P05

Spine-Limb Coordination Controller for a Sprawling Posture Robot

Tomislav Horvat*,** and Auke J. Ijspeert*
*Biorobotics Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
**Email: tomislav.horvat@epfl.ch

1 Motivation and state of the art

Many animals actively use their spine during locomotion. By properly coordinating it with the limbs, their locomotion capabilities can be vastly improved in both kinematics and dynamics. Researchers are trying to use the same principles in robots. The robotic spine often comes in a form of an (over)actuated kinematic chain, which either directly creates contacts with an environment (snake robots), or connects two (or more) girdles (attachment points for the legs). Its role and control depend a lot on the spine configuration and the robot type.

In control of snake robots that allow 3D motion, the usual approach is to directly drive joints with carefully designed parametrized wave functions [1] or to define desired body shape in Cartesian space and fit the robot kinematics to it [2]. Navigation-oriented control of planar (2D) snake robots often utilizes a predecessor-follower control scheme [3].

Segmented spines are still fairly underutilized in legged robots. Most of the research focuses on improving robot performance by utilizing a low degree of freedom spine (active or passive) with a bending in sagittal (vertical) plane [4]. Salamander robots in [5] and [6] utilize a segmented spine that allows bending in transverse (horizontal) plane. Role of the spine is to allow for multimodal locomotion. In water it propels the robot using an anguilliform swimming gait while on land it extends limbs' reach and improves turning capabilities. Salamander robots in [5] for both swimming and walking are controlled in joint space by coupled phase oscillators. The behavior of the spine and synchronization between spine and limbs are solely determined by coupling weights and intrinsic frequencies of phase oscillators. Such approach does not take into account the posture of a robot in Cartesian space, which is important for precise control of (i) leg trajectories with respect to the robot's body, (ii) coordination between limbs and the spine and (iii) overall robot's posture.

2 Our approach

The robotic platform we use to study spine-limb coordination is Pleurobot - a sprawling posture quadruped with segmented spine [6]. Since the spine allows for independent control of both girdles, we assigned a separate local coordinate frame to each girdle, as shown in Figure 1. Such placement allows for precise control of the girdle movement by defining feet trajectories with respect to the girdle's center and the line of locomotion, while being able to independently control girdle's orientation. The feet are following half-sine shaped trajectories relative to the girdle coordinate frame. The phase offsets between limbs and duty factory are fixed and set manually.

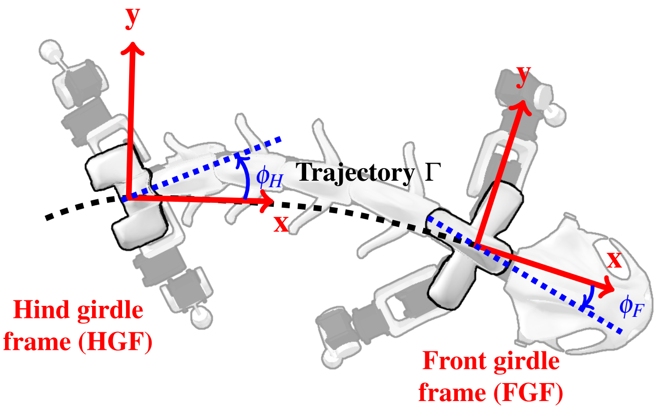

Figure 1: The right hand reference frames of Pleurobot (the z-axis points towards the reader). The front girdle frame is positioned in center of the line connecting shoulders and its orientation is determined by the instantaneous direction of locomotion. The trajectory Γ is an idealized path that the front girdle follows in the world frame. The hind girdle frame is positioned in the center of the line connecting hips and its orientation is determined by the tangent to the Γ. Girdle oscillates by rotating around the z-axis of the corresponding coordinate frame.

In [7] we showed how coordination between girdle orientation (oscillation) and limb movement can extend maximum reach of the limbs. To each girdle, we assigned a phase oscillator whose output directly drives girdle's oscillation. To achieve proper synchronization of girdle's oscillation and limb movement, we modulated oscillator's phase to match the limb's phase. In order to account for nonperiodic locomotion (e.g. changing walking frequency), we used a DFT (Discrete Fourier Transformation) of predicted future limb phases to get the instantaneous phase at the walking frequency (see [7] for more details).

Inspired by use of sensory feedback in [8], we can simplify the aforementioned method. Let's assign to each girdle an oscillator in the following form:

$$\begin{aligned} \dot{r} &= a \cdot (R - r), \\ \dot{\theta} &= 2\pi f_{walk} + \sigma F_* cos(\theta) \\ \phi_{ref} &= r \cdot sin(\theta), \end{aligned} \qquad (1)$$

where a is the amplitude convergence parameter, R is the desired oscillation amplitude, σ is the gain of sensory feedback and F_* is the sensory feedback which modulates the oscillator's phase θ. The oscillation reference ϕ_{ref} of each oscillator is directly driving the rotation (ϕ_F and ϕ_H in Figure 1) of the matching girdle. As the sensory feedback F_* we can use different physical values accessible by the robot. Here, we test two of them: position feedback F_p and force feedback F_f:

$$\begin{aligned} F_p &= q_{pr,L} + q_{pr,R}, \\ F_f &= N_{z,L} - N_{z,R}, \end{aligned} \tag{2}$$

where $q_{pr,L}$ and $q_{pr,R}$ are protraction/retraction angles of left and right shoulder/hip measured around z-axis of the corresponding coordinate frame. $N_{z,L}$ and $N_{z,R}$ are normal ground reaction forces produced by left and right leg and measured by a foot-mounted force sensor. The variable F_p has positive values when the left leg is in retraction (stance) and the right leg is in protraction (swing). As a result, girdle rotates counter clockwise (positive angles ϕ_F, ϕ_H) which effectively extends the leg's reach. The same effect is achieved with the force feedback. The variable F_f has positive values when the left foot supports more body weight then the right foot. Since it is expected for the foot to carry more weight when it is in the stance (compared to swing), the girdle rotates counter clockwise.

The final step is to solve inverse kinematics of the spine [7] with conditions that girdle orientations match angles ϕ_F and ϕ_H, while keeping both girdles on the line of locomotion (trajectory Γ in Figure 1).

A comparison between using position and force feedback on the simulated Pleurobot is shown in Figure 2. Oscillations of front and hind girdle are in counter phase when using force feedback. This results in standing wave along the spine, which is in accordance with animal observations [6]. Using position feedback results with a traveling wave along the spine which is closer to our results in [7]. In both cases the girdle oscillations help the locomotion by reducing the protraction/retraction of the limbs and extending their reach.

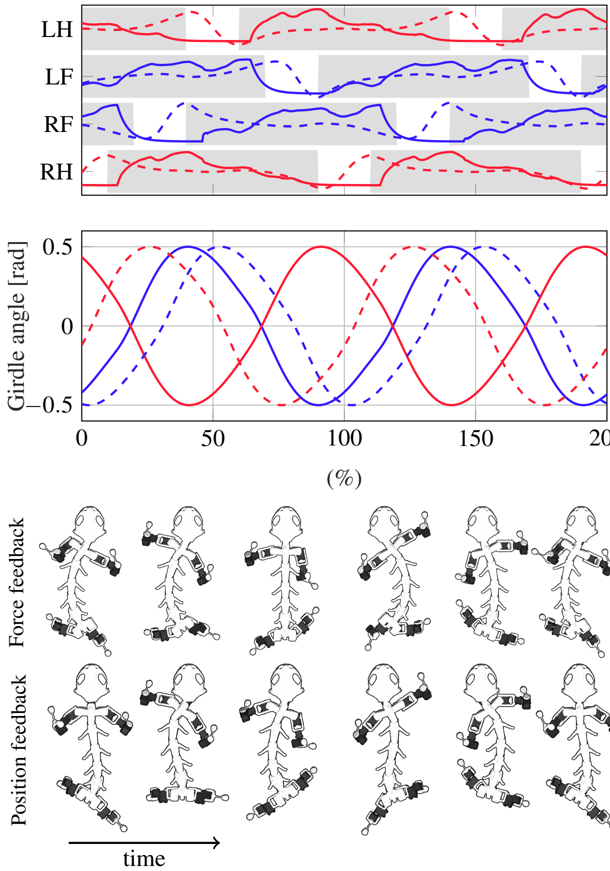

Figure 2: Comparison between position and force feedback for spine-limb coordination. (Upper graph) An overlay of gait diagram with normal feet force measurements (full) and protraction/retraction angles (dashed). (Lower graph) A resulting front (blue) and hind (red) girdle oscillations for force feedback (full) and position feedback (dashed). (Bottom graphics) Equally spaced snapshots of one full walking cycle for both types of feedback.

3 Discussion

Coordinating the spine with limb motion is important for improving robot's locomotion capabilities. The spine movements are driven by girdle oscillations. Each girdle has a phase oscillator which provides a reference for its oscillations. Synchronization with the limb phase is achieved by using a sensory feedback. Such approach removes a need to manually tune the girdle motion every time the gait characteristics are changed (e.g. leg phase offsets). From two of the proposed sensory feedbacks, using position feedback proved to be easier since it does not require extra force sensors. However, it remains to be investigated which method works better for sudden changes in walking frequency, compare convergence rates and possible improvements in energy consumption of the robot. Finally, the proposed methods need to be tested on the real robot.

References

[1] M. Tesch, K. Lipkin, I. Brown, R. Hatton, A. Peck, J. Rembisz, and H. Choset, "Parameterized and scripted gaits for modular snake robots," *Advanced Robotics*, vol. 23, no. 9, pp. 1131–1158, 2009.

[2] H. Yamada and S. Hirose, "Study on the 3d shape of active cord mechanism," in *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.*, pp. 2890–2895, IEEE, 2006.

[3] P. Liljeback, K. Y. Pettersen, Ø. Stavdahl, and J. T. Gravdahl, "Snake robot locomotion in environments with obstacles," *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 6, pp. 1158–1169, 2012.

[4] G. A. Folkertsma, S. Kim, and S. Stramigioli, "Parallel stiffness in a bounding quadruped with flexible spine," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2210–2215, IEEE, 2012.

[5] A. J. Ijspeert, A. Crespi, D. Ryczko, and J.-M. Cabelguen, "From swimming to walking with a salamander robot driven by a spinal cord model," *Science*, vol. 315, no. 5817, pp. 1416–1420, 2007.

[6] K. Karakasiliotis, R. Thandiackal, K. Melo, T. Horvat, N. Mahabadi, S. Tsitkov, J. Cabelguen, and A. Ijspeert, "From cineradiography to biorobots: an approach for designing robots to emulate and study animal locomotion," *Journal of The Royal Society Interface*, vol. 13, no. 119, p. 20151089, 2016.

[7] T. Horvat, K. Melo, and A. J. Ijspeert, "Spine controller for a sprawling posture robot," *IEEE Robotics and Automation Letters*, vol. 2, no. 2, pp. 1195–1202, 2017.

[8] D. Owaki, T. Kano, K. Nagasawa, A. Tero, and A. Ishiguro, "Simple robot suggests physical interlimb communication is essential for quadruped walking," *Journal of The Royal Society Interface*, vol. 10, no. 78, p. 20120669, 2013.