Combining Bio-inspired Sensing with Bio-inspired Locomotion

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Abstract: In this paper we present a preliminary Braitenberg vehicle–like approach to combine bio-inspired audition with bio-inspired quadruped locomotion in simulation. Locomotion gaits of the salamander–like robot *Salamandra robotica* are modified by a lizard's peripheral auditory system model that modulates the parameters of the locomotor central pattern generators. We present phonotactic performance results of the simulated lizard-salamander hybrid robot.

Keywords: bio-inspired robotics, audition, locomotion, central pattern generators

1. INTRODUCTION

Lizards have an amazingly directional peripheral auditory system [2] given its simplicity in design. Moreover, it is reported to have the highest directionality among all vertebrates [3]. The system has been extensively studied, modelled and applied as a controller for wheeled robots in phonotaxis tasks. We apply the same to a salamander–like quadruped robot *Salamandra robotica* designed and built in the Biorobotics Laboratory at EPFL. The notable feature of this robot is its undulatory locomotion, mimicking tetrapods such as salamanders and lizards that exhibit lateral bending of the trunk during locomotion. These animals stabilize their heads such that it is always oriented towards the direction of motion, possibly to minimize the oscillation of the head-centered reference frame for auditory spatial information which would otherwise oscillate along with the head, resulting in oscillating auditory cues. In order to observe the effect of such oscillating cues on the robot's sound localization ability, we integrate the auditory system model into the robot and evaluate its phonotactic performance in simulation.

2. THEORETICAL BACKGROUND

2.1 The Lizard Peripheral Auditory System

The auditory system (Fig. 1(a)) is composed of a tympanum (TM) on each side of the head, connected via wide internal Eustachian tubes (ET). Since the sound wavelengths to which it responds to (170–340 mm) are larger than the head size (∼13 mm), the incident sound waves diffract around the animal's head, creating essentially equal sound pressures at the two tympani. The acoustical coupling formed by sound transmission through the ET translates small phase differences between sound waves arriving at either tympanum, whose magnitude depends on the relative direction from which the sound appears to originate, into relatively larger differences in perceived sound amplitude at either tympanum. The directionality can be visualized (Fig. 2) via an equivalent electrical model [4] (Fig. 1(b)) and given mathematically as

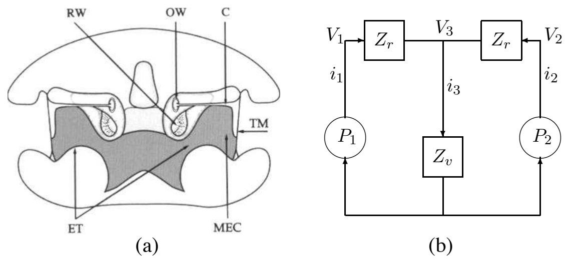


Fig. 1: (a) Lizard ear structure and (b) electrical model.

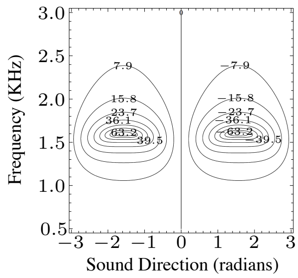


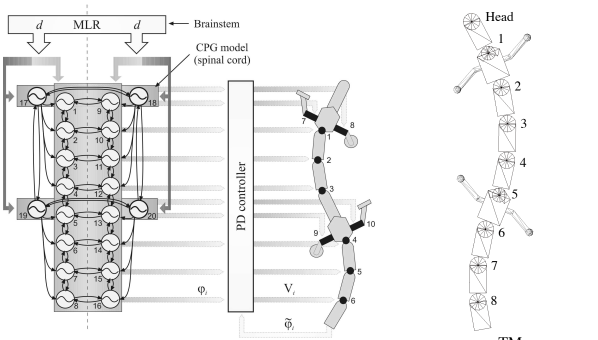
Fig. 2: Amplitude difference (i_{ratio}) between either side.

$$\begin{aligned} \left|\frac{i_1}{i_2}\right| &= \left|\frac{G_{\text{I}} \cdot V_1 + G_{\text{C}} \cdot V_2}{G_{\text{C}} \cdot V_1 + G_{\text{I}} \cdot V_2}\right| \text{ or} \\ i_{\text{ratio}} &= 20\left(\log|i_1| - \log|i_2|\right) \text{dB}, \end{aligned} \quad (1)$$

where i_1 and i_2 model left and right tympanal vibrations respectively and G_{I} and G_{C} are ipsilateral and contralateral frequency-dependent (1000–2200 Hz) gains.

2.2 *Salamandra robotica*

Salamandra robotica (Fig. 3) is designed to be a tool for neuroscientific studies in the role of spinal central pattern generators in producing various locomotion gaits in salamanders [1]. It exhibits locomotion patterns that match those of a real salamander. The neuronal model used to generate different locomotion gaits is based on central pattern generator (CPG) circuits in the spinal cord of the salamander. Since lizards exhibit terrestrial locomotion patterns similar to salamanders, it makes sense to combine the former's auditory sensing model and the latter's neuromotor model. Furthermore, an accurate model of the robot in a realistic physics-based simulation environment (Webots™) is readily available (Fig. 3(b)).



(a) CPG model (figure by A. Ijspeert, courtesy Biorobotics Laboratory, EPFL). (b) Webots^{TM} model.

Fig. 3: *Salamandra robotica*

2.3 Sensory Guidance of Locomotion

Braitenberg vehicles conceptually describe the generation of different behaviours as a consequence of varying the structure of the sensorimotor couplings. We model the coupling between the ear model and the locomotor CPGs as a cross connection (Eq. (2)), with the *left* sensory output (i.e. the left tympanal vibration i_l) modulating the body CPGs to the *right* side and vice versa. The modulated parameters are the amplitudes μ_l and μ_r of the left and right body CPG oscillations respectively. Decreasing μ decreases bending of the trunk, attenuates the head oscillations and thus the auditory cue oscillations. In order to observe the effect of change in the amplitude of auditory cue oscillations on sound localization ability, we define a gain parameter α which governs the extent to which μ is modified. Since the variation in the response of the auditory system model varies for different frequencies, the sensory outputs are normalized to generalize the sensorimotor coupling over the relevant frequency range of 1000–2200 Hz, making α frequency-independent.

$$\begin{aligned} \mu_l &= \operatorname{sgn}(i_r - i_l) \cdot (1 + \alpha \cdot \operatorname{sgn}(i_r - i_l)) \\ \mu_r &= \operatorname{sgn}(i_l - i_r) \cdot (1 + \alpha \cdot \operatorname{sgn}(i_l - i_r)) \end{aligned} \quad (2)$$

3. EXPERIMENTS AND RESULTS

The goal the robot in the phonotaxis tasks was to localize and locomote towards a simulated sound source of given frequency and angular displacement with respect to its head, placed 5 m away from the robot. The angular displacement was varied over the frontal $\left[-\frac{\pi}{2}, +\frac{\pi}{2}\right]$ region in $5°$ steps, resulting in 37 trials. The frequency was randomly chosen to be 1900 Hz from the 1000–2200 Hz range and kept constant over all the trials. For each trial, the robot's trajectory and CPG outputs were logged. The heading errors (Fig. 4) were determined by first dividing the trajectory into 10 parts and computing the heading vector for each part. These were then averaged and the absolute difference between the average heading and the ideal heading, which is a straight line from the robot to the source, was computed. Figure 5 depicts sample body CPG outputs during a right turn from one of the trials.

4. CONCLUSIONS AND FUTURE WORK

We have integrated a lizard's peripheral auditory system model into a salamander–like quadruped robot and

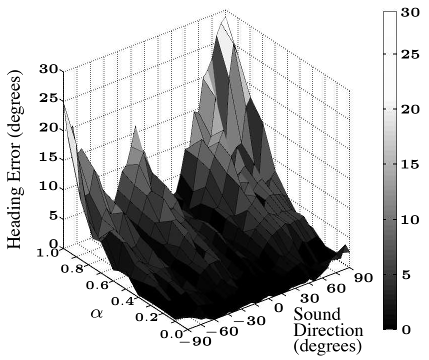


Fig. 4: Absolute angular error in heading.

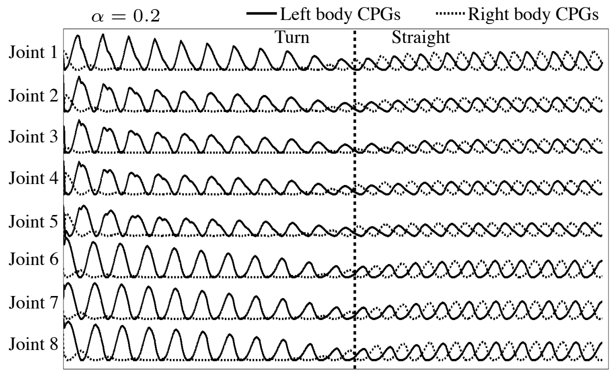


Fig. 5: CPG outputs while turning. Sound source at $+75°$.

evaluated the phonotactic performance of the lizard-salamander hybrid in simulation. In spite of the head oscillations typical in undulatory locomotion, the robot successfully localizes the sound source. Decreasing α increases contralateral inhibition and ipsilateral excitation, respectively reducing and amplifying μ of the body CPGs on either side, attenuating the head oscillations and consequently the auditory cue oscillations, resulting in tighter turns towards the sound source. However, the error surface is flat at $-45° \pm 10°$ and $+25° \pm 10°$. This is due to the initial conditions of the CPGs which swing the head roughly $25°$ to the right and then $45°$ to the left. This "bias" can be eliminated by allowing the oscillations to settle down before sensory modulation. In the future, real-world trials will be conducted for comparison.

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