# Study on Body limb Coordination Mechanism Underlying Sprawling Locomotion

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| 著者 | SUZUKI SHURA |
| 学位授与機関 | Tohoku University |
| 学位授与番号 | 11301甲第19839号 |
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| | すずき　しゅら |
| 氏名 | 鈴木朱羅 |
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| 指導教員 | 東北大学教授　石黒　章夫 |
| 論文審査委員 | 主査　東北大学教授　石黒　章夫　東北大学教授　吉澤　誠<br>東北大学教授　中尾　光之　東北大学准教授　加納　剛史 |

# 論文内容要約

Locomotion, moving from one place to another, is an essential ability for animals to survive in severe nature. Quadruped animals exhibit versatile locomotion modes, such as walking, swimming, jumping, and crawling, and by using these modes, they freely move around complex, unpredictable, and unstructured environments. The impressive locomotive skills are realized by flexible coordination of the legs and other body parts, such as the trunk, head, and tail, i.e., body--limb coordination. Their motor control mechanisms are composed of central pattern generators (CPGs), reflexes, and descending commands from higher control centers. However, the mechanisms responsible for body--limb coordination remain elusive because of the complicated interactions between these components.

Modeling study with numerical simulation or robot experiment is an approach that can contribute to further investigations of animal motor control while considering the above-mentioned complicated interactions. Mathematical models are fairly easy to remove the components that less affect the focusing issue, thereby simplifying the problems. Numerical and robotic simulations are reproducible, and all parameters of the model are controlled and measured. This facilitates investigations of the effect of parameters change on behavior. In particular, in the case of locomotion control, these simulations are very useful for examining the dynamics and the interplay of the body, neural system, and environments. This thesis employed the approach and aimed to understand body--limb coordination mechanisms underlying quadruped locomotion. Sprawling locomotion is an interesting example to understand body--limb coordination mechanisms, and this thesis focused on this as model behavior.

Sprawling locomotion is a walking gait with lateral bending of the body used by many amphibians and lizards. Lateral bending with steps provides a longer stride and stronger thrust, even animals with short legs, and the body--limb coordination flexibly change in response to the velocity. Further, the first terrestrial vertebrates also used this locomotion pattern. Therefore, sprawling locomotion is key to understanding how quadruped acquired body--limb coordination mechanisms with limb development. Previous modeling studies designed several CPG models and reproduced various behaviors of sprawling quadrupeds, such as walking, swimming, and turning. However, these models coordinated axial and limb movement by neural couplings of CPGs and did not consider the extent to which sensory feedback mechanisms are responsible for body--limb coordination. The main purpose of the thesis is to understand the role of sensory feedback for body--limb coordination in sprawling locomotion.

The thesis mainly consists of three parts, and the details are described in Chap. 2-4, respectively. First, we designed the model that can coordinate legs and the trunk without neural couplings of CPGs, and investigated the effects of sensory feedback on locomotion performance. The proposed model has bidirectional sensory feedback between legs and the trunk. The body consists of simple legs and a one-degree-of-freedom trunk, allowing us to ignore intersegmental coordination and focus on the leg--trunk coordination, in which the trunk bending provides effective locomotion. The bidirectional feedback produces proper body--limb coordination without neural couplings of CPGs. Numerical and robotic simulations showed that sensory feedback improves locomotion performance in several aspects, rapid convergence to stable gait, fault tolerance, easy parameter tuning.

Next, we investigated the mechanism responsible for gait transition with flexible change of body--limb coordination patterns. For instance, salamander exhibits lateral sequence walking gait with a standing wave of lateral bending at lower speeds, and it replaces to walking trot gait with a traveling wave of lateral bending as speed increases. Here, we redesigned the model with bidirectional feedback for a simulated salamander robot with a multi-degrees-of-freedom trunk. The simulation results showed that the redesigned model reproduced the gait transitions between the two by changing one parameter related to speeds. To our best knowledge, no previous models reproduce the gait transition successfully, which changes the body--limb coordination. Further, the model predicts that the locomotion speed when gait transition occurs is related to sensory feedback strength. Therefore, the results suggested that sensory feedback plays an essential role in shaping flexible body--limb coordination patterns.

Finally, the thesis introduced the universal model for multi-legged locomotion with lateral bending. The bidirectional feedback model demonstrated that various behaviors of sprawling quadrupeds. Then, we tested the applicability of the model, whether the model can also reproduce other animal behaviors using lateral bending with limb movements. We tried to reproduce the behaviors of polypterus and centipede. Polypterus is a fish that can walk on land by using two fins and standing waves of lateral bending. Centipede is an invertebrate that has many legs and a flexible trunk. The centipede walks by propagating waves of leg movement with traveling waves of lateral bending at higher speeds. The simulation results showed that the universal model exhibited polypterus and centipede walking as well as salamander walking. It means that the model reproduced the three types of locomotion patterns with the different body--limb coordination patterns by one control principle. It implied that the model would extract the common principle of body--limb coordination crossing specific differences.

In summary, the thesis illuminated the usefulness and the possibility of sensory feedback involving body--limb coordination in sprawling locomotion through mathematical modeling and simulations.
The main significance of this works is that the demonstration of spontaneous salamander gait transitions and the reproduction of three types of legged locomotion with lateral body bendings by one control principle. These results imply the significant role of sensory feedback in body--limb coordination and provide a clue to unveil sophisticated motor control in animals and design agile and high functional robot control orchestrating high-redundant body.