A Salamander Robot Driven by Cross-Coupled Sensory Feedback Control between Legs and Trunk

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1 Introduction

Quadrupeds locomote freely on complex terrains in the unexpectable real world. Such agility implies that they have a sophisticated motor control mechanism which provides insights to enhance the mobility of legged robot. Thus, a better understanding of this mechanism contributes to the design of agile quadruped robots in addition to biological significances.

A key insight in quadruped locomotion is that they achieve rapid and highly adaptive locomotion by the coordination between their legs and other body parts, such as a trunk, head and tail, *i.e.*, body-limb coordination [1–3]. For example, galloping cheetahs bend the trunk to elongate their stride length and kick the ground firmly [1], and walking lizards swing their tails for balance [2]. These behaviors are observed in many animals; however, the essence of the control mechanism responsible for body-limb coordination is still largely unclear.

The aim of this study involves understanding the mechanism of body-limb coordination through mathematical modeling and empirical experiments with a quadruped robot. In particular, we focus on salamanders as model animal because they are primitive legged vertebrates [3] and seem to have a simple body-limb coordination mechanism. Our previous study [4] proposed a minimal quadruped model with a single spinal joint, and the model reproduced trotting gait with lateral bending. In this study, we proposed an extended model for salamander-like robots with multi-spinal-joint driven by mutual sensory feedback control between legs and trunk and developed a salamander-like robot. As a result, the robot succeeded to reproduce salamander-like terrestrial locomotion which is walking with lateral bending to elongate stride length.

2 Robot

2.1 Mechanical System

Figure 1 shows an overview of the developed salamander-like robot. It has a flexible trunk with four leg segments. The trunk is a chain of ten body segments with servo motors (Dynamixel AX-12A, ROBOTIS) which can make body undulation. Fore leg segments are connected in between third and fourth body segments, and rear leg segments are connected in between sixth and seventh body segments. Each leg has a servo motor (RS405CB, Futaba) for lifting leg up/down and a phase oscillator which defines its target angle (the detail described in Sec.2.2). The leg do not move anteroposteriorly, so the robot have to combine with the leg and trunk motion for walking. These motors are controlled by microcomputers (NXP LPC1768, ARM). Besides, force sensors (FSR400, Interlink Electronics inc.) are at each foot tip.

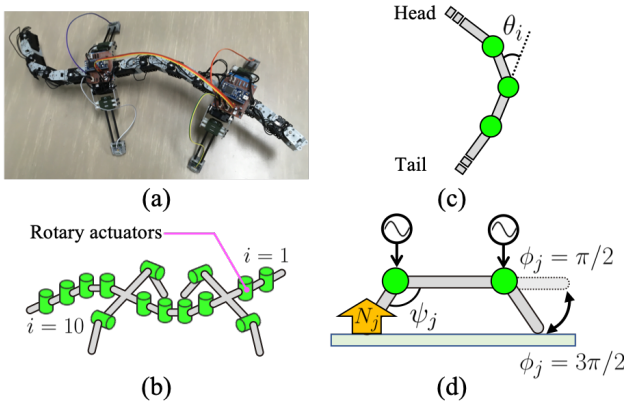


Figure 1: A salamander robot. (a) developed robot, (b) schematic of robot, (c) top view of body segments, (d) front view of a body segment with legs.

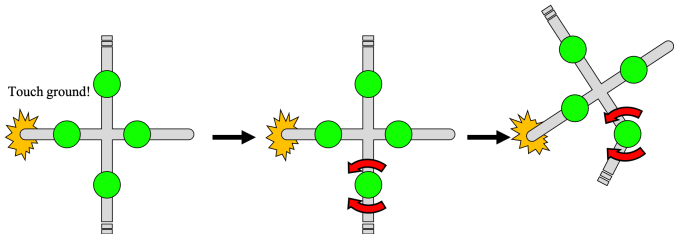
2.2 Control Rule

In this section, we described control rules of each leg and body segment, respectively. First, body segments are controlled as follows:

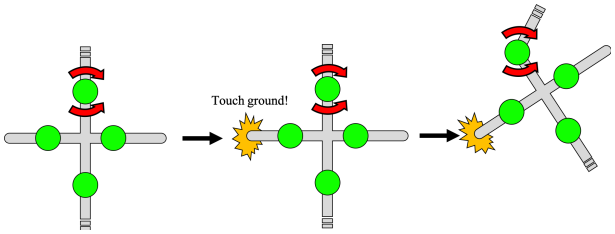
$$\bar{\theta}_i = \theta_{i-1} + \sigma_1 \tanh(\rho F_i), \tag{1}$$

$$F_i = \begin{cases} N_{LF} - N_{RF} & (i = 3), \\ N_{LH} - N_{RH} & (i = 7), \\ 0 & \text{otherwise}, \end{cases} \tag{2}$$

where $\bar{\theta}_i$ denotes the target angle of the servo motor in each body segment. The suffix i corresponds to the segment number in order from head to tail (Fig. 1b). σ_1 and ρ are the



(a) Sensory feedback from leg to trunk



(b) Sensory feedback from trunk to leg

Figure 2: Cross-coupled sensory feedback control between legs and trunk

weights of sensory feedback. N_j represents ground reaction force detected at the force sensor and the suffix j denotes the leg identifier (LF: left fore, RF: right fore, LH: left hind, RH: right hind respectively). The first term in the right-hand side of Eq. 1 denotes curvature derivative control [5] which generates traveling wave of lateral undulation. The second term in the right-hand side of Eq. 1 is the sensory feedback control from legs to trunk (Fig. 2a). The feedback bends body segments, which are posterior to fore/hind legs ($i = 3,7$), in response to ground contacts of the legs.

Second, legs are controlled as follows:

$$\bar{\psi}_j = C_0 + C_{amp} \sin \phi_j, \tag{3}$$

$$\begin{aligned}
\dot{\phi}_{LF} &= \omega - \sigma_2 N_{LF} \cos \phi_{LF} - \sigma_3 \tau_2 \cos \phi_{LF}, \\
\dot{\phi}_{RF} &= \omega - \sigma_2 N_{RF} \cos \phi_{RF} + \sigma_3 \tau_2 \cos \phi_{RF}, \\
\dot{\phi}_{LH} &= \omega - \sigma_2 N_{LH} \cos \phi_{LH} - \sigma_3 \tau_6 \cos \phi_{LH}, \\
\dot{\phi}_{RH} &= \omega - \sigma_2 N_{RH} \cos \phi_{RH} + \sigma_3 \tau_6 \cos \phi_{RH},
\end{aligned} \tag{4}$$

where $\bar{\psi}_j$, C_0 and C_{amp} denotes the target angle, neutral angle and amplitude of servo motor in each leg, respectively. ϕ_j denotes the phase of the oscillator. ω represents intrinsic angular velocity, and σ_1 and σ_2 are the weights of sensory feedback. The second term in the right-hand side of Eq. 4 is local sensory feedback rule proposed by Owaki et al. [6] and it generates adaptive interleg coordination. The third term in the right-hand side of Eq. 4 is the sensory feedback control from trunk to legs (Fig. 2b). The feedback modulates phases of the oscillators in response to the torque at the anterior body segment ($i = 2,6$). The interplay of mutual feedback control as shown in Figure 2 forms walking by lateral bending that exploits leg contact as a pivot.

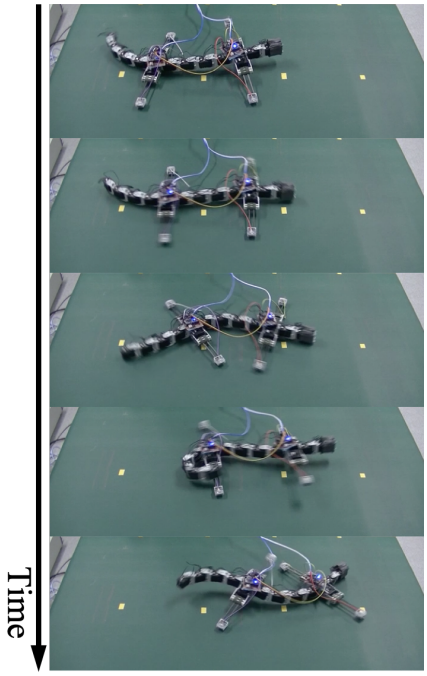


Figure 3: Snapshots of resulting gait.

3 Experimental Result

We conducted the robot experiment and observed the locomotion (Fig. 3). The robot showed legged locomotion with lateral bending to extend the stride length which is similar to salamander walking. This result suggests that the proposed control rule captures the essence of body-limb coordination underlying salamander walking.

Acknowledgements

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