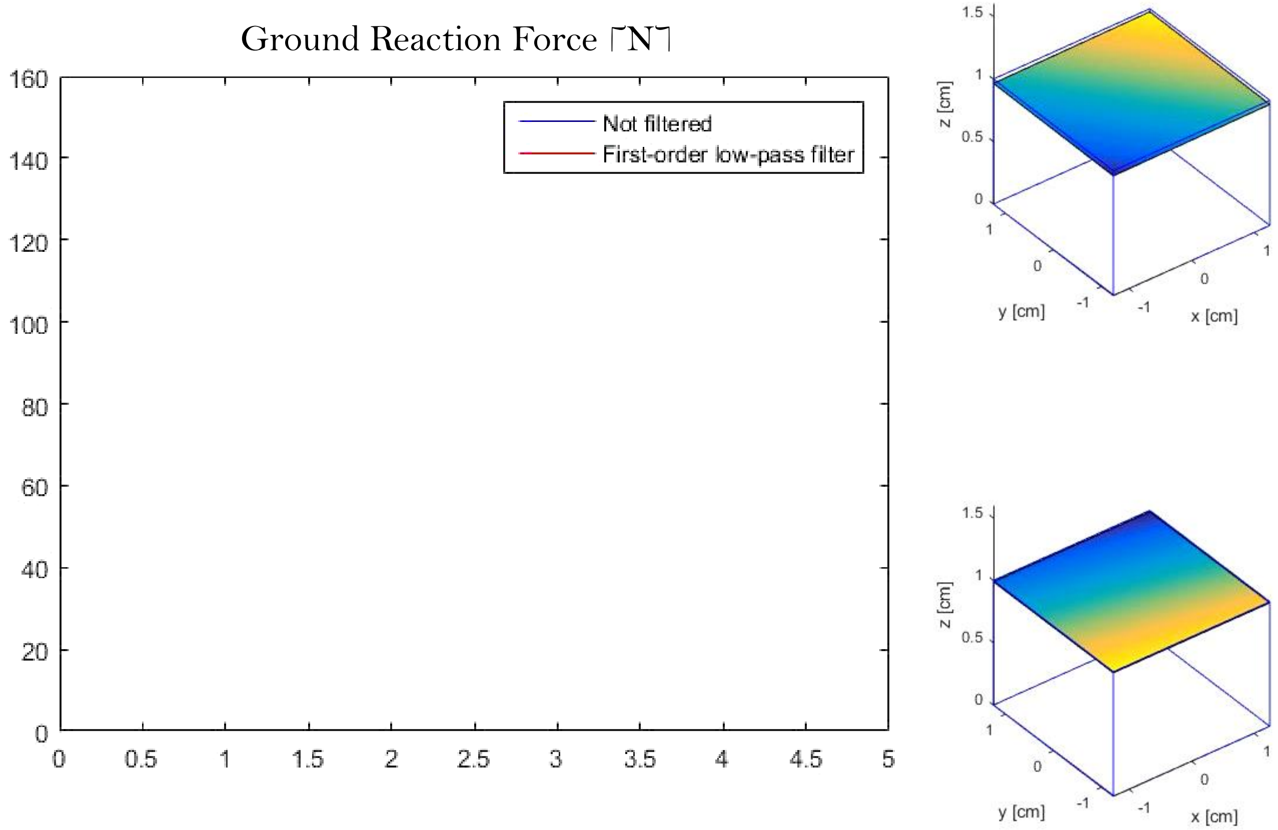
Crawling?

Future Work

1. More experiments!
2. Rough Terrain
3. Compliance
4. Mophology changes

Tegotae



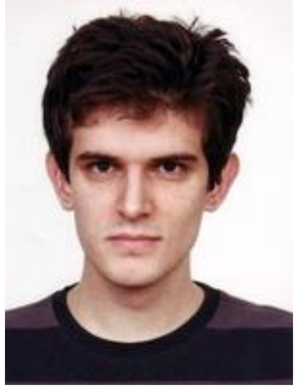


Acknowledgements



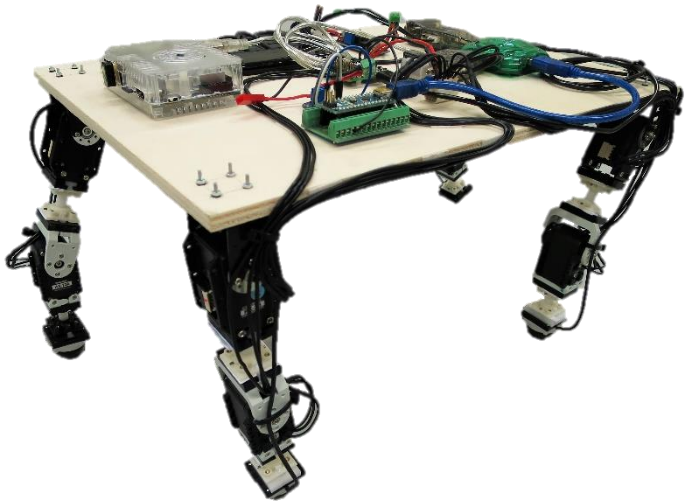

BIOROB
EPFL Biorobotics Laboratory






Final Presentation

CPG and Tegotae based Locomotion Control of Quadrupedal Modular Robots



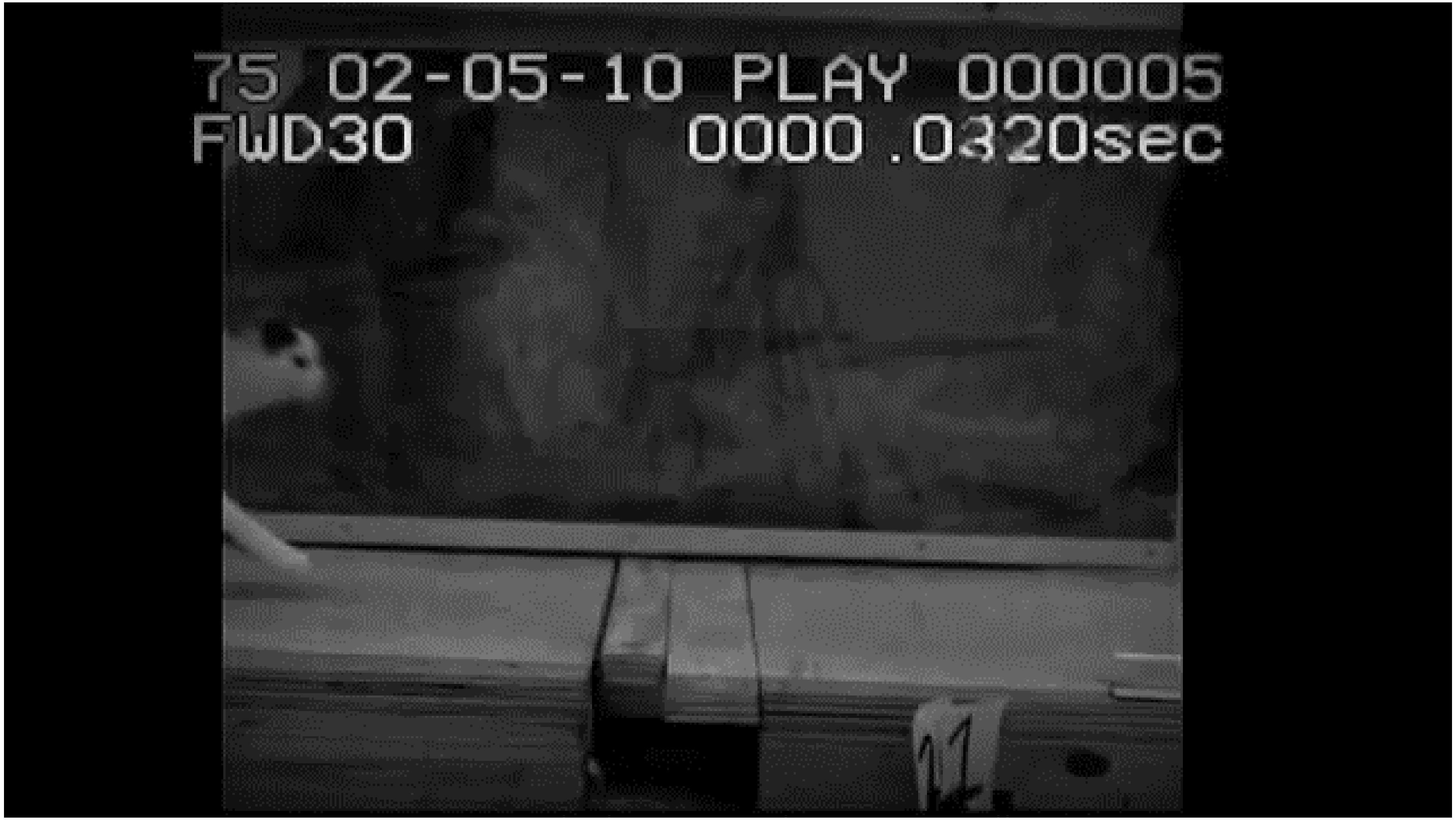
Author:

Rui Vasconcelos

Supervisors:

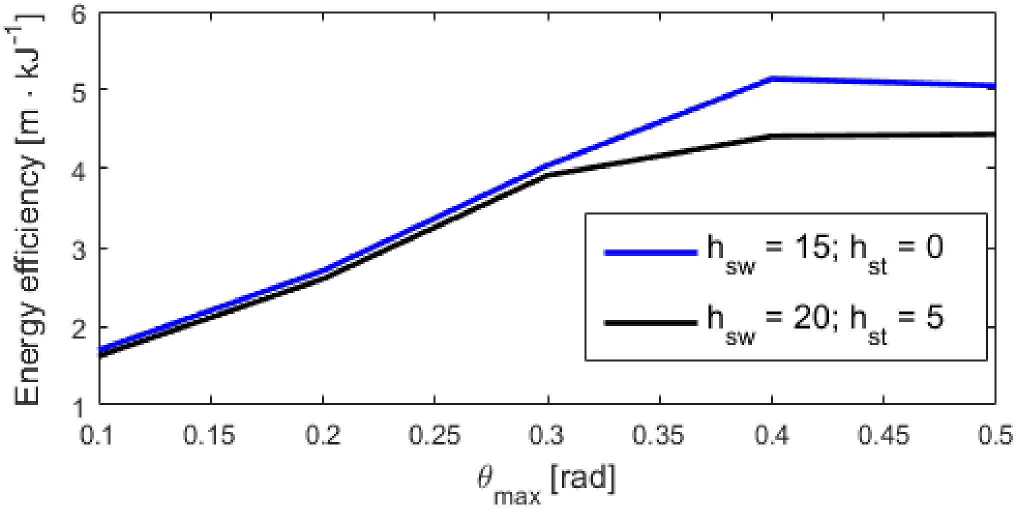
Simon Hauser
Florin Dzeladini
Prof. Auke Ijspeert
Prof. Paulo Oliveira

Appendix: Cat Gallop

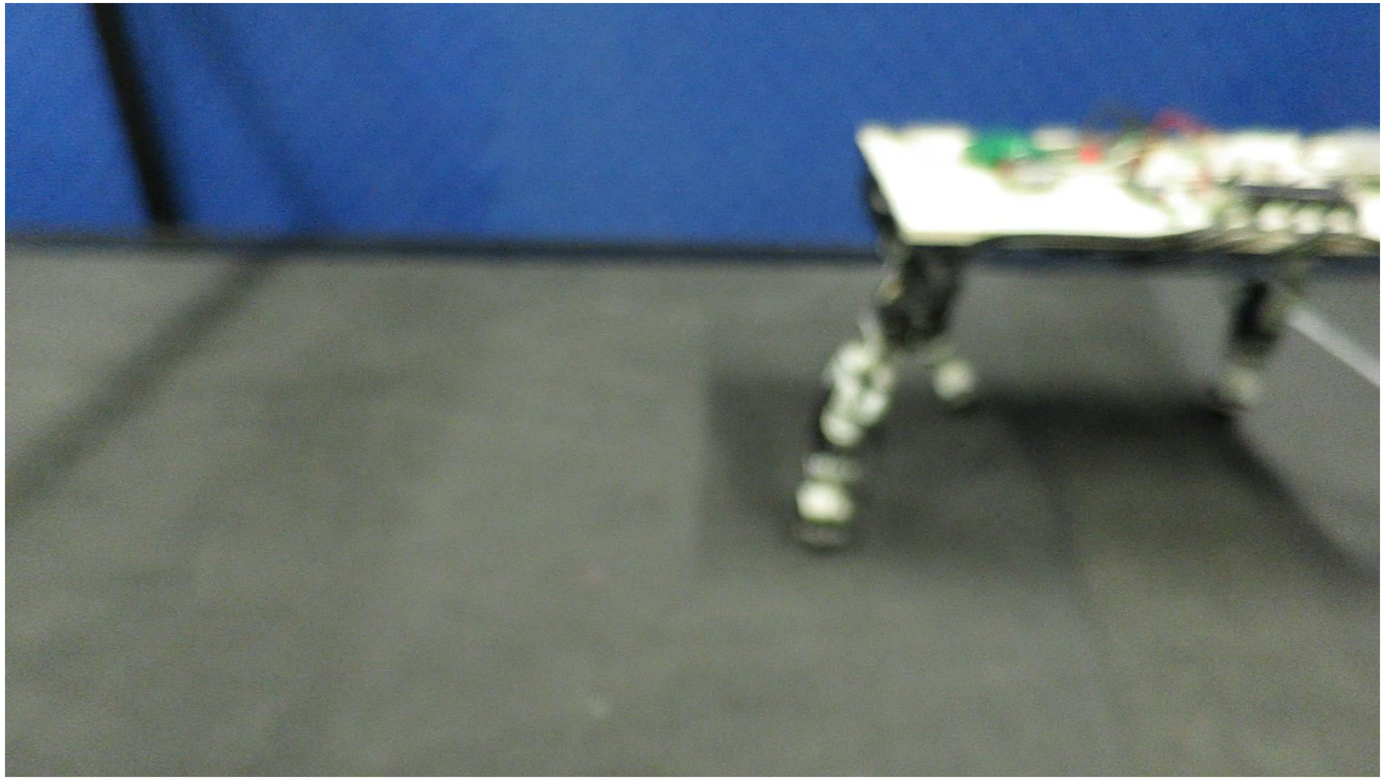


Appendix: Validation on $h_{st} \neq 0$

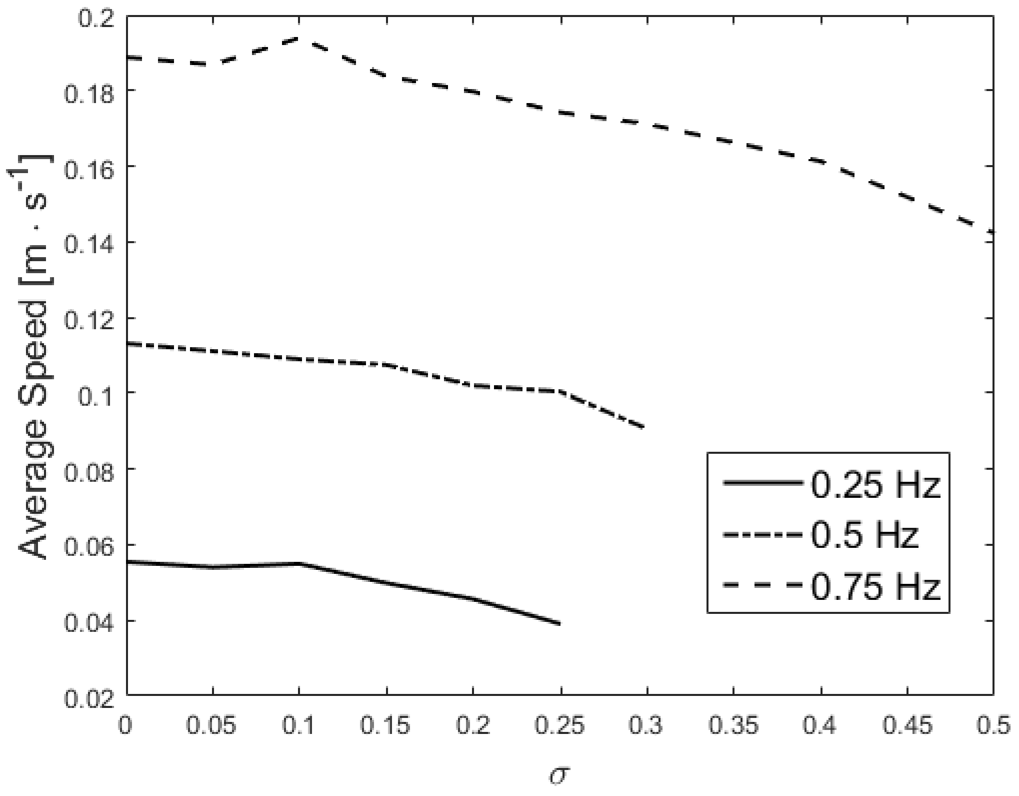
Validation on hardware

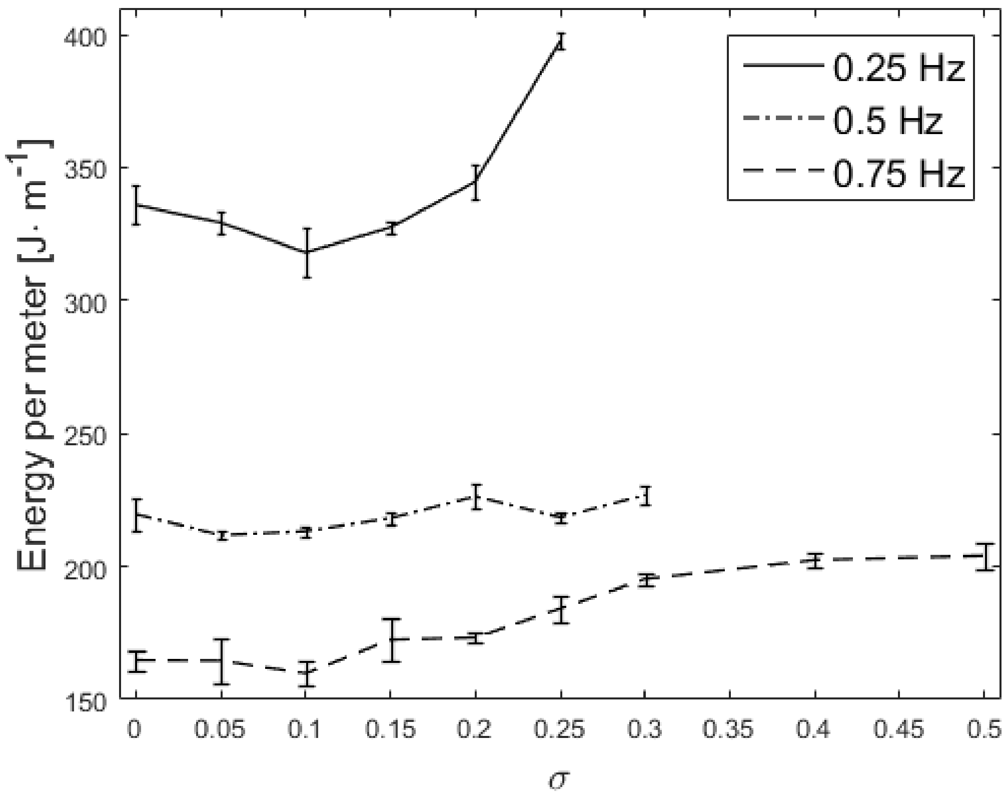


$h_{st} = 5\ mm$



Appendix: Statistics on CLSS





Appendix: Simulation VS Hardware

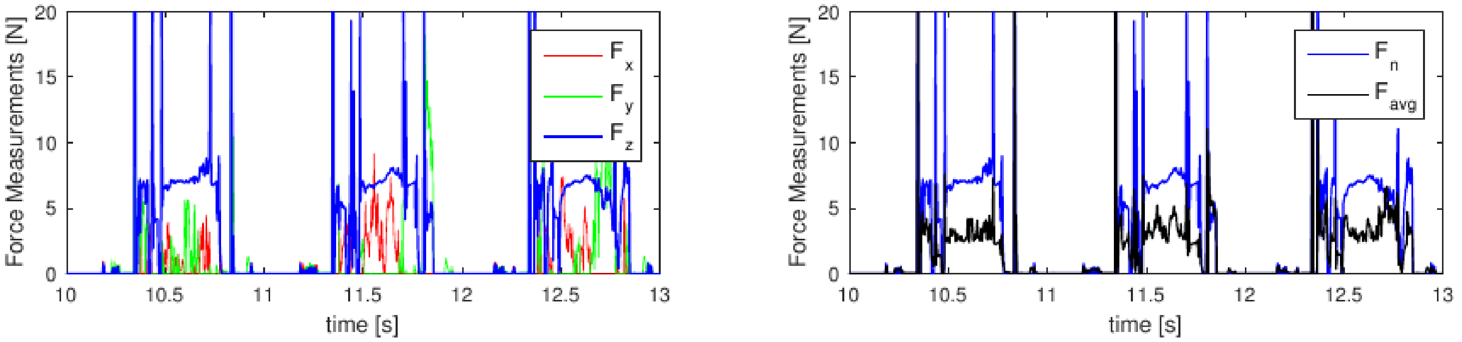


Figure 3.17: **Simulation:** Force measurements from simulation, of steady state open loop trot gait with $df = 0.5$, performed by base morphology at 1 Hz – On the left, the 3-dimensional components of force in local reference frame are presented, where F_z is the component in the axis of the lower limb. On the right, normal force $F_n = F_z$ is compared with average of force components, F_{avg}.

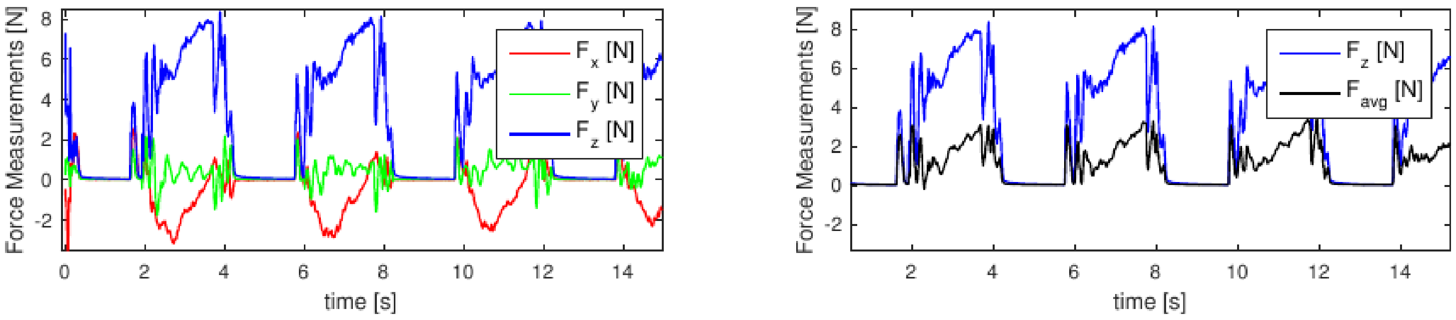
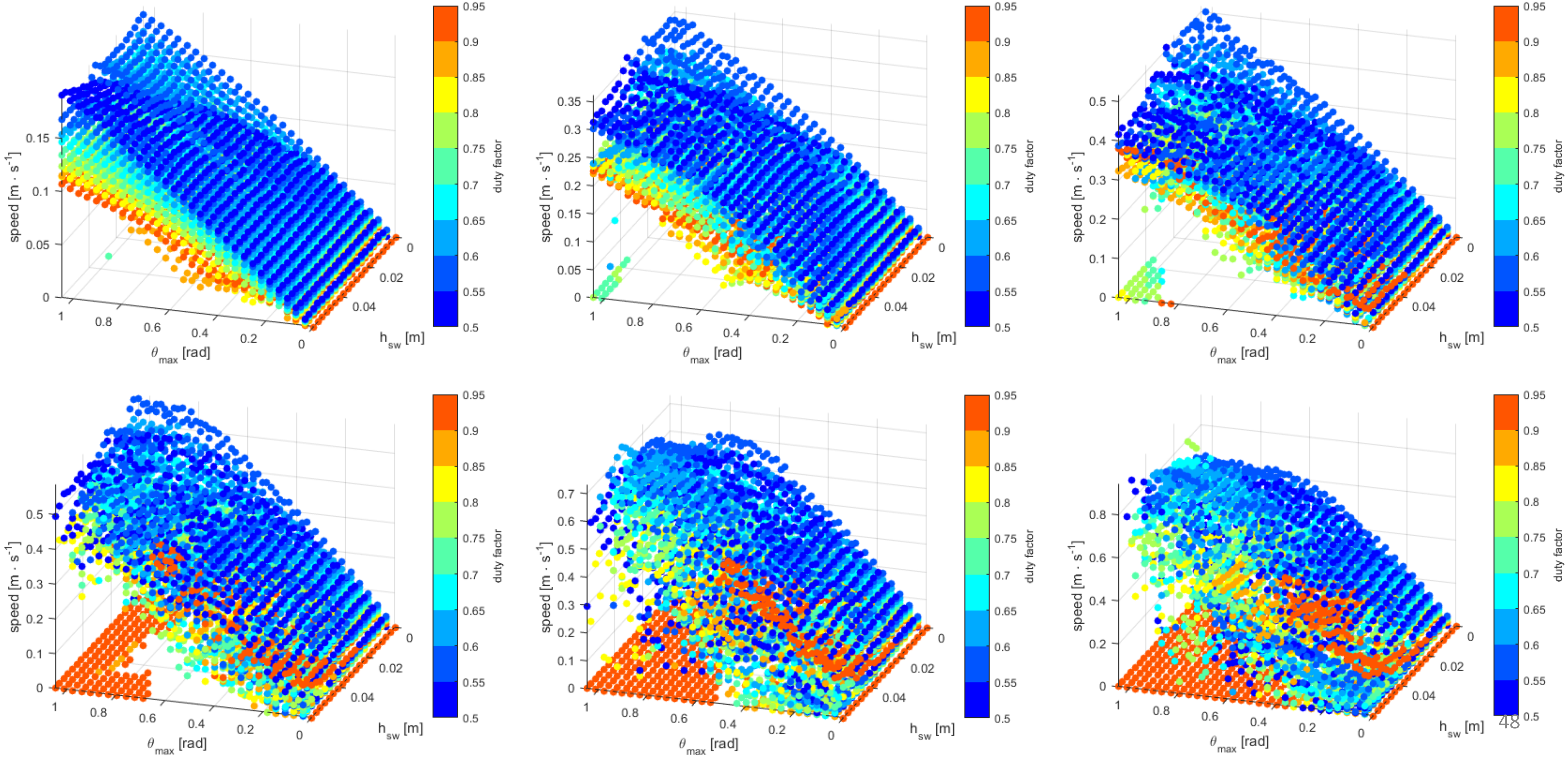
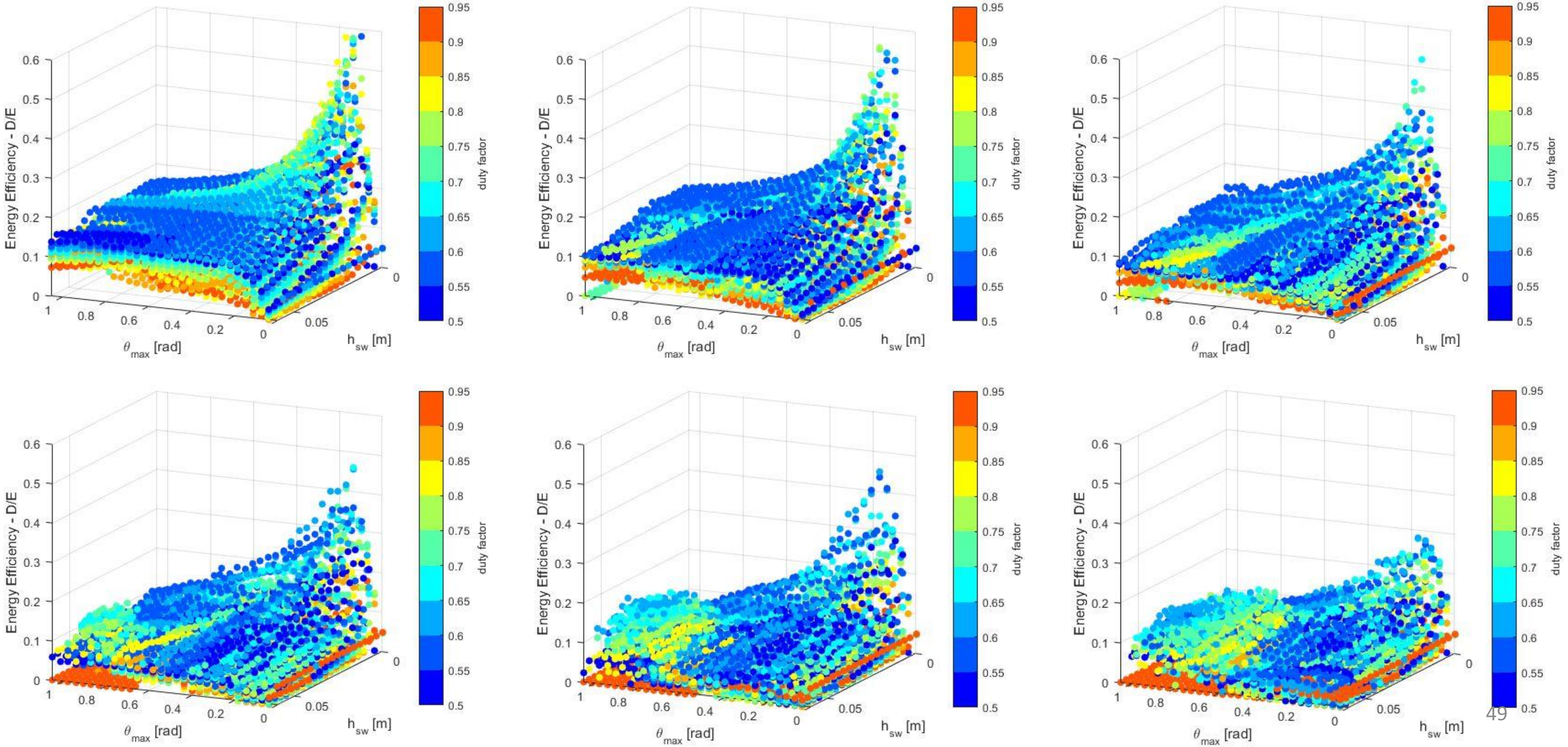


Figure 3.18: **Hardware:** Force measurements from *Optoforce* sensors of steady state trot gait performed at 0.25 Hz – On the left, the 3-dimensional components are presented. On the right, the normal component F_z is compared with the average of the components F_{avg}.

Appendix: Open Loop Systematic Search



Appendix: Open Loop Systematic Search

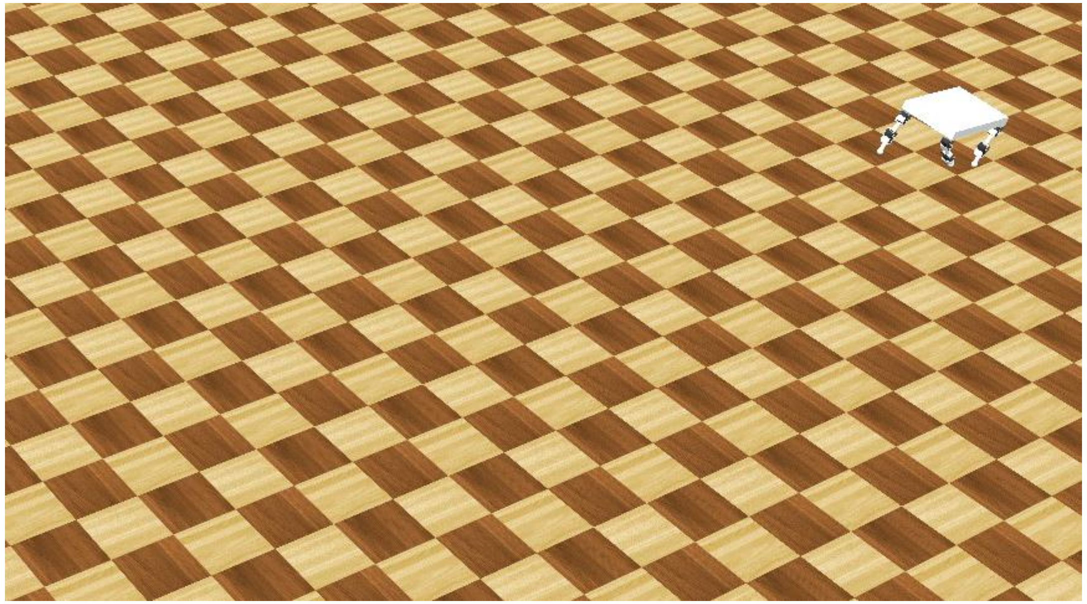


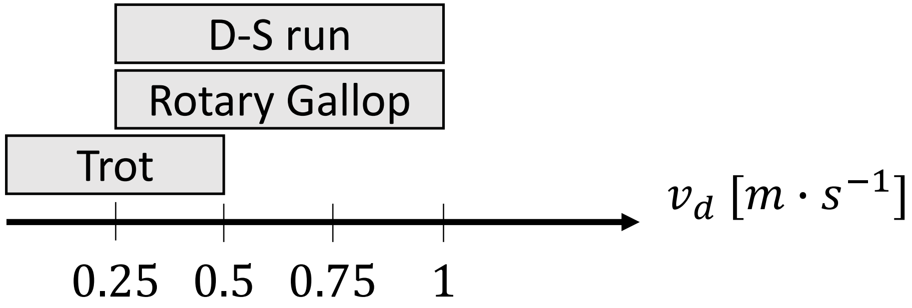
Appendix: D-S run

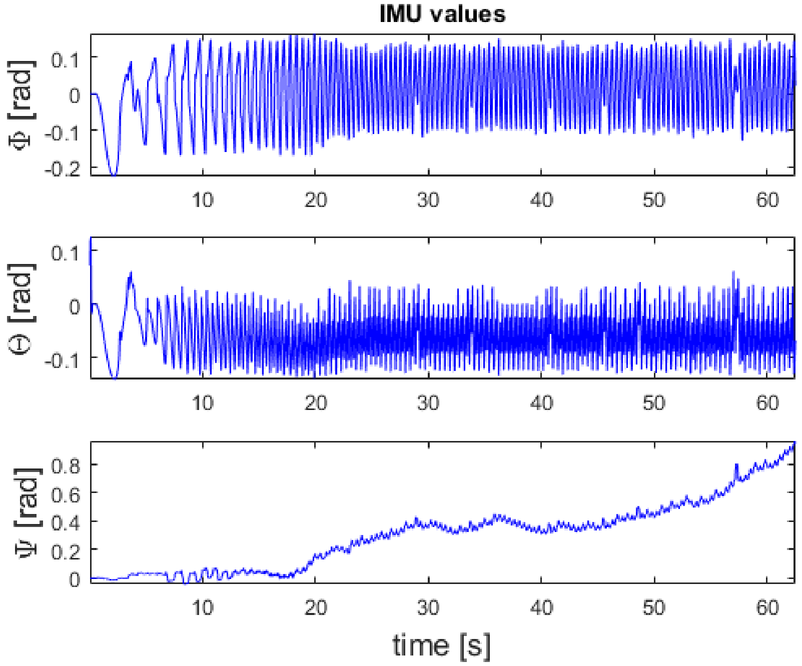
Open Loop CPG

Maximize:

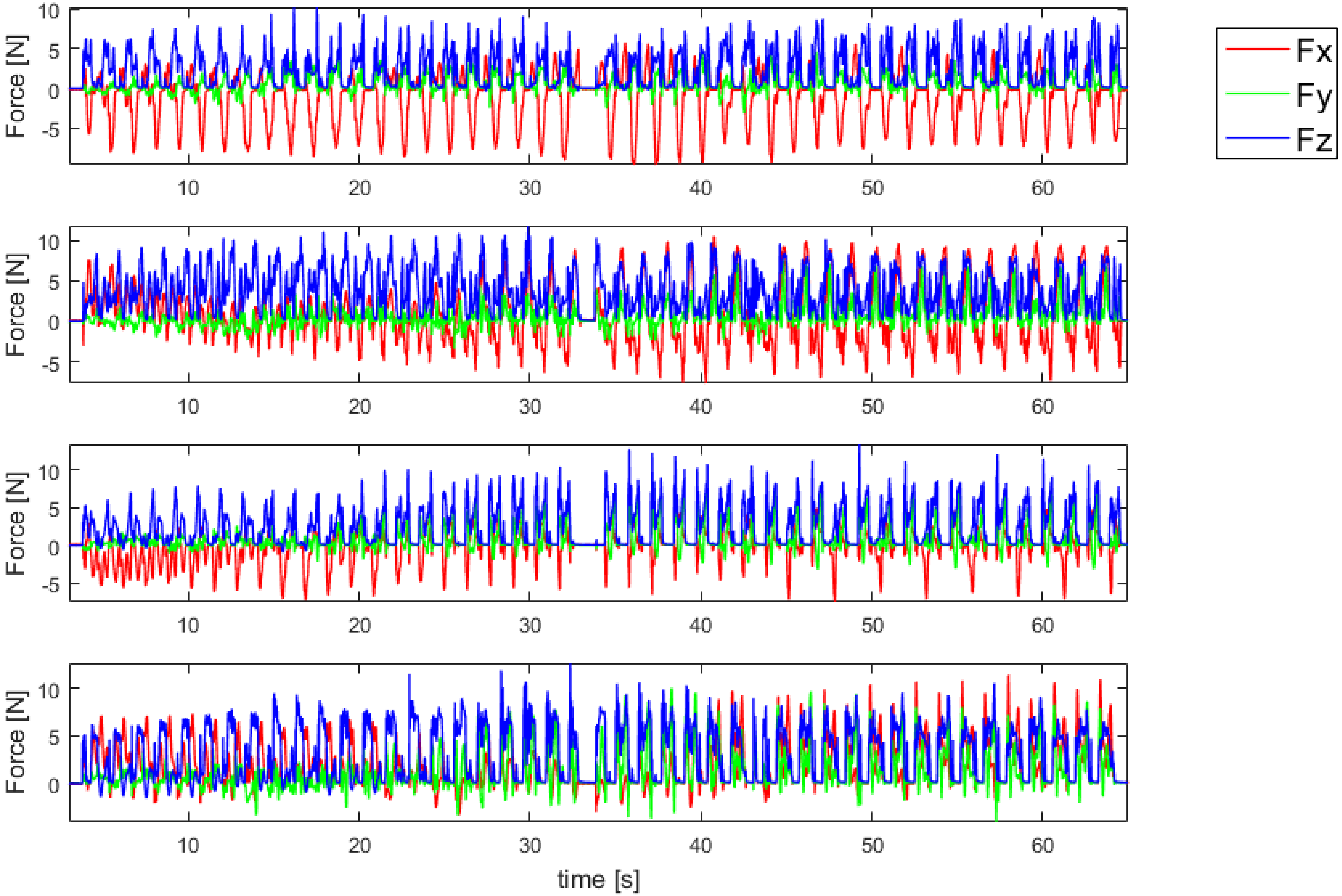
$$Z(f, \theta_{max}, h_{st}, h_{sw}, df, \psi_{12}, \psi_{23}, \psi_{34}) = \sum_{kT=30}^{90} \frac{1}{P_m(kT)} = \frac{1}{E_t}$$



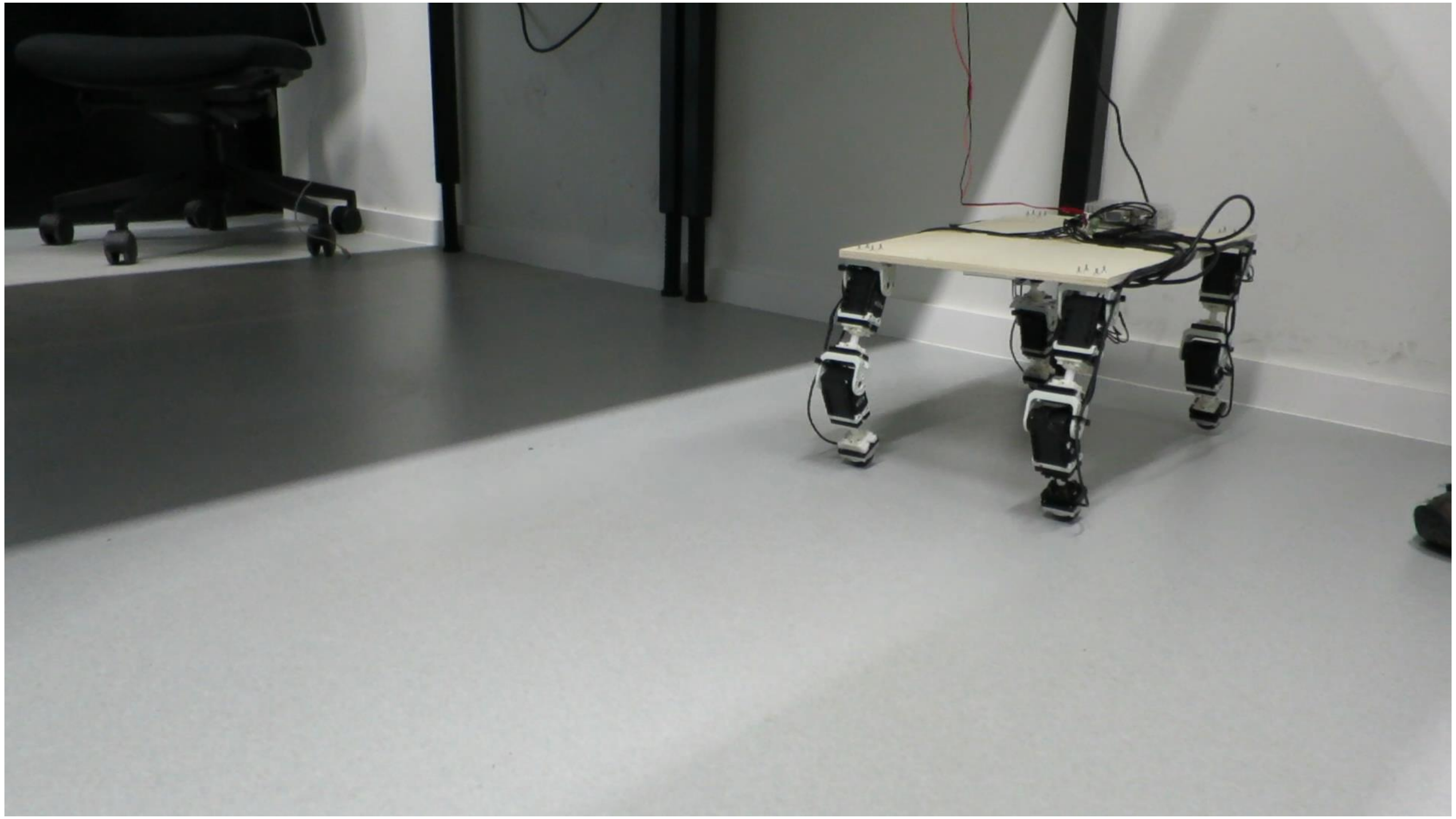




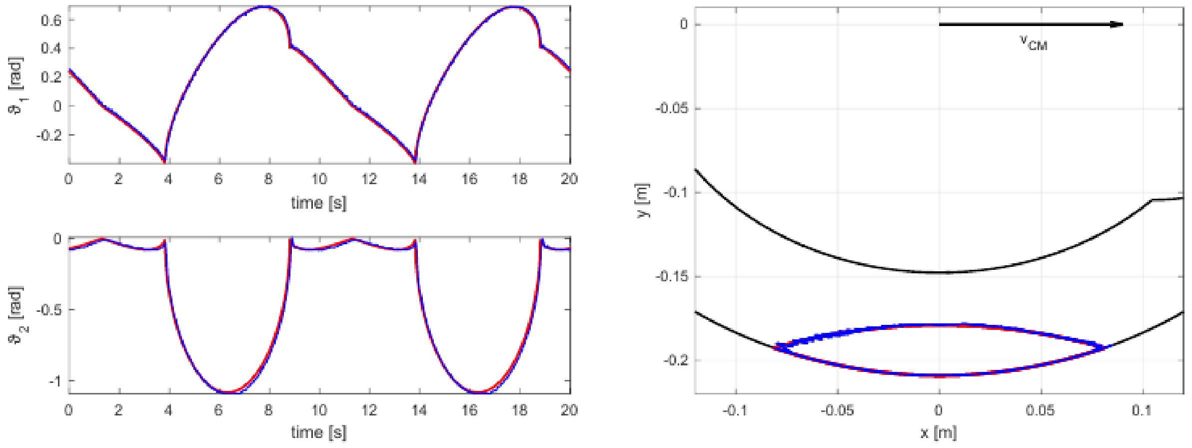
Appendix: 0.75 Hz Binary Convergence



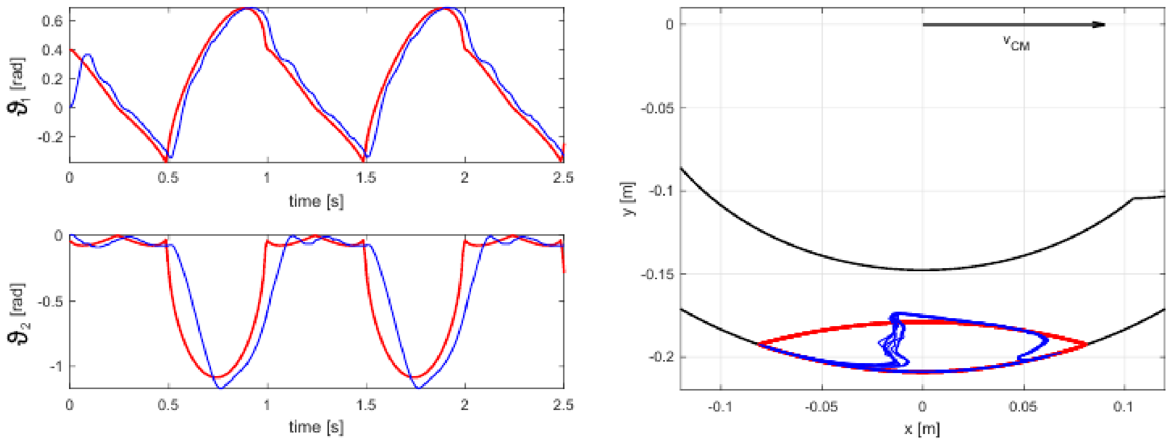
Appendix: Robot version 1



Appendix: Hardware Limitations



(a) 0.1 Hz.



(b) 1 Hz.

Figure 3.9: Effect of frequency on trajectory following.

Appendix: PSO Results

Table 5.1: Results of energy efficiency PSO for constant frequency.

PSO Characteristics			Top Fitness				Best Particle Parameters						
f	IT Nr.	Best IT	ϵ_t	$\overline{v_{CM}}$	S_t	Gait	θ_{max}	h_{st}	h_{sw}	df	ψ_{12}	ψ_{23}	ψ_{34}
0.5	200	200	2.1121	0.0163	6853.4	trot	0.06	≈ 0	0.12	0.8395	-2.2621	2.8152	2.9894
0.5	300	290	3.0532	0.017	5771.1	trot	0.069	≈ 0	≈ 0	0.8455	2.9031	-2.2482	2.8776
0.5	300	300	2.7	0.0221	2859.2	trot	0.084	≈ 0	≈ 0	0.7914	-2.99	-2.2866	2.9785
0.5	400	341	2.1277	0.0138	7342.3	trot	0.05	≈ 0	0.184	0.7535	-3.1042	3.0667	3.1283
0.5	400	360	2.7518	0.0192	507.73	trot	0.073	≈ 0	≈ 0	0.7646	-2.2236	2.978	2.488
0.5	680	660	2.3044	0.0157	2700.5	trot	0.058	≈ 0	0.185	0.7655	2.8902	-2.7892	-2.9408
1	200	192	0.2353	0.2474	4.25	trot	0.418	1.7	12.9	0.731	-2.9936	-2.1185	1.8671
1	200	199	1.4028	0.0369	1104.5	trot	0.067	0.012	0.234	0.7626	-2.8172	2.3386	-2.4382
1	400	366	0.555	0.1411	342.6	trot	0.211	1.1	5.5	0.6219	-2.9386	3.056	3.1191
1	400	391	0.2389	0.4846	3.9652	D-S run	0.914	6	47.4	0.6465	3.1398	-3.1012	3.1229
1	400	335	1.6683	0.0364	6556.3	trot	0.064	0.01	0.197	0.7387	-2.8655	3.9662	3.0158
1	680	617	2.0222	0.045	2520.4	trot	0.086	≈ 0	≈ 0	0.802	-2.1618	2.9419	2.5112
1.5	300	296	0.2524	0.5382	4.072	D-S run	0.664	3.1	23.2	0.6406	3.1121	3.1311	-3.1076
1.5	300	266	1.094	0.0572	554.64	trot	0.066	≈ 0	0.198	0.724	3.062	-2.8667	2.8335
1.5	400	359	0.0951	0.4827	8.976	rotary gallop	0.467	0.456	59	0.4232	0.9652	1.3454	1.4183
1.5	400	365	0.1193	0.597	14.9134	rotary gallop	0.544	1.4	57.3	0.4593	1.5107	1.2875	2.5777
1.5	400	366	1.1057	0.0658	4254.2	trot	0.0728	0.013	0.22	0.6938	3.0971	3.081	3.055
1.5	680	623	0.117	0.6176	7.328	rotary gallop	0.541	2.32	57	0.4958	-1.6486	-0.9766	-2.4938

Appendix: PSO Results

Table 5.2: Results of energy efficiency PSO for desired speed v_d.

PSO Characteristics			Top Fitness					Best Particle Parameters							
v_d	IT Nr.	Best IT	E_t	ϵ_t	$\overline{v_{CM}}$	S_t	Gait	f	θ_{max}	h_{st}	h_{sw}	df	ψ_{12}	ψ_{23}	ψ_{34}
0.25	300	273	196.2	0.079	0.257	11.8	rot. gallop	3.132	0.155	1.34	17.14	0.21	2.362	0.402	2.043
0.25	300	296	53.13	0.295	0.262	33.19	trot	1.399	0.3385	0.68	8.5	0.74	-2.2777	2.3839	-1.996
0.25	400	310	77.18	0.2	0.257	2.54	trot	0.875	0.6023	3.1	26.9	0.77	2.3306	-2.1973	2.1988
0.25	400	385	169.5	0.089	0.252	68.25	rot. gallop	1.113	0.328	0.93	13.4	0.44	1.6142	1.163	1.987
0.25	600	415	159.9	0.094	0.251	5.6792	rot. gallop	2.184	0.2184	1.4	38.5	0.18	3.0207	0.8269	2.4381
0.25	680	317	172.7	0.089	0.255	7.611	pace	2.148	0.2095	1.63	37.7	0.22	-2.571	-1.177	-2.521
0.5	300	299	253.7	0.12	0.51	8.8997	L-S run	1.895	0.4548	4.4	59.4	0.3	-1.5644	-0.8953	-2.4599
0.5	300	284	339.4	0.089	0.504	1.778	rot. gallop	1.609	0.4824	10.2	47.96	0.39	1.4821	0.9352	-3.0533
0.5	400	373	274.4	0.125	0.57	1.774	pace	2.516	0.334	13.7	36.17	0.35	-2.209	-0.9087	-2.2677
0.5	400	397	117.8	0.261	0.513	2.822	trot	1.491	0.6452	3.07	21.47	0.65	-3.0611	3.0632	-3.0645
0.5	600	583	139.4	0.225	0.522	7.8542	D-S run	1.16	0.8017	3.2	37.1	0.67	3.1413	2.6758	-3.1093
0.5	700	579	131	0.23	0.501	21.262	D-S run	1.399	0.6942	4.39	27.73	0.68	-2.8927	2.8913	-3.0235
0.75	300	296	217	0.207	0.75	11.968	D-S run	1.732	0.7081	3.4	27.6	0.59	-3.1063	2.3567	-3.1308
0.75	400	380	337.9	0.139	0.783	3.1801	rot. gallop	2.411	0.4923	16.7	51.9	0.34	-1.5073	-1.0858	-1.9772
0.75	600	591	390.4	0.12	0.775	3.9524	rot. gallop	2.33	0.4885	7.05	53.5	0.38	1.6322	2.1716	1.4061
0.75	700	410	207.9	0.217	0.753	10.1817	D-S run	1.578	0.7749	4.76	34.57	0.58	-2.7079	2.399	3.0419
1	300	294	479.3	0.13	1.035	2.2923	bound	2.743	0.5101	6.2	56.7	0.4	-0.6652	-1.95	0.0177
1	400	361	320	0.19	1.01	18.962	D-S run	2.31	0.6998	8.2	26.78	0.53	2.831	2.6956	-3.1034
1	400	266	632.3	0.099	1.046	4.6482	rot. gallop	3.955	0.4244	14.3	30	0.31	1.554	1.8795	1.6095
1	600	593	317.9	0.189	1.002	1.7754	D-S run	2.186	0.7234	6.8	25.4	0.55	3.0952	2.4665	-3.0087
1	700	521	649.4	0.098	1.063	1.2427	bound	3.174	0.4851	11.3	48.4	0.34	0.3377	-2.133	0.037