Master Project

February 16, 2011
Final Presentation

Using sensory feedback to improve locomotion performance of the salamander robot in different environments

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Structure of the presentation

- Structure of the presentation:

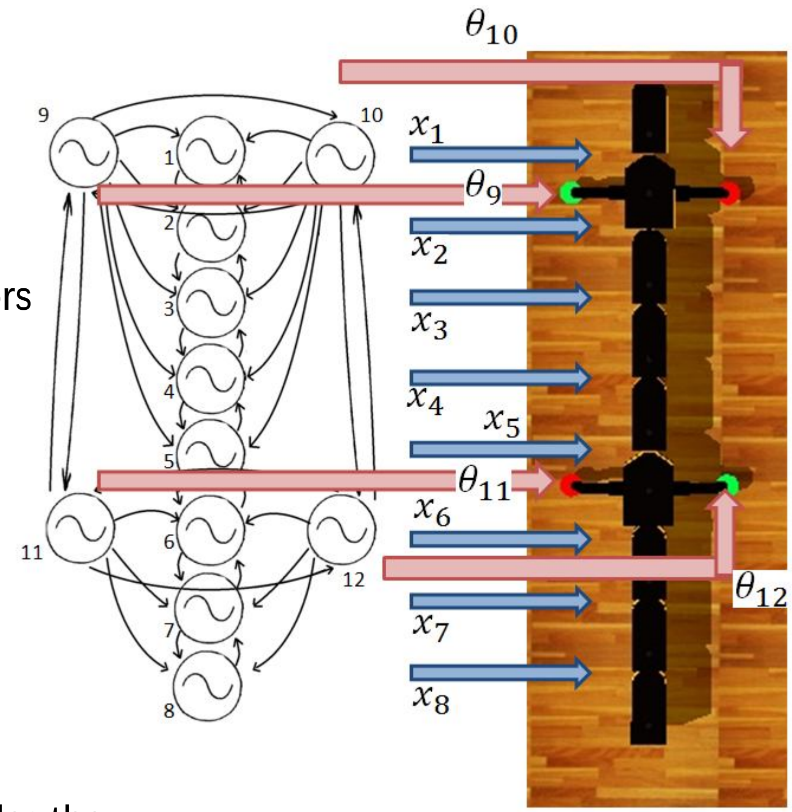
I. Overview

- Project began with exploration of possible sources of sensory feedback
- Make salamander more adaptable to unpredictable environments

- Motivated by the controller by Righetti and Ijspeert[1]:
  - Appealing because of the ability to control phase durations
  - Has been applied before to other quadruped robots, but not to the salamander
- The goal is to generate adaptive walking, based on the control of phase durations, using touch sensors from the limbs for sensory input

II. CPG network and oscillator model

- CPG network
  - 1 body CPG (8 oscillators)
  - 1 limb CPG (4 oscillators)
- Coupling
  - Interlimb coupling
  - Frontal limbs project to 5 first body oscillators
  - Hind limbs project to the 3 last
- Hopf oscillators
  - X variable of oscillator i controls angle of joint i
  - Phase of limb oscillators controls the position of the limbs
- Phase relations
  - Body describes S-shaped standing wave
  - Limbs in phase with all the other limbs besides the diagonally opposed (antiphase)



II. CPG network and oscillator model

- Hopf oscillators proposed by Righetti and Ijspeert:

oscillator frequency

feedback term

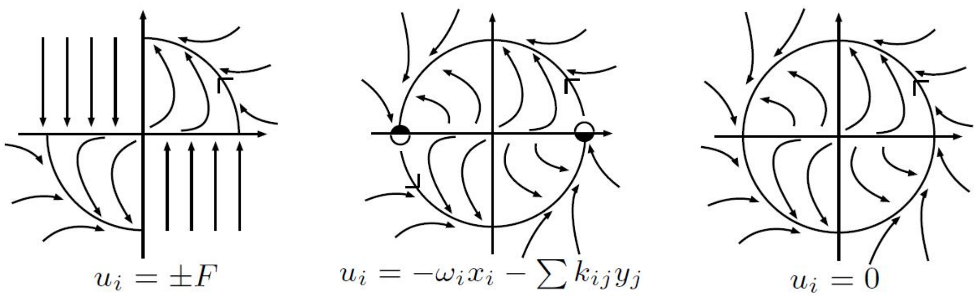
coupling weights

$$\dot{x}_i = \alpha(\mu - r_i^2)x_i - \omega_i y_i$$
$$\dot{y}_i = \beta(\mu - r_i^2)y_i + \omega_i x_i + \sum k_{ij} y_j + u_i$$

- The term u_i is responsible for the feedback:

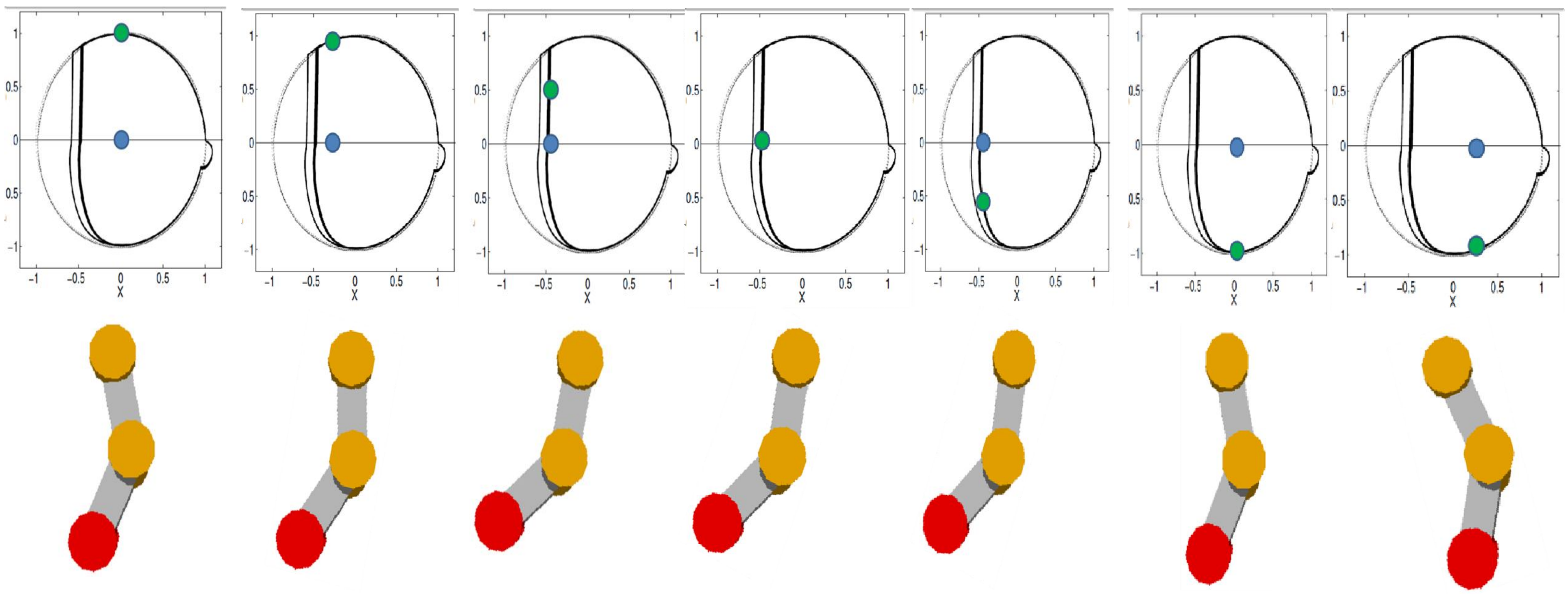
$$u_i = \begin{cases} -\text{sign}(y_i)F & \text{fast transitions} \\ -\omega_i x_i - \sum k_{ij} y_j & \text{stop transition} \\ 0 & \text{otherwise} \end{cases}$$

- Phase space



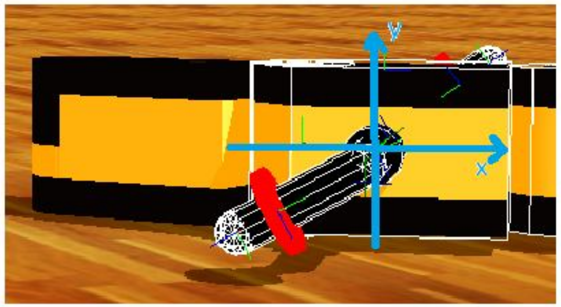
II. CPG network and oscillator model

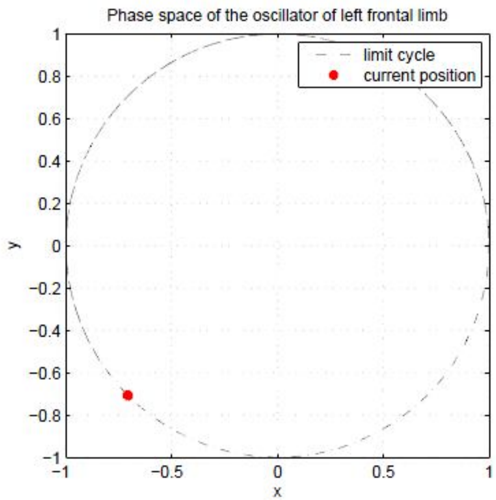
- Hopf oscillators control policy
  - X variable controls corresponding joint angle



II. CPG network and oscillator model

- Salamander’s limbs are rotative
  - Need to be controlled by a monotonically increasing signal
  - x,y are not valid options
  - Solution: oscillator’s phase





II. CPG network and oscillator model

- Phase transitions are not used in the same way, instead, frequency changes depending on sensory feedback:

$$\omega = \frac{\omega_{stance}}{e^{\gamma}+1} + \frac{\omega_{swing}}{e^{-\gamma}+1}$$

- Where

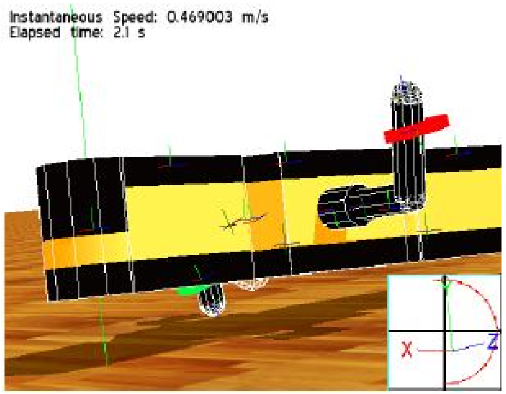
$$\gamma = \begin{cases} -1000, & \text{if} \quad \text{limb is on the ground,} \\ 1000, & \text{if} \quad \text{limb is off the ground,} \end{cases}$$

- Also, to avoid skiping stance phases, use limb stopping:

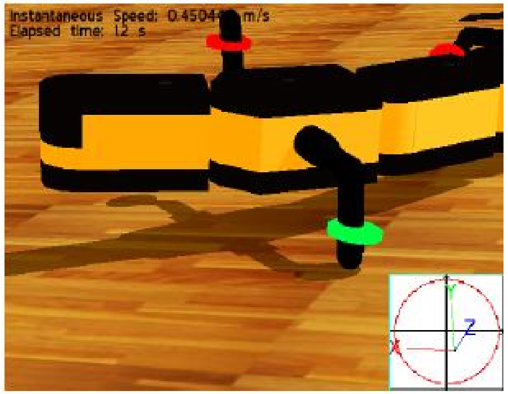
$$\omega_i = \begin{cases} 0, & \text{if} \quad \theta_i = -90^\circ \text{ and limb is not on the ground,} \\ \frac{\omega_{stance}}{e^{\gamma}+1} + \frac{\omega_{stance}}{e^{-\gamma}+1}, & \text{otherwise} \end{cases}$$

II. CPG network and oscillator model

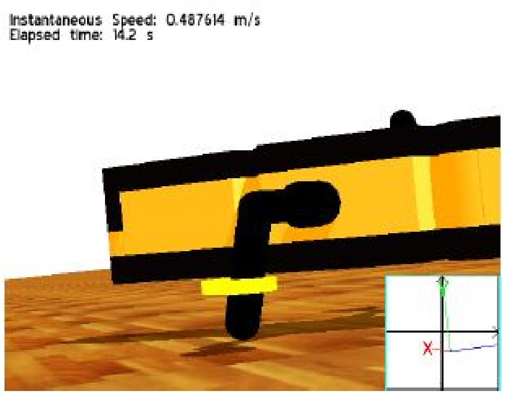
- Visual inspection of locomotion phase



Red = Swing



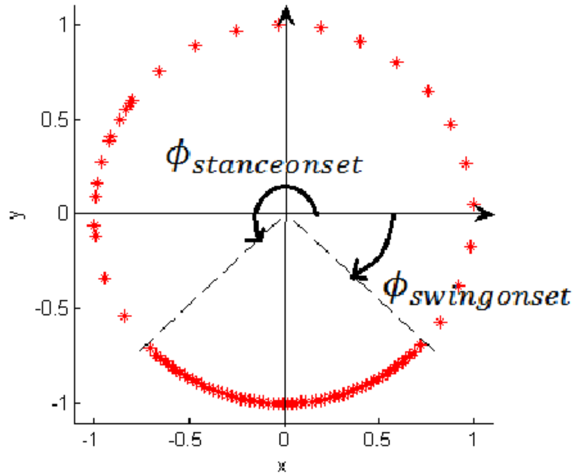
Green = Stance



Yellow = limb stopped

III. Optimization of the open-loop controller

- For the presented network, 4 parameters define a gait in open-loop:
  - Swing/stance frequency
  - Angle to onset swing/stance phase
- Closed-loop control only needs swing and stance frequencies

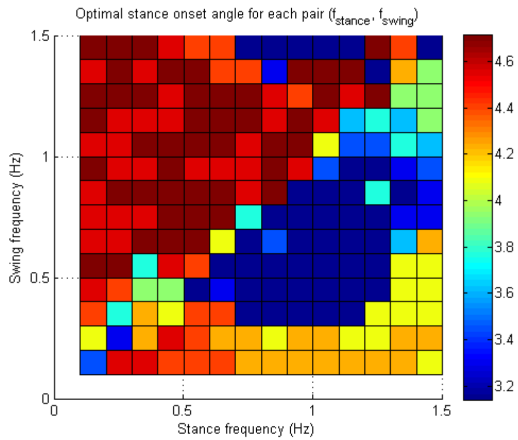


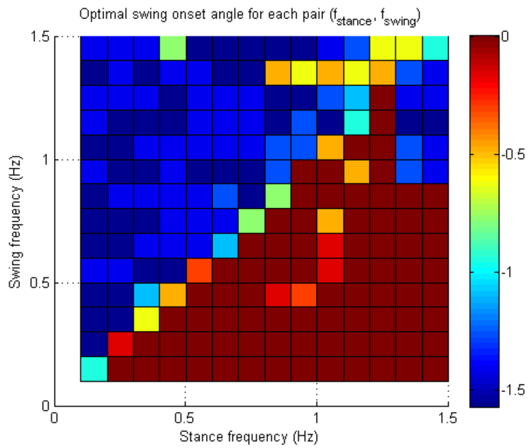
- The open-loop controller is optimized to find the highest speed for each pair of frequencies and corresponding angles
- Then the optimized open-loop controller is compared to the closed-loop in different environments

III. Optimization of the open-loop controller

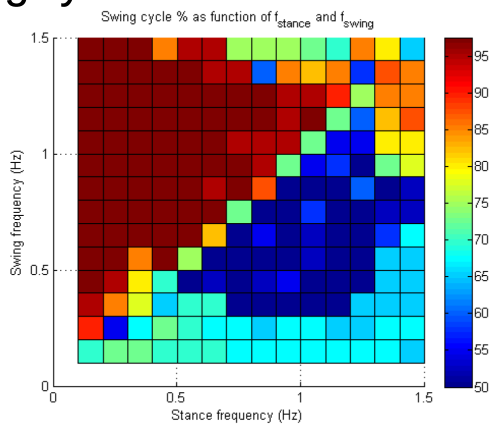
- Results of optimization

Ideal angles:

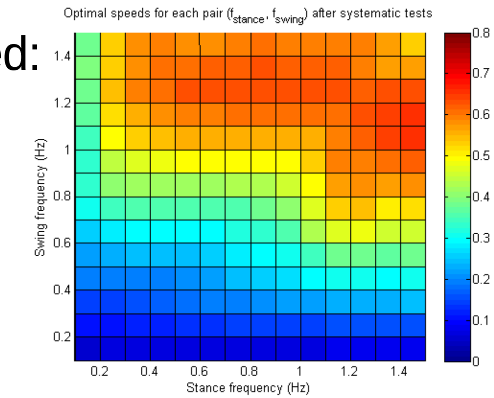




Swing cycle %:



Speed:



III. Optimization of the open-loop controller

- The optimization resulted in pairs of angles that maximize the duration of the phase with highest frequency

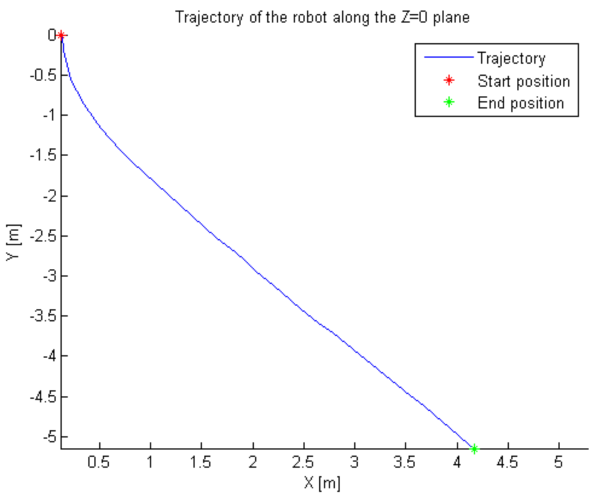
- This leads, for example, to lower duty factors

IV. Controller performance

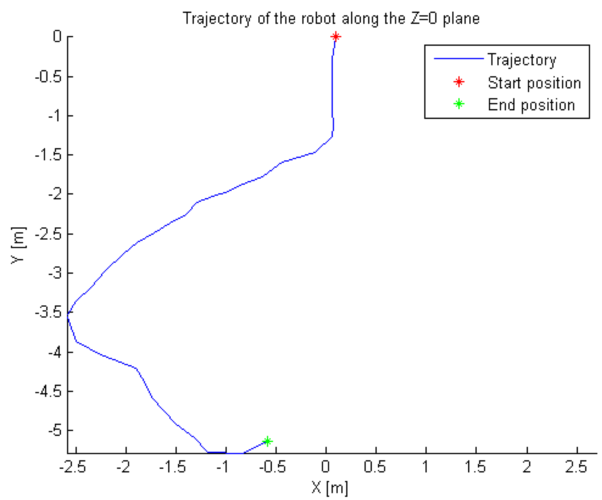
- Performance indicators:
  - Average speed
  - Tortuosity – indicator of the curvature of trajectory:

$$\tau = \frac{L}{C}$$

L – travelled distance
C – distance between initial and final positions



$\tau = 1.0$

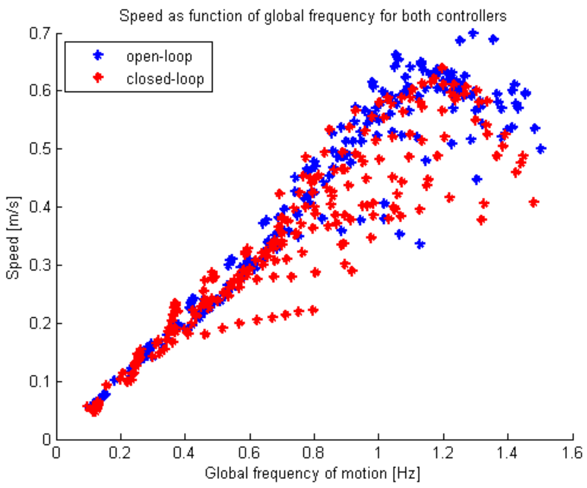


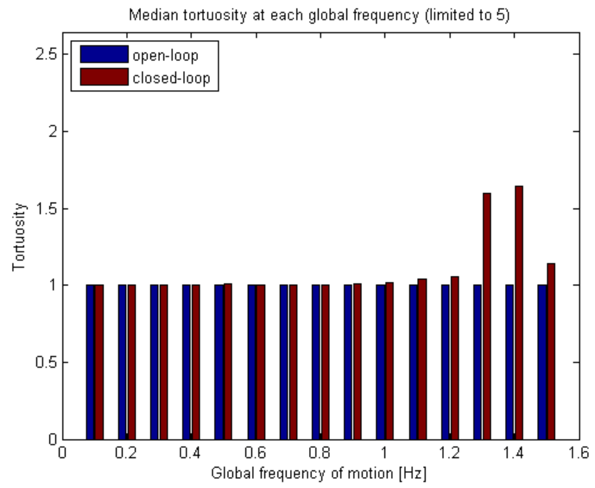
$\tau = 1.65$

IV. Controller performance

- The controllers were tested in 5 different terrains:
  - Flat
  - Slopes
  - Terrains with holes
  - Rough, uneven terrains
  - Terrains with different frictions

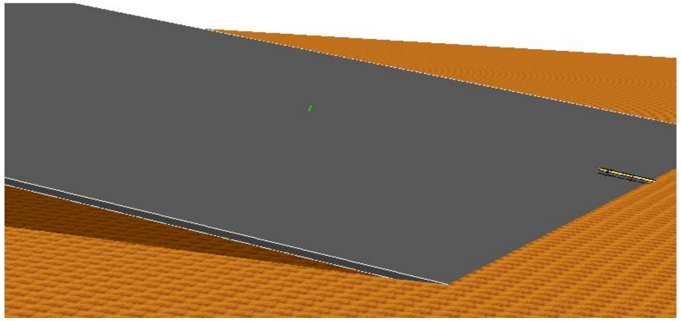
- Flat terrain
  - Open-loop controller performs better in speed – consequence of the optimization
  - Tortuosity is similar except for high frequencies



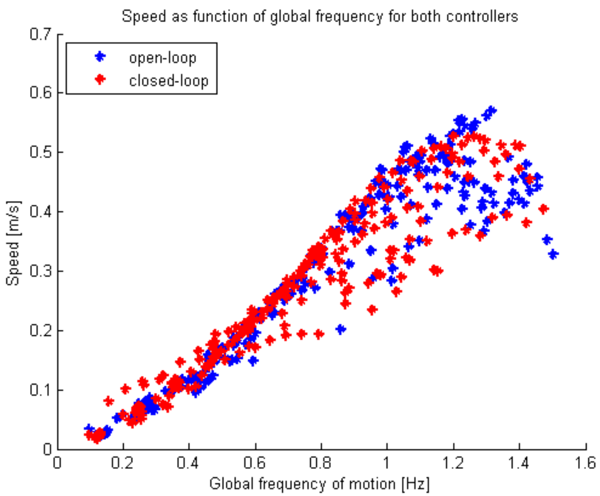


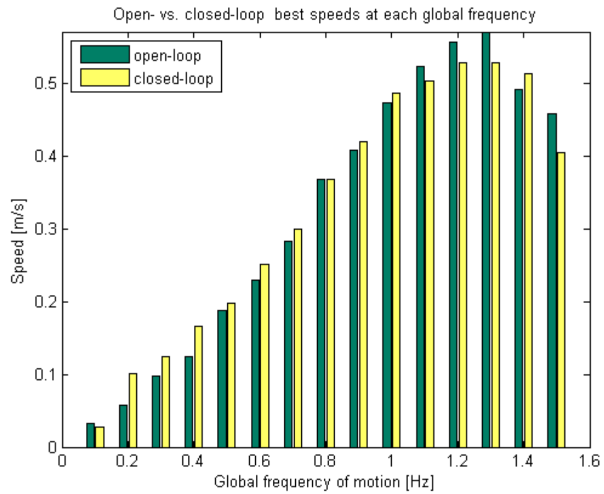
IV. Controller performance

- Slopes
  - 10º inclination
  - 20º inclination



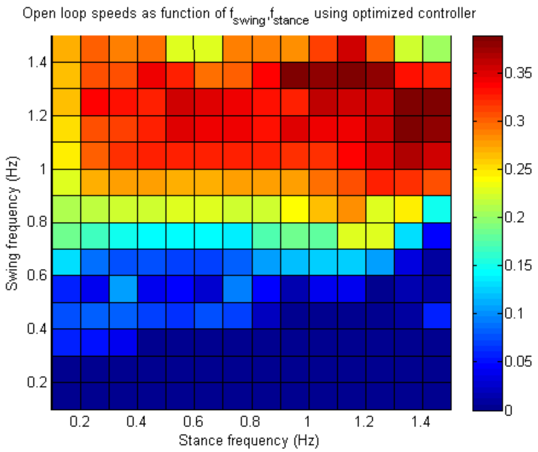
- 10º inclination
  - Closed-loop controller outperforms the open-loop at low frequencies



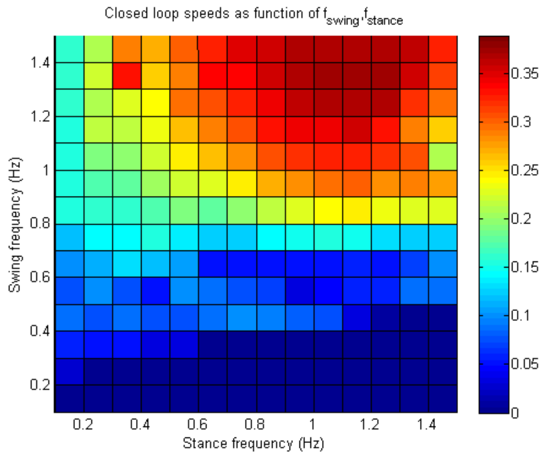


IV. Controller performance

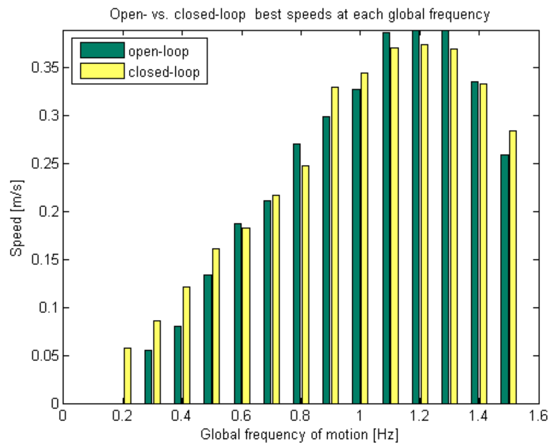
- 20º inclination
  - Dark blue region in the graphs corresponds to very low speeds
  - This region is smaller for the closed loop controller – suggests advantage of sensory feedback



Open-loop



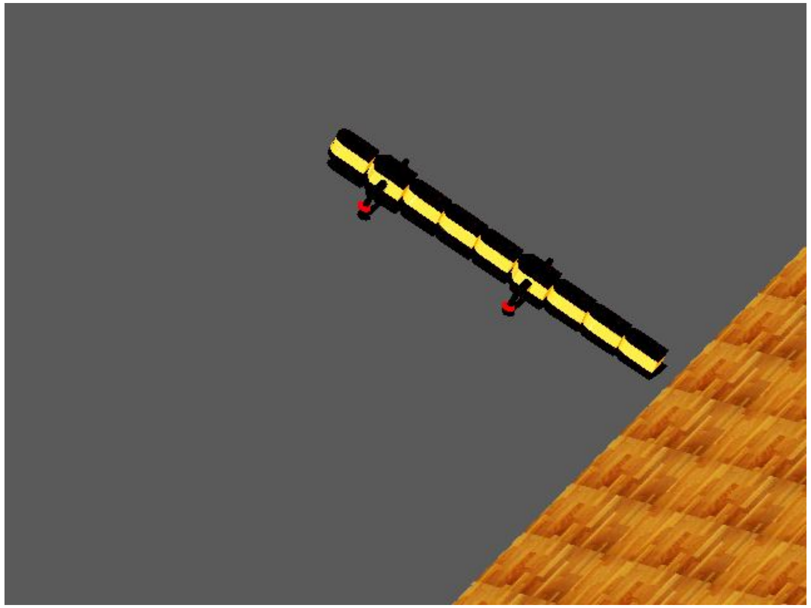
Closed-loop



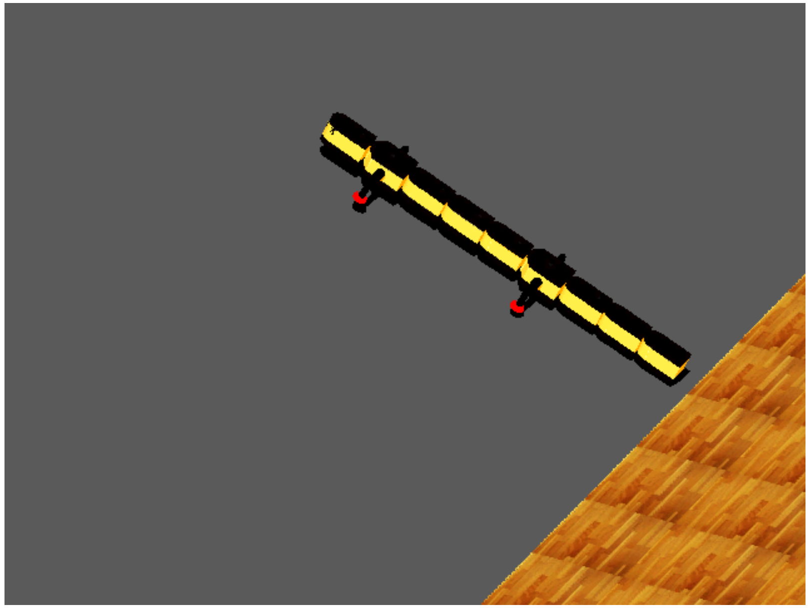
IV. Controller performance

- 20º slope
  - Simulations at global frequency of motion of 0.2 Hz

Open-loop:

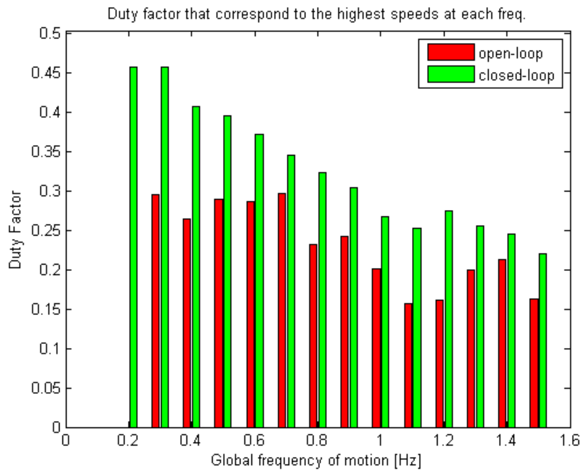


Closed-loop:

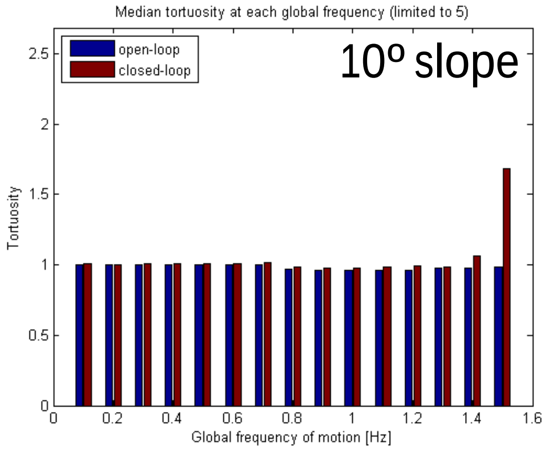


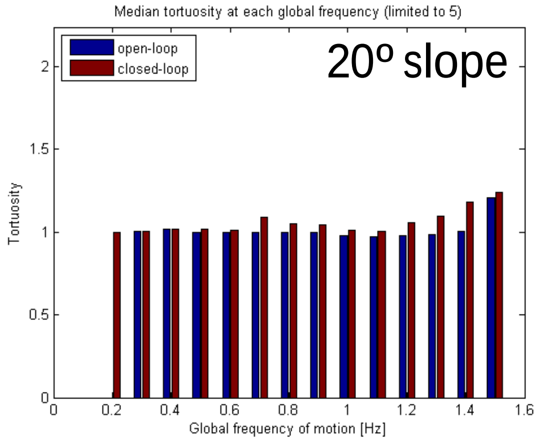
IV. Controller performance

- 20º slope
  - Movies show that the most successful gait is the one that stays longer in stance phase
  - Duty factors are higher in closed-loop
  - Sensory feedback adjusts the phase durations



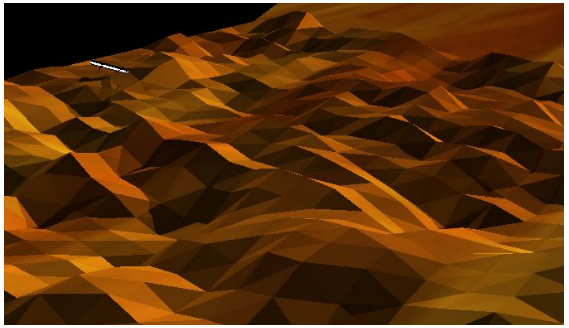
- Slopes – Tortuosity
  - Closed-loop being slightly outperformed

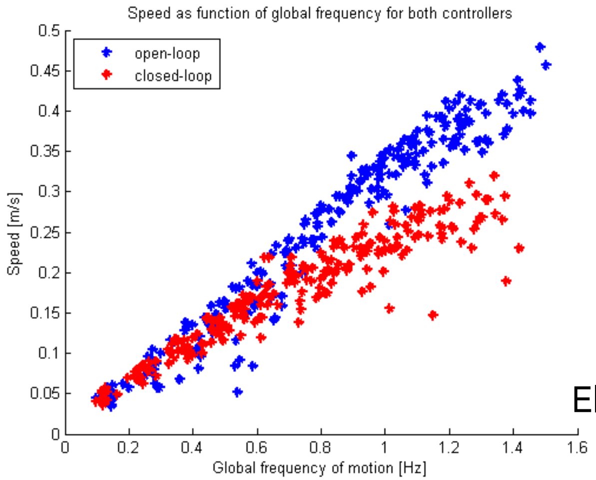




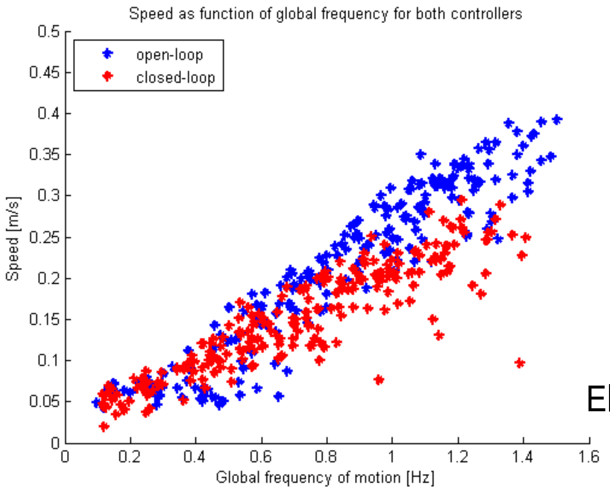
IV. Controller performance

- Uneven terrains
  - Two difficulty levels:
    - elevation of peaks = 2
    - elevation of peaks = 5
  - In none of the cases sensory feedback is an advantage





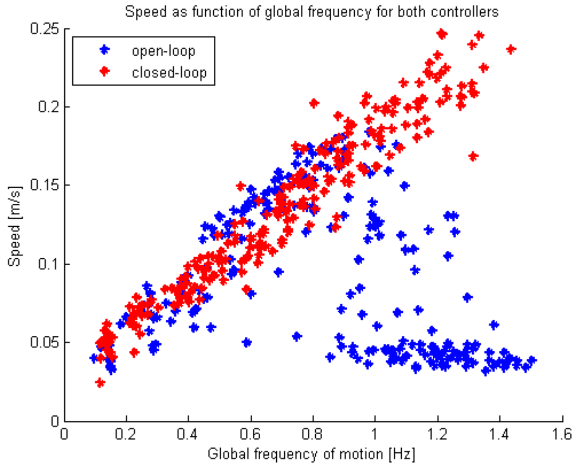
Elevation =2



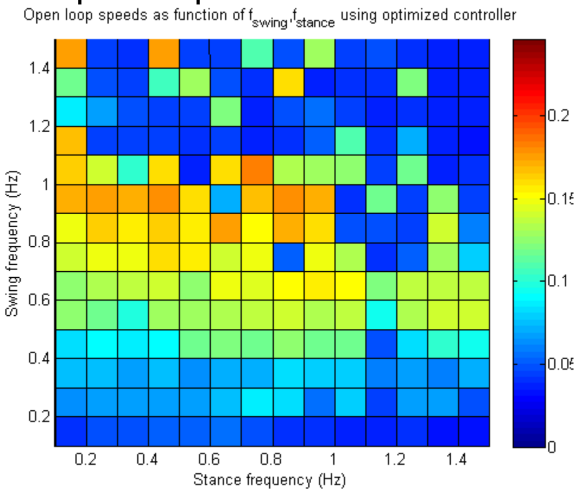
Elevation =5

IV. Controller performance

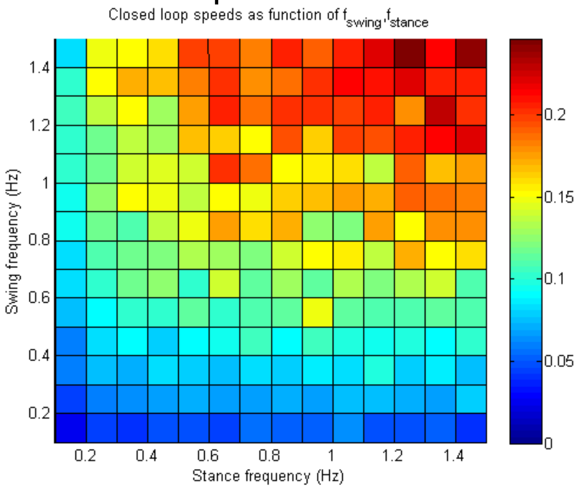
- Uneven terrains
  - Unexpected behaviour: changing the body amplitude to A=0.25, the closed--loop controller is the one that generates higher speeds



Open-loop

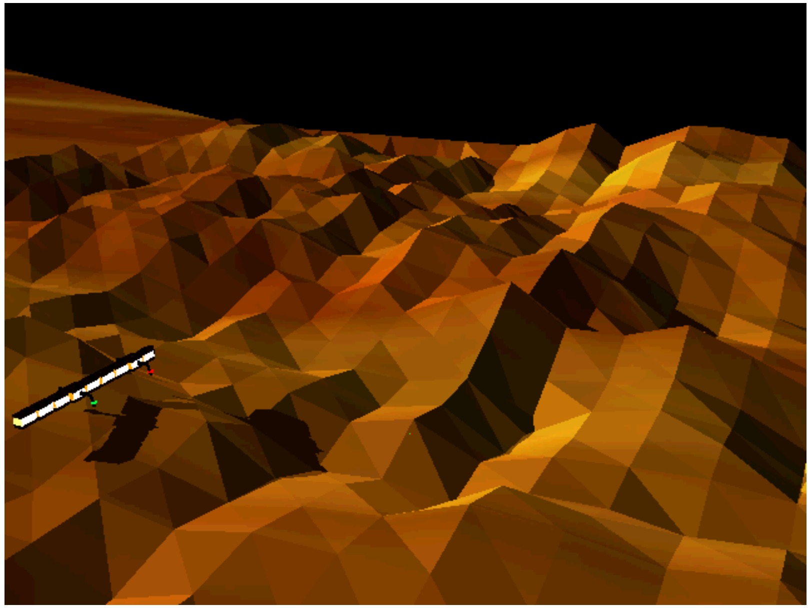


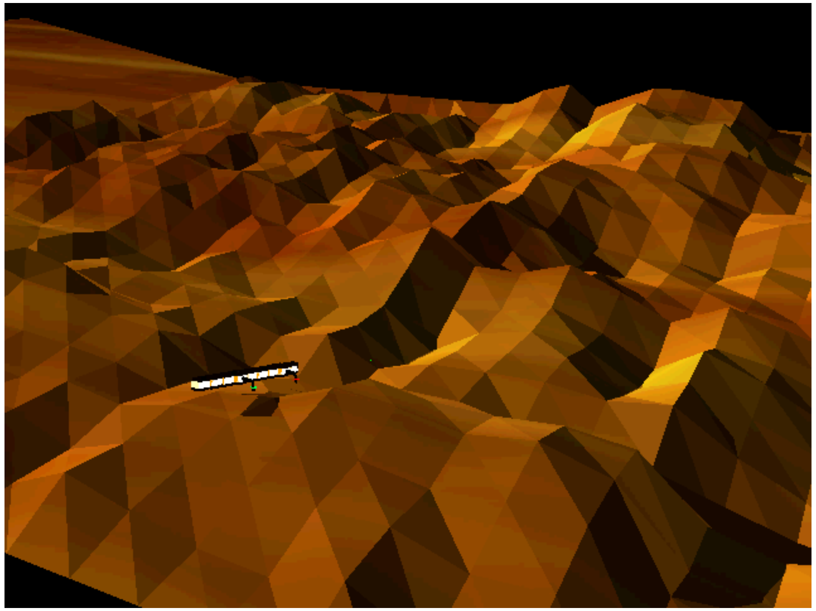
Closed-loop



IV. Controller performance

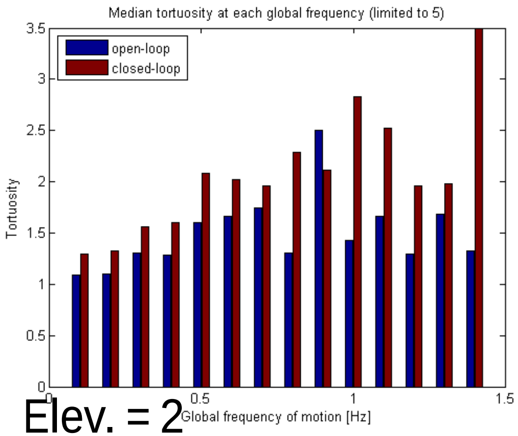
- Uneven terrains
  - Salamander gets stuck in valleys
  - Maybe it did not happen to A=0.5 because bumping on the solid hills released the robot



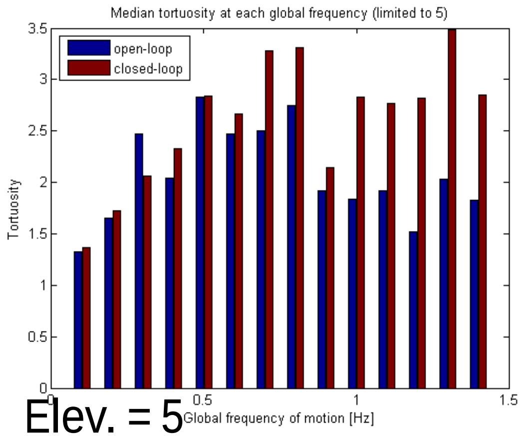


IV. Controller performance

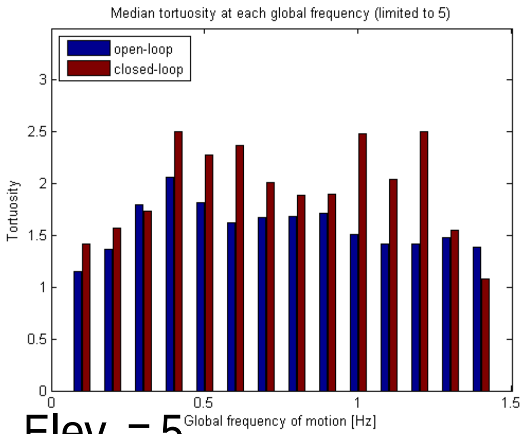
- Uneven terrains
  - Why does feedback help ?
    - First, with sensory feedback it is easier to go up to the top of slopes
    - Second, the random body oscillations make the robot move and find other alternatives out of the hole
- Uneven terrains – tortuosity
  - Both quite unstable, still closed-loop is outperformed



Elev. = 2



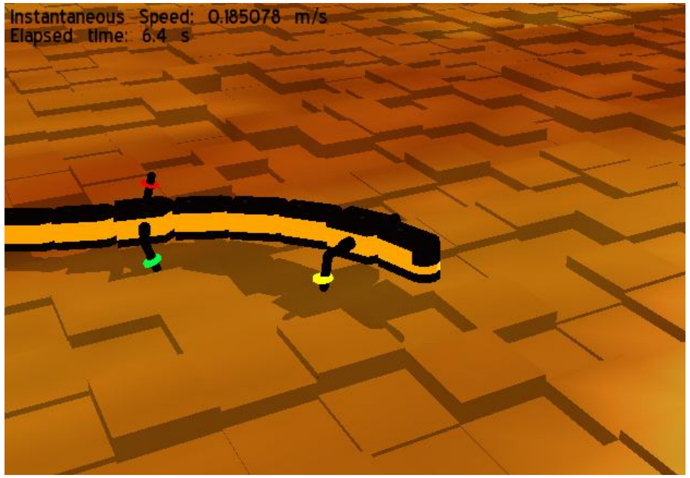
Elev. = 5



Elev. = 5, A=0.25 rad

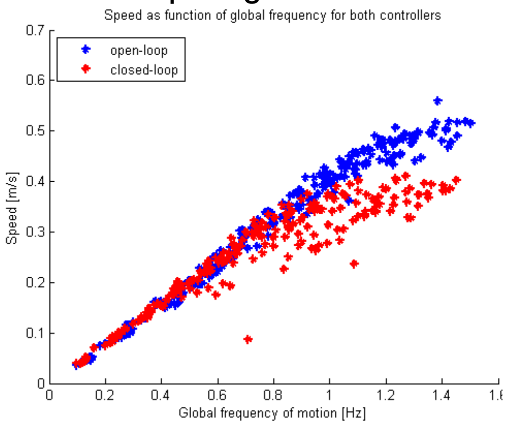
IV. Controller performance

- Terrains with steps
  - Steps of varying height
  - Simulate wholes
  - In open-loop limbs may skip stance phase, in closed-loop limbs stop

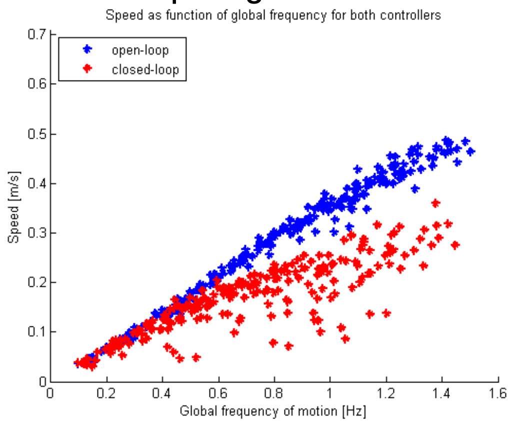


- Speed

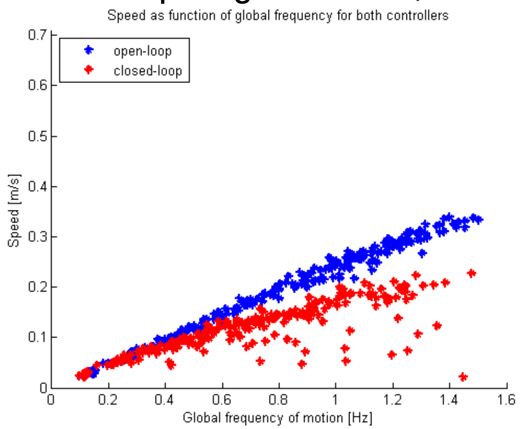
Max. Step height = 2.5cm



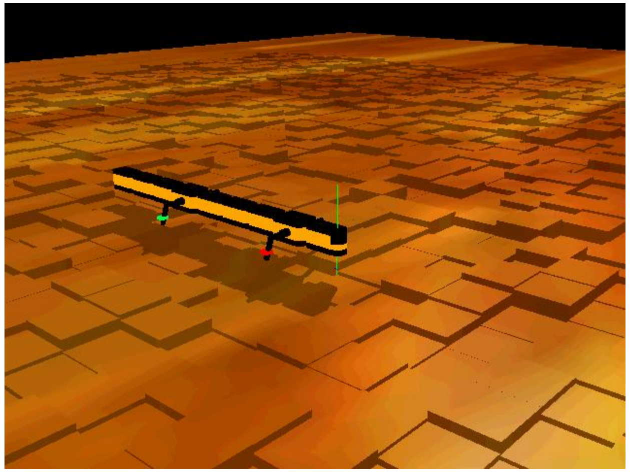
Max. Step height = 5.0 cm



Max. Step height = 5.0cm, A=0.25 rad

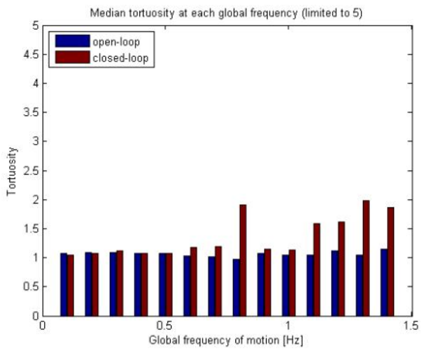


IV. Controller performance

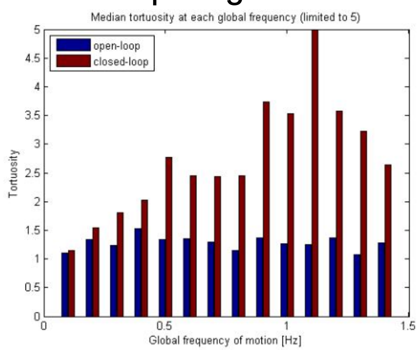


- Terrain with steps
  - Closed-loop controller performs worst in terms of speed
  - Coupling between limbs and body may be responsible
- Terrain with steps – Tortuosity

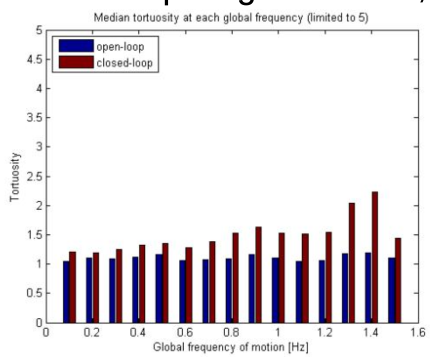
Max. Step height = 2.5cm



Max. Step height = 5.0 cm



Max. Step height = 5.0cm, A=0.25 rad

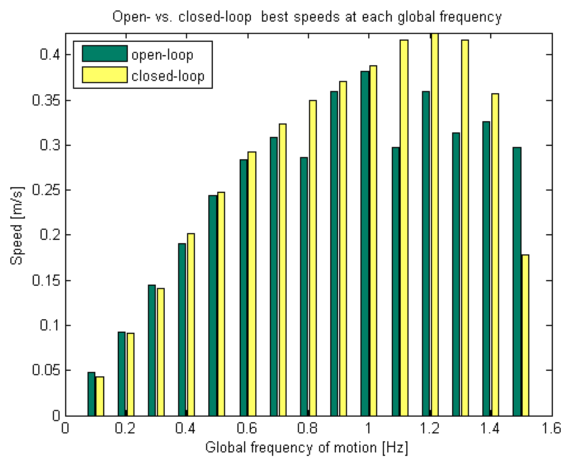


IV. Controller performance

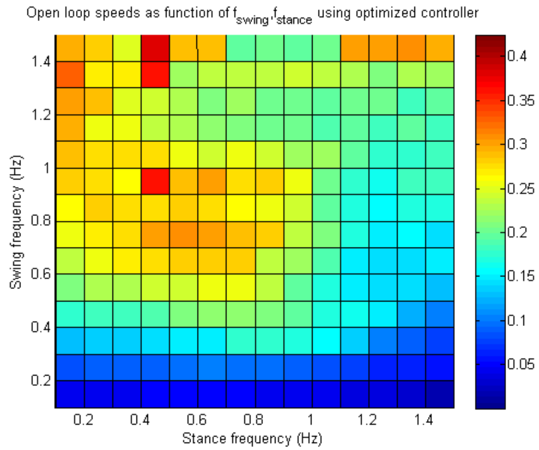
- Worlds with friction
  - 3 parts of the robot enter in the friction model
    - Limbs
    - Limb touch sensors
    - Body segments
  - This tests are divided by which part is changed its friction
    - Only limbs
      - Low friction
      - High friction
    - Limbs and body
      - Low friction
      - High friction

IV. Controller performance

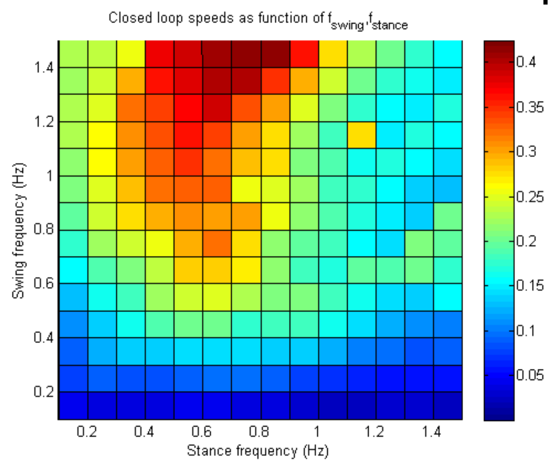
- Low limb friction
  - Closed-loop reaches higher speeds
  - Low stance frequencies have better results since these avoid slipping



Open-loop

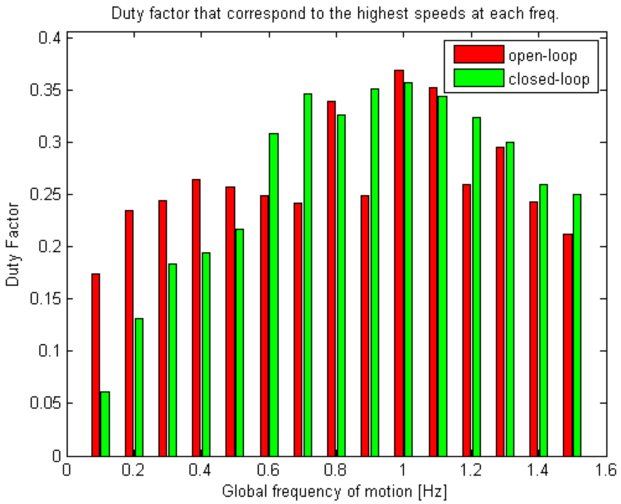


Closed-loop



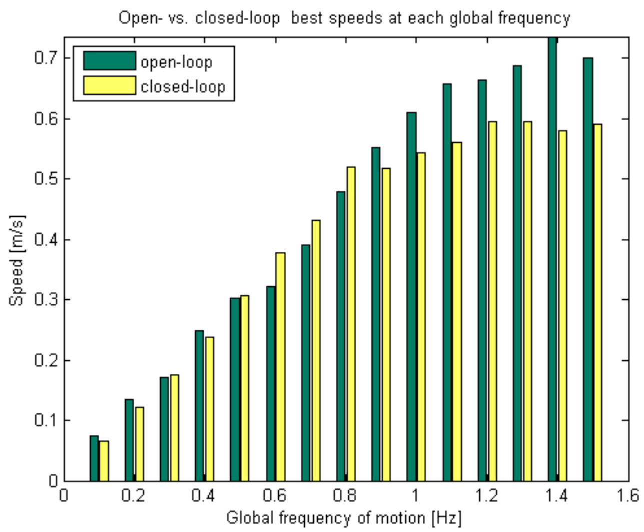
IV. Controller performance

- High duty factors are maintained especially at high speed



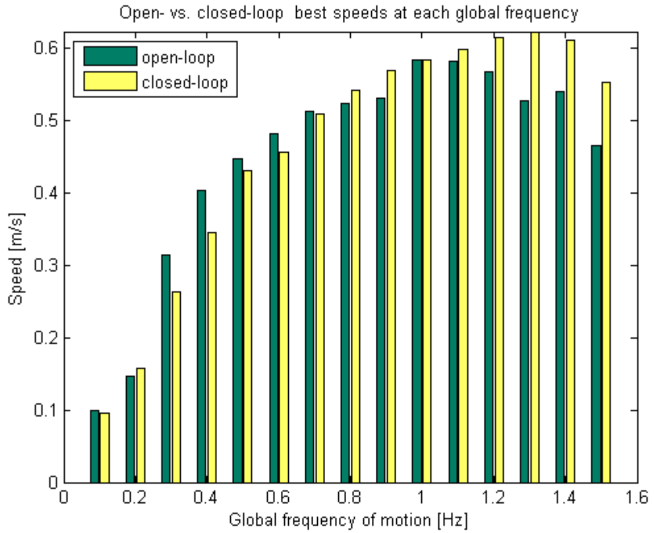
IV. Controller performance

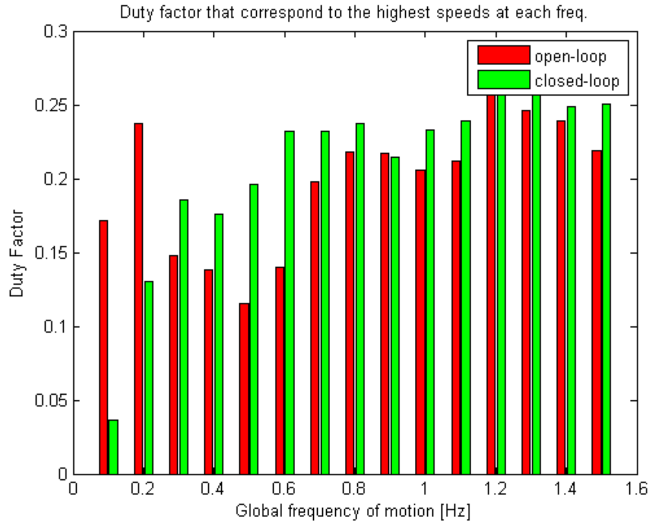
- High limb friction
  - High reaction force from the ground, higher speeds



IV. Controller performance

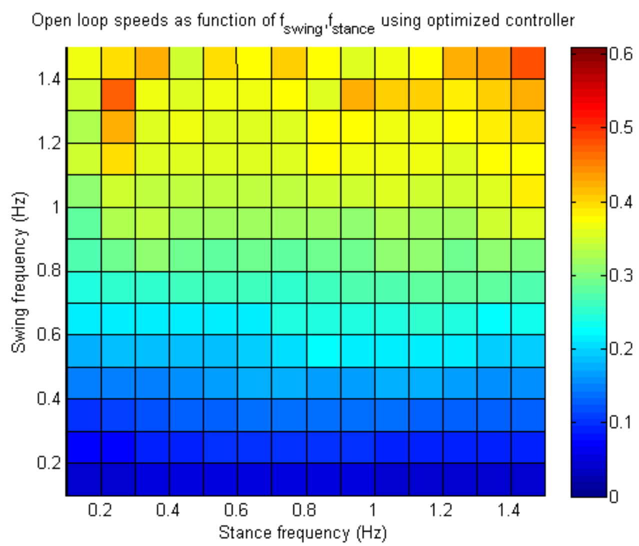
- Low friction (all parts)
  - Once again, high speeds at higher frequencies
  - Consequence of the correct detection of stance phase

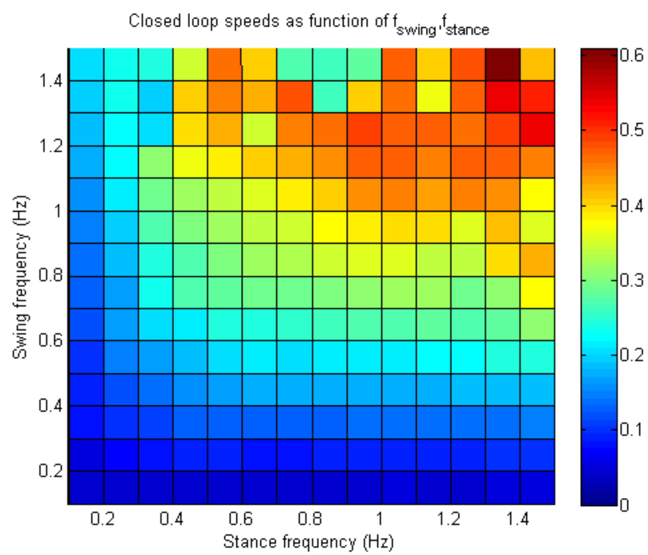




IV. Controller performance

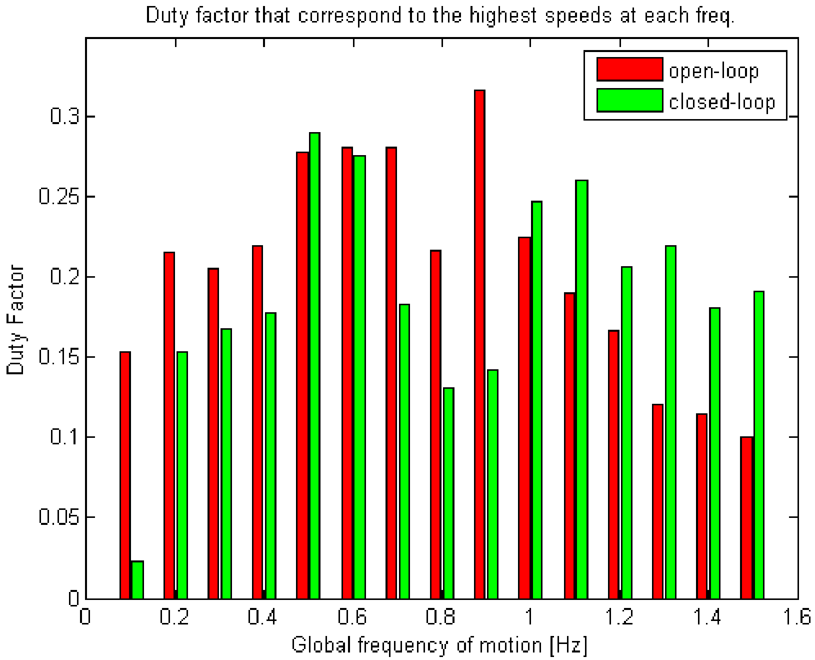
- High friction (all parts)
  - Stance phase has very short duration in open-loop
  - Closed-loop uses high stance frequencies for longer periods since it correctly identifies the stance





IV. Controller performance

- High friction (all parts)
  - Also duty factor is high for high frequencies

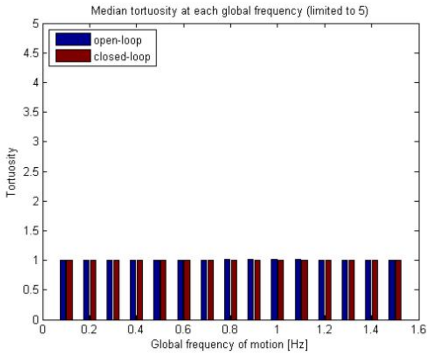


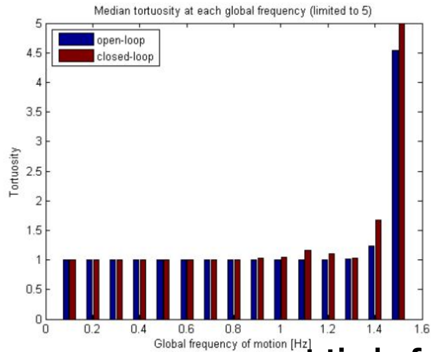
IV. Controller performance

- Friction worlds – Tortuosity

High limb friction

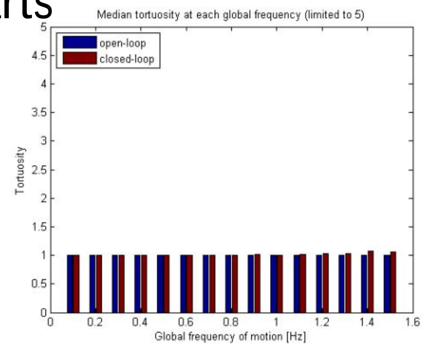
Low limb friction

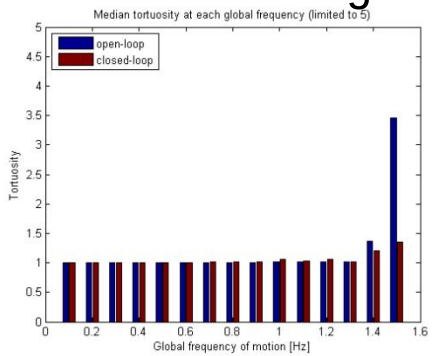




Low friction 3 parts

High friction 3 parts





IV. Conclusions and future work

- Closed-loop controller is more efficient with changes of static parameters (friction, inclinations)
- It correctly identifies locomotion phases
- Has difficulties with irregular terrains

- Study the effect of coupling
- Develop a new model of limbs
- Develop a way to use in the real robot

References

- [1] - L. Righetti and A. J. Isjpeert. Pattern generators with sensory feedback for the control of quadruped locomotion. *Proceedings of the 2008 IEEE International Conference onRobotics and Automation (ICRA 2008),* 26:819-824, May 19-23, 2008.

The End

Thank you all !
Questions?