Group B–3:Realization of Adaptive Locomotion based on Dynamic Interaction between Body, Brain, and Environment

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***Abstract*— The behavior of a robot is emerged from the interaction between body, control, and environmental dynamics. The research group B–3 aims to design body and control dynamics for emerging adaptive locomotion. We investigate three types of locomotion, biped, quadruped, and snake-like and developed robots. We also discuss on the lower control architecture for realizing reactive adaptive locomotion.**

I. Introduction

The research program entitled Emergence of Adaptive Motor Function through Interaction between Body, Brain, and Environment - Understanding of Mobiligence by Constructive Approach - started in 2005, as a MEXT Grant-in-Aid for Scientific Research on Priority Areas. One of the main goals of the project is to find a principle of emergence of adaptive locomotion. To approach the issue from the constructivist viewpoint, our research group B–3 aims to develop locomotive agents with various modalities based on dynamic interaction between body, control and environment.

In this report, we will state research goals for emergence of adaptive locomotion, and report on the current stage of the research. The following is divided into four parts: Firstly, we overview the whole research issue. Then, we discuss on snake-like, quadruped, and biped locomotion in order.

II. Design principle for emergence of adaptive locomotion

We investigate robots that have many degrees of freedom, snake-like robot, quadruped robot, and biped robot. The control architecture we propose will have two kinds of dynamics for realizing adaptability and mobile efficiency: a lower control system with rhythm generators and/or feedback controllers with local sensors and a higher control system with agent intentions based on external sensors (Fig. 1). These systems are dynamically coupled and interact with the body and environmental dynamics so that the artificial systems can reveal adaptive behaviors. By deriving such control mechanisms for various modes of locomotion, we hypothesize that we can understand which part should be dependent on the morphology of the system, and which part not.

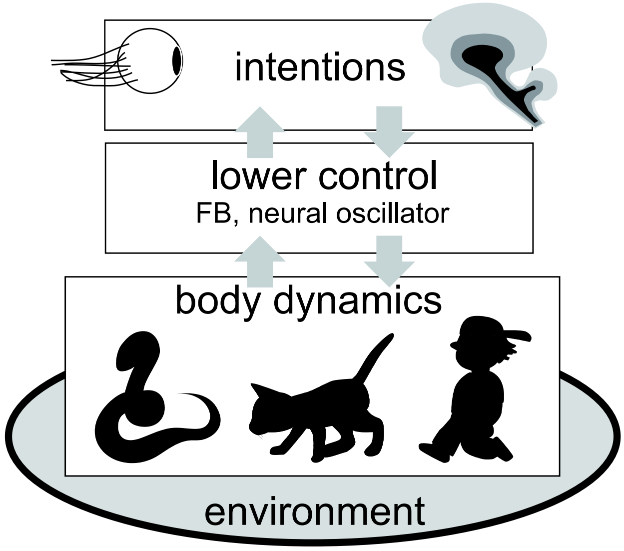

Fig. 1. Overall architecture for adaptive locomotive agents

III. Snake-like locomotion

Snakes have long cord-shaped bodies and, making the most of this characteristic, they can move in narrow environments and soft grounds. They mechanically interact with complicated and dynamic environments by curving their bodies to make friction or stress to realize purposive locomotion. The locomotion include creeping on soil, sand, marshland, in water or even on tree branches, going up and down on stairs, and going across different tree branches (Fig. 2).

This locomotion mechanism is essentially different from legged animals, and therefore, there is a possibility that we can distinguish a part of mobiligence independent on motion mechanisms from the dependent part by making this kind of motion clear.

A. CPG-network for snake-like locomotion

Locomotion in snakes is fundamentally based on efferent propagation of curving pattern and, like lamprey, distributed control realized in spinal cord is assumed to be utilized.

Fig. 2. Real snake

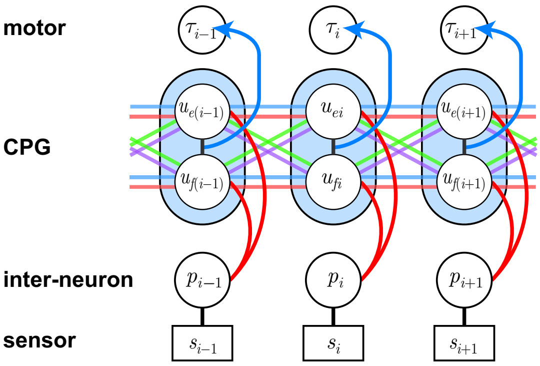

Fig. 3. CPG-network for controling snake-like robot

Based on this assumption, we constructed a distributed control architecture using CPG-network@ realizing propagation of oscillation pattern (Fig. 3) and confirmed realization of creeping locomotion by implementing the architecture to real snake-like robot (Fig. 4) [1]. Each segment of this robot has 1-DOF yaw rotation.

At the present stage, we are implementing sensors to measure mechanical interaction with the environment (Fig. 5) and aiming at realization of adaptation to changing ground friction by feeding back the sensory signals to the CPG-network.

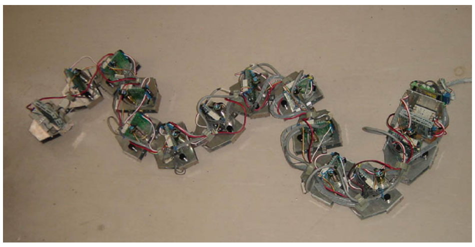

Fig. 4. 1-DOF snake-like robot

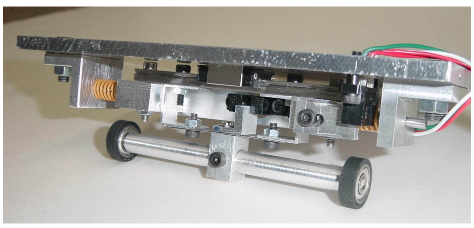

Fig. 5. Developed sensor

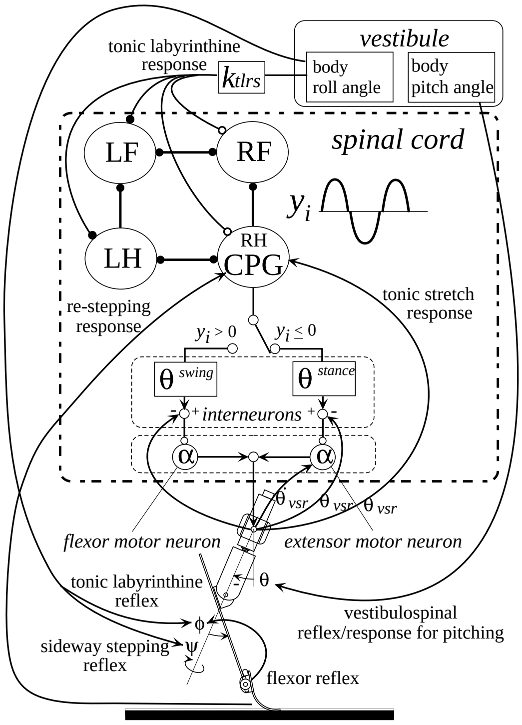

Fig. 6. Control diagram for dynamic walking.

IV. Quadruped Locomotion

Quadruped locomotion is the normal mode for mammals. Not like snake-like locomotion, it relies on not only friction force but dynamic effects. Its stability is not so severe compared to the bipedal locomotion. The mammals exhibit several locomotion modes depending on the movement speed.

A. *Walking on irregular terrain*

We proposed the necessary conditions for stable dynamic walking on irregular terrain in general, and we designed the mechanical system and the neural system by comparing biological concepts with those necessary conditions described in physical terms. PD-controller at joints constructed the virtual spring-damper system as the visco-elasticity model of a muscle. The neural system model consisted of a CPG (central pattern generator), reflexes and responses (Fig. 6). We validated the effectiveness of the proposed neural system model control[2] using the quadruped robots called "Tekken1&2."

Intending a dog-type service robot in future, we developed a self-contained quadruped robot named "Tekken3&4." We newly equipped robots with a laser range sensor and a CCD camera for navigation and demonstration. We tried to improve the mechanical reliability of robots for 11 days exhibition at Aichi expo[3].

B. *Running on irregular terrain*

We tried the design and stability analysis of a simple quadruped running controller that can autonomously generate steady running of a quadruped with good energy efficiency and suppress such disturbances as irregularities of terrain. In

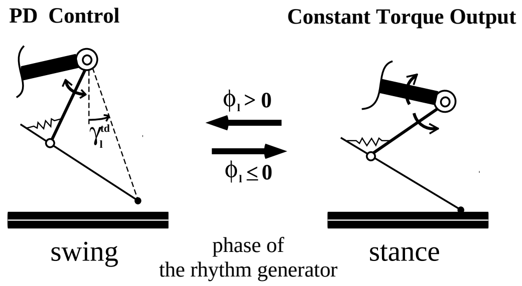

Fig. 7. Control diagram for running. ϕ_i means the output phase of the rhythm generator of the i-th leg.

this study, we first considered the fixed point of quasi-passive running based on a sagittal plane model of a quadruped robot. Next, we regarded friction and collision as disturbances around the fixed point of quasi-passive running, and proposed an original control method to suppress these disturbances.

Since it is difficult to accurately measure the total energy of the system in a practical application, we used a Delayed Feedback Control (DFC) method based on the stance phase period measured by contact sensors on the robot's feet with practical accuracy. The rhythm generator outputs the phase (stance/swing), and switches the state of the torque generator(Fig.7). The DFC is applied to both the rhythm generator and the torque generator. The DFC method not only stabilized the running around a fixed point, but also resulted in the transition from standing to steady running and stabilization in running up a small step.

The effectiveness of the proposed control method was validated by simulations. At low and medium speeds, the rhythm generator was dominant and it was possible to realize the generation of the bounding gait from the standing and the energy accumulation by the mutual entrainment. At high-speed running, the role of the rhythm generator became small since the spring mechanism mostly generated the rhythm of the steady running.

V. Biped locomotion

Bipedal locomotion is unique for humans and several other animals. Biped locomotion is more dynamical than the other locomotion modes. Also, the stability issue is more severe. A joint driving mechanism with antagonistic pairs of muscles is supposed to be essential for humans and animals to realize various kinds of locomotion such as walking, running, and jumping. We have designed a biped whose joints are driven by antagonistic pairs of McKibben artificial muscles. Since the body is well-designed for walking, required control is surprisingly compact[5], [6], [7].

A. Design of a 3D biped walker

If the body is well-designed, it reduces the control cost, not only amount but also quality. In Fig. 8, we show photos of the biped robot. The sketch Fig. 9 shows its rough size and joints. It has an upper body, two 4-DOF legs, and two 1-DOF arms, totally 10-DOFs. The arm only has 1-DOF to lift sideways.

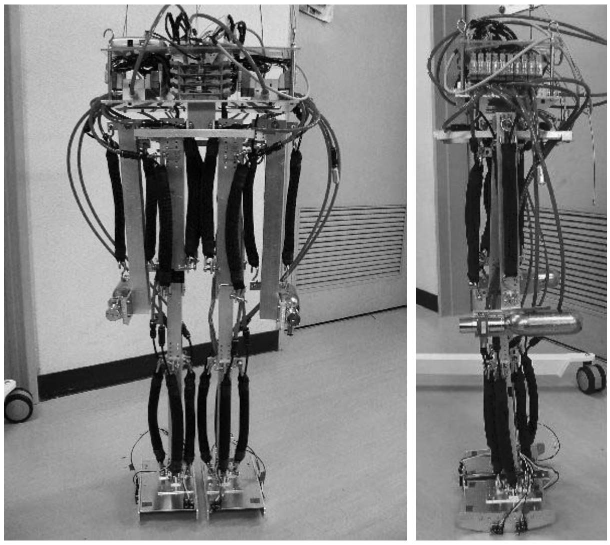

Fig. 8. A 3D pneumatic actuated walker "Pneu–Man". It has 10 joints with 10 pairs of McKibben artificial muscles, totally 20 muscles. CO_2 bottles are attached to tips of arms for balancing.

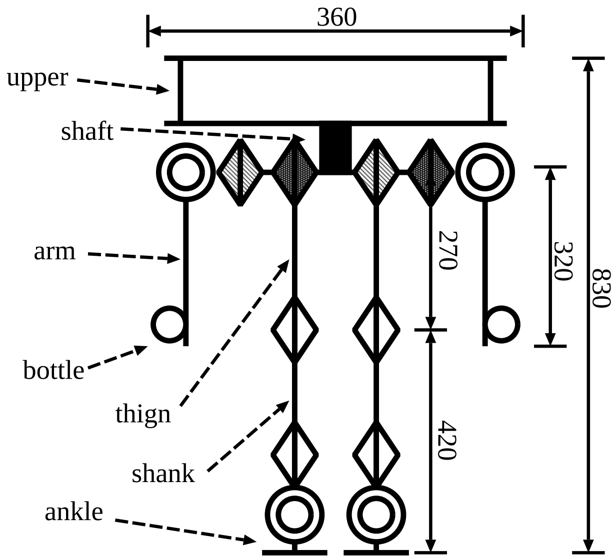

Fig. 9. A sketch of the 3D walker "Pneu–Man". The swing joint of left arm is physically connected to the right hip joint, and that of right arm to the left hip joint.

The leg has a 1-DOF hip joint, a 1-DOF knee joint, and a 2-DOF ankle. The ankle has a ball joint and is driven by 2 pairs of artificial muscles along roll and pitch axes.

Its height and weight are 0.83[m] and 7.0[kg], respectively, including a micro processor, 40 electrical valves, a battery for the processor and the valves, two CO_2 gas bottles to drive the artificial muscles. The robot is basically self-contained.

B. Walking control of the biped "Pneu–Man"

We apply ballistic control that opens the valves for swinging the free leg fixed time after foot impact. The only sensors that the robot has are several touch sensors on the soles.

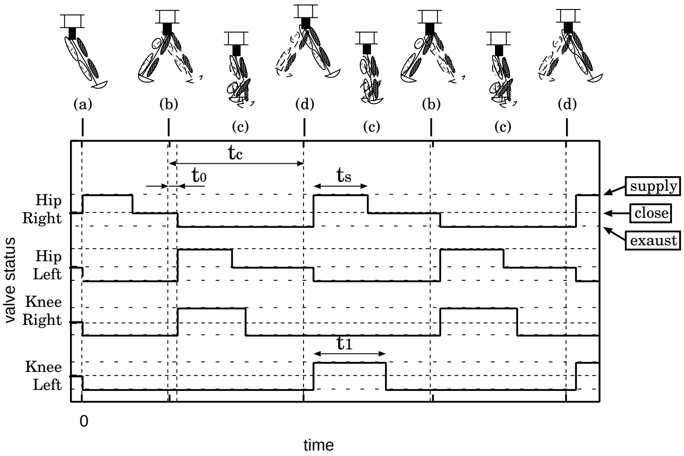

Fig. 10. The control scheme for supplying/exhausting/closing the valves

In figure 10, we show the operation strategy of the valves. In the figure, the operation of back muscles of the hip joint and of knee joints are indicated. The rest, the fore muscles of the hip joint, the fore muscles of the knee joints, and the muscles of the ankle joints are pre-pressured before we start the walking experiments. Since we cannot precisely control the amount of air, we instead determine the open duration to the supply air 0.7 [MPa]. That of fore hip muscles, of fore knee muscles, of fore pitch ankle muscle, of back pitch ankle muscle, of outer roll ankle muscle, and of inner roll ankle muscle are 200 [ms], 200 [ms], 270 [ms], 80 [ms], 500 [ms], and 170 [ms], respectively. These values are determined through experiments in a trial and error manner.

The control parameters we can change are t_0 and t_s, time to start swing after the free leg touches the ground and valve opening duration to swing the free leg, respectively. t_c is walking cycle, which is the consequence of the control. We also can change t_1, the valve opening duration to bend the knee, which is, however, not effective to change the overall behavior of the robot.

C. Realization of walking

We conducted experiments to demonstrate the walking performance of the system. We searched for the best walking parameters for stable walking by trial and error. When $t_0 = 10$[ms] and $t_s = 250$[ms], the robot could walk more than 16 steps. In the experiment, due to the experimental cost reason, we did not use the CO_2 bottles but the air compressor connected with tubes, which limits the movement of the robot, unfortunately. In figure 11, we show a walking sequence of the developed biped with the proposed controller.

VI. Future work

We have developed snake-like, quadrupled, and biped robots so that we can verify the interaction between the robot body and environment. We are in the stage to investigate and test the lower level controllers such as simple reflex controllers and/or neural oscillators. We should further investigate on not only the lower level controllers but higher layer for intensive behaviors. In such situation, we should take the dynamic interaction between them into account for emergence of adaptive locomotion.

Fig. 11. A walking sequence of the developed biped with proposed control

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