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Decentralized Control Mechanisms for a Walking Fish (*Polypterus senegalus*)

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1 Introduction

The primitive tetrapods transitioned from aquatic to terrestrial habitats. When they moved on land, they used sprawling locomotion, a walking gait with lateral body undulation observed in extant amphibians, and reptiles [1]. However, the possible control mechanisms underlying primitive tetrapod walking remain elusive. A better understanding of the potential control mechanisms contributes to unveiling the terrestrialization of vertebrates and the design of amphibious quadruped robots.

To address this issue, we focused on *Polypterus senegalus*, which is a elongated fish regarded as an extant analog of the primitive tetrapods [2]. The fish can perform sprawling-locomotion-like behavior that combines the body bending with two pectoral fin oscillations. Due to the evolutionary position, the control mechanisms underlying the behavior are likely related to those of the primitive tetrapods.

In this proceeding, we aimed to understand the potential mechanisms underlying the terrestrial locomotion of *Polypterus senegalus* using mathematical modeling and simulations. Specifically, we present a decentralized control and its implementation into a simulated *Polypterus senegalus*. The controller was proposed in our previous work [3] and enabled a salamander robot to generate stable sprawling locomotion. The results showed that the controller enables a simulated *Polypterus senegalus* to generate a stable walking as well. These results suggest that the sensory feedback mechanisms play an essential role in fish and amphibian walking. A shared control pattern between these two diverse groups suggests that the common ancestors of fish and tetrapods, namely the first terrestrial vertebrates, likely adopted a similar mechanism for their walking.

2 The Model

2.1 Body Structure

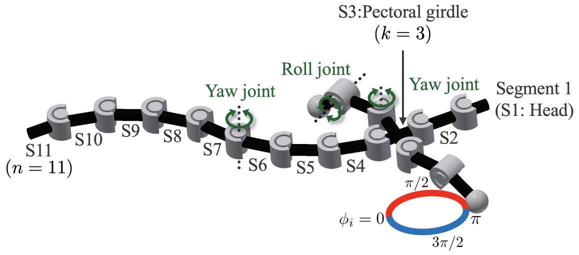

Figure 1: Schematic of body model (in the figure $n = 11$, $k = 3$).

The simulated body is a very abstract model of the *Polypterus senegalus* composed of n trunk segments and two pectoral fins, as shown in Fig. 1. The segments are concatenated via yaw hinge joints with a parallel combination of a rotary actuator, passive spring, and passive damper. Pectoral fins are attached on both sides of the k-th segment. Each fin has two rotary actuators in the yaw and roll directions, controlled by the phase oscillators.

Each fin tip has a force sensor that detects the normal force from the ground, and each trunk joint has angle and torque sensors. The angle sensors detect the angle θ_i^b of the i-th trunk joint from the head. Here, the i-th trunk joint connects the i-th and $i+1$-th segments from the head. The joint angle θ_i^b is positive when the trunk joint bends to the right. The torque sensors detect the torque generated by the rotary actuators at the trunk joint.

2.2 Control Circuit

Here, we described the detail of a decentralized control algorithm, which coordinates lateral body bending and fin oscillations by bidirectional feedback between the body and fins. Each fin has a phase oscillator that determines the target position of the fin tip as shown in Fig. 1. The fins are controlled by proportional-derivative (PD) control so that they approach their target positions. The time evolution of the oscillator phase is described as follows:

$$\dot{\phi}_j = \omega + f_{LL,j} + f_{BL,j}, \tag{1}$$

$$f_{LL,j} = -\sigma_{LL} N_j \cos\phi_j, \tag{2}$$

$$f_{BL,j} = \begin{cases} +\sigma_{BL}\tanh(\rho_{BL}\tau^b_{k,act})\cos\phi_j \ (j = l) \\ -\sigma_{BL}\tanh(\rho_{BL}\tau^b_{k,act})\cos\phi_j \ (j = r), \end{cases} \tag{3}$$

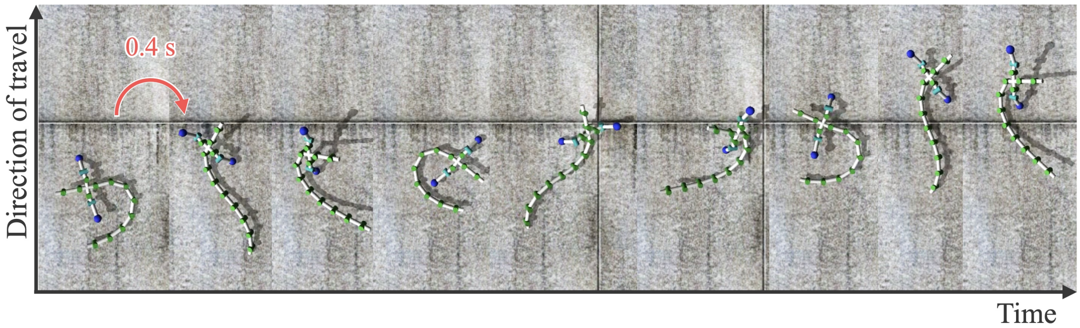

Figure 2: Snapshots of the resulting gait with an interval of 0.4 [s]. See from left to right.

where ϕ_j denotes the oscillator phase of the fin on the j side (left fin: $j = l$, right fin: $j = r$), ω [rad/s] denotes the intrinsic angular velocity of the phase oscillators, σ_{LL} [rad/N·s], σ_{BL} [rad/s], and ρ_{BL} [1/N·m] are the weights of the sensory feedback terms. N_i [N] represents the normal force detected at the fin tip. $\tau^b_{i,act}$ [N·m] represents the torque generated by the trunk actuator of the i-th segment.

Equation (2) denotes local sensory feedback due to normal forces, proposed by Owaki et al. [4], and it generates interlimb coordination in response to the speed and physical properties of the robot.

Equation (3) denotes body-to-limb feedback. When the k-th trunk actuator bends the body to the right ($\tau^b_{k,act} > 0$), the oscillator phase of the left fin is modulated toward $\pi/2$ to lift the fin, and the oscillator phase of the right fin is modulated toward $3\pi/2$ to place the right fin on the ground. This facilitates that the k-th trunk actuator bending the body to the right ($\theta^b_k > 0$), and the body moves forward when the anchored fin serves as a pivot.

The torques at trunk actuators are described as follows:

$$\tau^b_i = -k_p\theta^b_i - k_d\dot{\theta}^b_i + \tau^b_{i,act}, \tag{4}$$

$$\tau^b_{i,act} = f_{LB,i} + f_{BB,i}, \tag{5}$$

$$f_{LB,i} = \begin{cases} \sigma_{LB}\tanh\{\rho_{LB}(N_r - N_l)\} & (i = k), \\ 0 & \text{otherwise}, \end{cases} \tag{6}$$

$$f_{BB,i} = \begin{cases} 0 & (i = 1), \\ -\sigma_{BB}(\theta^b_i - \theta^b_{i-1}) & \text{otherwise}, \end{cases} \tag{7}$$

where θ^b_i is the actual angle of the trunk actuator, σ_{LB} [N·m/rad], ρ_{LB} [N·m] and σ_{BB} [1/N] represent the weights of the sensory feedback.

Equation (6) denotes the limb-to-body feedback such that k-th trunk segments bend in response to the ground contacts of the fins. When the left fin is on the ground ($N_l > 0$), the k-th trunk actuator bends the body to the left ($\tau^b_{k,act} < 0$). Similarly, when the right fin is on the ground ($N_{i,r} > 0$), the k-th trunk actuator bends the body to the right ($\tau^b_{k,act} > 0$). The interactions of the body-to-limb and limb-to-body feedbacks establish the proper relationship between the fins and trunk for terrestrial walking.

Equation (7) denotes the curvature derivative control proposed in the study of snake-like locomotion [5]. It generates torque proportional to the curvature derivative of the body curve such that the lateral body undulation propagates posteriorly. The interplay between limb-to-body and body-to-body feedbacks arranges the waveform of the lateral body undulations.

3 Experimental Result

We conducted robot simulations using the Open Dynamics Engine [6], and observed the walking behavior similar to *Polypterus senegalus* terrestrial locomotion. Figure 2 presents snapshots during resulting locomotion. The proposed model exhibited the C-shaped standing waves of the lateral undulations with limb motion. Interestingly, we observed that the simulated *Polypterus senegalus* pushed against the ground by the posterior body for forward propulsion. The resulting locomotion, therefore, is qualitatively similar to the *Polypterus senegalus* walking pattern [2, 7].

Acknowledgements

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