Towards Understanding of Versatility of Animal Behavior: A Mathematical Model for Ophiuroid Omnidirectional Locomotion

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Abstract: Our objective is to understand behavioral versatility of animals from the perspective of well-coordinated rhythmic and non-rhythmic movements. To this end, we focus on ophiuroids as simple "best" model living organisms that exhibit spontaneous role assignment of rhythmic and non-rhythmic arm movements, and we model such arm movements by using an active rotator model that can describe both oscillatory and excitatory properties. Simulation results show that the spontaneous role assignment of arm movements is successfully realized by using the proposed model, and the simulated locomotion is qualitatively equivalent to the locomotion of real ophiuroids.

Keywords: Decentralized control, Behavioral versatility, Ophiuroid omnidirectional locomotion, Active rotator model

1. INTRODUCTION

Animals exhibit adaptive and versatile locomotion in real time under unpredictable real world constraints via spatiotemporal coordination of movements of bodily parts. In the field of robotics, a dynamical system approach based on decentralized control mechanisms has been employed to reproduce the ability of animals to perform synergetic movements. In particular, coupled oscillators or distributed neural networks (CPGs) have been widely used for the control systems of robotic agents [1][2]. The core idea underlying these studies is to exploit the intrinsic structural stability of a limit cycle, which induces self-organized behavior of the entire system without any preprogrammed trajectory tracking control.

These studies have provided us with remarkable insights into *adaptability*, which is an important aspect of animal behavior. However, animals well coordinate rhythmic and non-rhythmic movements whereby versatile behavior is generated according to the situation. Such behavioral *versatility*, which is another indispensable aspect, cannot be described solely in terms of limit cycles that exhibit rhythmicity. In order to realize behavioral versatility, we should rethink the limit-cycle-based approach and introduce an extended systematic design scheme that can describe rhythmic and non-rhythmic movements effectively. Accordingly, we focus on *ophiuroid omnidirectional locomotion*, in which the coordination of both rhythmic and non-rhythmic movements is required for achieving efficient locomotion [3].

Thus, our primary objective is to clarify the autonomous decentralized control mechanism that effectively explains ophiuroid omnidirectional locomotion in which the assignment of rhythmic and non-rhythmic movements to the arms can be achieved spontaneously and changed dynamically according to the situation. To this end, we propose a simplified model of ophiuroid robot that is controlled in a fully decentralized manner. As the first step, we carry out simulation experiments, whose results show that the spontaneous role assignment of rhythmic and non-rhythmic arm movements is successfully realized by applying attractant stimuli to the arms.

2. THE MODEL

A schematic illustration of the ophiuroid robot employed in this study is shown in Fig. 1 (a). The robot consists of a *central disk* and five arms. Two motors that can rotate in the vertical (pitch) and horizontal (yaw) direction are implemented in each joint. The joint angle is controlled according to proportional-derivative control.

In order to describe both rhythmic and non-rhythmic arm movements of ophiuroids, we implement distributed control systems based on an *active rotator model* in the joints, as shown in Fig. 1 (b). The time evolution of the phase of the active rotator embedded in the ith arm, ϕ_i, is described as [4]

$$\frac{d\phi_i}{dt} = \omega - a_i \cos\phi_i, \tag{1}$$

where ω is the intrinsic frequency and a_i is a parameter that determines the property of the active rotator.

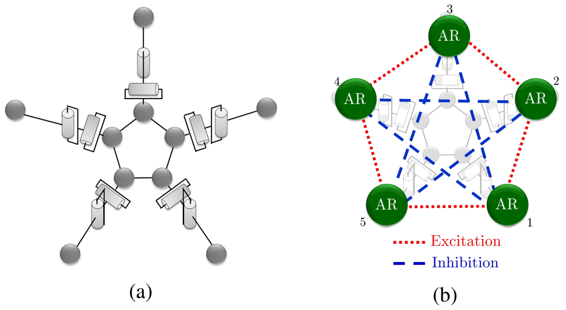

Fig. 1 Schematic illustration of an ophiuroid robot: (a) top view of mechanical system and (b) decentalized control system using active rotators (ARs).

The behavior of the active rotator is divided into three states. When $-\omega < a_i < \omega$, the active rotator exhibits *oscillatory behavior* whereby it rotates along the unit circle with angular velocity $\omega - a_i \cos\phi_i$, resulting in rhythmic movements (*side arm*). On the other hand, when $a_i < -\omega$ and $\omega < a_i$, there exists a pair of equilibrium points at which the condition $\omega - a_i \cos\phi_i = 0$ is satisfied, where one is stable and the other is unstable. In such cases, the active rotator exhibits *excitatory behavior* whereby it converges to the stable equilibrium point when no external force is applied, resulting in non-rhythmic movements (*posterior arm, leading arm*). By modulating the parameter a_i in Eq. (1), we can easily switch between rhythmic and non-rhythmic movements.

In order to dynamically change the role of arm movements, we describe the time evolution of a_i as

$$\tau \frac{da_i}{dt} = \sum_j \varepsilon_{ij} \cos\phi_j + s_i - \varepsilon N_i + \alpha - a_i, \qquad (2)$$

where τ is the time constant and ε_{ij} is a constant that denotes the coupling strength between active rotators. s_i is the sensory input applied to the ith arm and α is a constant. The third term, $-\varepsilon N_i$, is the local sensory feedback term, where ε is a positive constant and N_i is the ground reaction force acting on the ith arm. This local sensory feedback control is employed so that the in-phase rhythmic movements of two arms, which are observed in efficient locomotion of real ophiuroids, are successfully realized.

3. SIMULATION RESULTS

Fig. 2 shows snapshots of the simulated locomotion of the ophiuroid robot. In the interval (i)-(iii), the attractant stimulus was applied to arm 3; it was switched to arm 1 at (iii) and to arm 2 at (v). As observed, the stimulated arm became the leading arm, and the robot moved toward the attractant stimulus with role assignment of the three types of arm movements.

Such spontaneous role assignment is clearly represented by the time evolutions of the parameters a_i and the phases ϕ_i, as shown in Figs. 3 and 4. As shown in

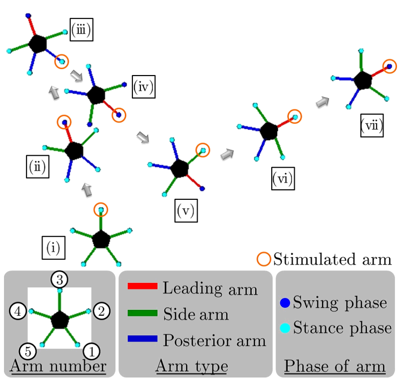

Fig. 2 Snapshots of the simulated locomotion of the ophiuroid robot. These were obtained for every 100,000 time steps, corresponding to the symbols (i)-(vii).

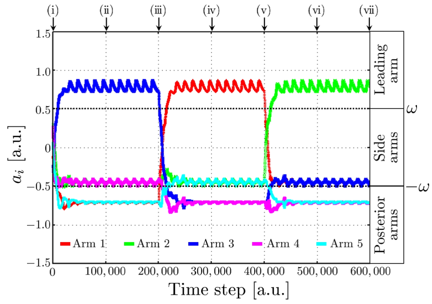

Fig. 3 Time evolution of the parameter a_i.

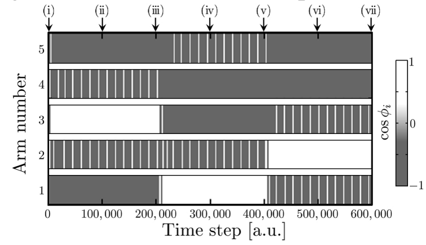

Fig. 4 Time evolution of the phase ϕ_i.

Fig. 3, $a_i > \omega$, $-\omega < a_{i\pm1} < \omega$, and $a_{i\pm2} < -\omega$ are satisfied when the attractant stimulus is applied to the ith arm. In addition, Fig. 4 shows that the phase ϕ_i of the side arms varies periodically, whereas those of the leading arm and posterior arms have a steady state value. These results clearly implies that the role assignment of rhythmic and non-rhythmic movements among the arms is realized spontaneously.

4. CONCLUSION AND FUTURE WORK

In this study, we modeled the ophiuroid omnidirectional locomotion that exhibits well-coordinated rhythmic and non-rhythmic arm movements. Simulation results showed that the proposed model can reproduce the role assignment of such versatile arm movements. In the future work, we plan to extend the model to describe movements of soft and deformable arms, *i.e.,* intra-arm coordination, in addition to inter-arm coordination.

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