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

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Structure of the presentation:

I. Overview

II. CPG network and oscillator model

III. Optimization of open-loop controller

IV. Controller performance

V. Conclusions and future work
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:

\[ \begin{align*} 
\dot{x}_i &= \alpha (\mu - r_i^2) x_i - \omega_i y_i \\
\dot{y}_i &= \beta (\mu - r_i^2) y_i + \omega_i x_i + \sum k_{ij} y_j + u_i 
\end{align*} \]

- 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

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

\[ \omega = \frac{\omega_{\text{stance}}}{e^\gamma + 1} + \frac{\omega_{\text{swing}}}{e^{-\gamma} + 1} \]

Where

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

Also, to avoid skipping stance phases, use limb stopping:

\[ \omega_i = \begin{cases} 0, & \text{if } \theta_i = -90^\circ \text{ and limb is not on the ground,} \\ \frac{\omega_{\text{stance}}}{e^\gamma + 1} + \frac{\omega_{\text{stance}}}{e^{-\gamma} + 1}, & \text{otherwise} \end{cases} \]
II. CPG network and oscillator model

- Visual inspection of locomotion phase

Red = Swing
Green = Stance
Yellow = limb stopped

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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:

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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

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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
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
Unseen terrains

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

![Graph showing speed as function of global frequency for both controllers.](image-url)
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
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
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 = 5.0 cm, $A = 0.25$ 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

\[ \text{Max. Step height} = 2.5 \text{cm} \]

\[ \text{Max. Step height} = 5.0 \text{ cm} \]

\[ \text{Max. Step height} = 5.0 \text{cm, } A = 0.25 \text{ rad} \]

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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
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

Low limb friction

Low friction 3 parts

High limb friction

High friction 3 parts
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
Thank you all! Questions?