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A Minimal Model for Body-limb Coordination in Quadruped Locomotion

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1 Introduction

Limbed locomotion is a terrestrial locomotion mode adopted by a majority of vertebrates and arthropods [1, 2]. These animals have an ability that combines high agility and adaptability. In contrast, legged robots do not have such a great ability, because they only imitate animal locomotion superficially and do not adopt the mechanism behind it. Thus, understanding the essential mechanism underlying limbed locomotion will help establish the fundamental technology for legged robots as well as contribute to biology.

A key insight in limbed locomotion is that effective propulsion is not achieved solely by limb movements but by the coordination of limb and body movement, i.e., "body-limb coordination." For example, Hildebrand suggested that the flexion and extension of the trunk contribute to increasing the propulsion force and extending the stride length for during a cheetah's gallop [3]. Several other studies investigated the role of body movement in animal locomotion [4–8]. However, these studies intensively focused on either the kinematic property or the myoelectric activity during locomotion, and the essential control mechanism for body-limb coordination is still largely unclear.

In this work, we aim to understand the essence of body-limb coordination through mathematical modeling and simulation. Specifically, we adopted quadrupeds that have flexible body trunk, e.g., newt and salamander, as our model because they make use of their long body actively for their locomotion [7–9]. We performed a simulation in which an extremely simple control scheme is implemented in a robot model that consists of minimal components, and succeeded in generating locomotion with body-limb coordination.

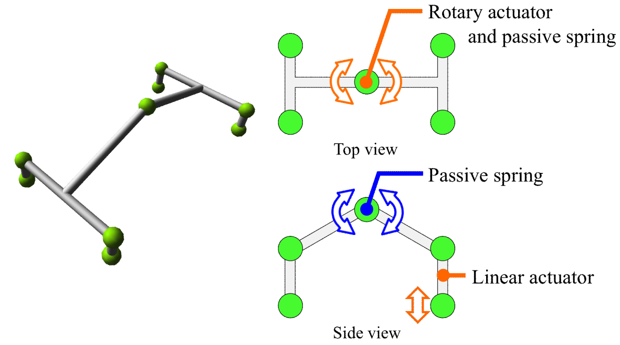

Figure 1: Robot model.

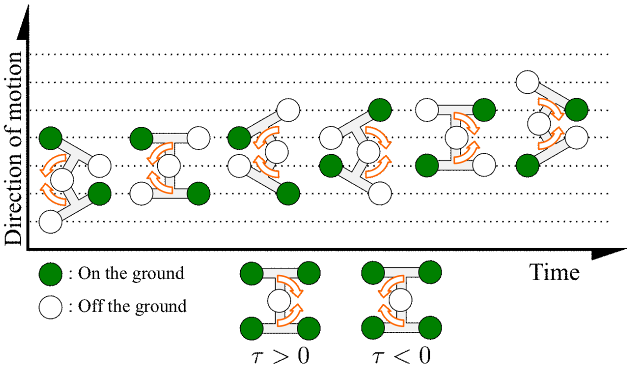

Figure 2: Expected locomotion exploiting body-limb coordination.

2 Minimal model for body-limb coordination

2.1 Musculoskeletal structure

Figure 1 shows an overview of the robot model. To focus on the effect of body-limb coordination, we designed the robot model with minimal components, namely a spine and four legs. The robot model has five actuated degrees of freedom (DOF), that is, a rotary actuator in the spine and a linear actuator in each leg. The rotary actuator drives the spine in the yaw direction at the center of the spine and the linear actuator drives a leg along the leg axial direction, as shown in the right-hand side of Fig.1. Additionally, two torsion springs along the pitch and yaw directions respectively, are implemented in the spine. Each foot has a touch sensor that reacts when the foot is on the ground.

When legs are actuated without the spine movement, the legs just taps on the spot. Likewise, when the spine is actuated without any leg movement, the spine just drags legs. That is to say, the robot does not generate locomotion if it drives legs and the spine separately. Designed with characteristics, this model is suitable to investigate the body-limb

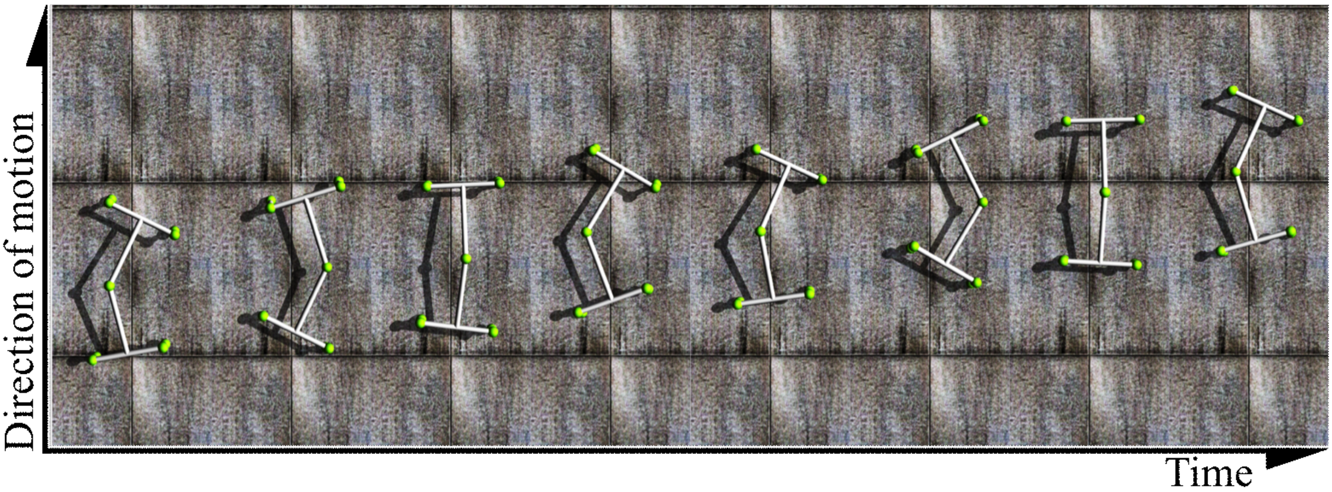

Figure 3: Snapshots of the locomotion by the robot model.

coordination mechanism.

2.2 Control scheme

As shown in Fig. 2, the body can move forward when the legs serve as pivots and the spine bends in the proper direction. To ensure such body-limb coordination, we designed a control scheme based on the following rules:

1. The diagonal pair of feet touch the ground simultaneously.
2. The spine bends according to the ground contact of the feet.

Based on the first rule, the linear actuator in each leg is controlled as follows:

$$F_i = -K_l(l_i - \bar{l}_i) \quad (1)$$

$$\bar{l}_i = \begin{cases} L_0 - L_{amp}\sin\omega t & (i = 1,4) \\ L_0 + L_{amp}\sin\omega t & (i = 2,3) \end{cases} \quad (2)$$

where F is the force produced by a linear actuator. i is the leg number (hereafter, i = 1-4 indicate Left fore(LF), Left hind(LH), Right fore(RF) and Right hind(RH), respectively) and K_l is the proportional gain of the linear actuators. l_i and $\bar{l}_i$ denote the actual leg length and the target leg length. Target leg length $\bar{l}_i$ is described in Eq. (2). Here, L_0 and L_{amp} denote the offset and amplitude of the target leg length. ω is the angular frequency of extension and retraction, and t is the simulation time.

Based on the second rule, the rotary actuator in the spine is controlled as follows:

$$\tau = K_r(-N_1 + N_2 + N_3 - N_4) \quad (3)$$

where τ is the torque produced by the rotary actuator, and K_r denotes the proportional gain of the rotary actuator and N_i is the binary value of the touch sensor: $N_i = 1$ means the foot is on the ground and $N_i = 0$ means the foot is off the ground. As shown in the bottom of Fig. 2, the rotary actuator produces a torque to bend the spine to the left when $\tau > 0$, whereas it produces a torque to bend the spine to the right when $\tau < 0$.

3 Simulation result

We conducted dynamic simulations using the Open Dynamics Engine (ODE) by applying the proposed control scheme to the robot in the simulation environment. As shown in Fig. 3, the robot model achieves moving forward with steady walking motion; furthermore the resulting locomotion is qualitatively similar to the walking of *Polypterus*, which is an animal is similar to the ancestor of tetrapods [10]. This result suggests that the proposed control scheme captures the essence of body-limb coordination.

Acknowledgement

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