2005 Annual Report

"Emergence of Adaptive Motor Function through Interaction among the Body, Brain and Environment - A Constructive Approach to the Understanding of Mobiligence - "

Project Leader: Hajime Asama (The University of Tokyo)

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Introduction of the *Mobiligence* Project

Emergence of Adaptive Motor Function through Interaction among the Body, Brain and Environment

- A Constructive Approach to the Understanding of *Mobiligence* -

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1. Introduction

The *Mobiligence* project is a five-year project started from 2005[1], which was accepted as a program of Scientific Research on Priority Areas of Grant-in-Aid Scientific Research from the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). In addition to the planned research groups which started in 2005, new two-years-research groups (applied research groups) will be selected and start from 2006. This paper presents the abstract of the project.

2. Objective of the *Mobiligence* Project

Human can behave adaptively even in diverse and complex environment. All the animals can perform various types of adaptive behaviors, such as a locomotive behavior in the form of swimming, flying walking, a manipulation behaviors such as reaching, capturing, grasping by using hands and arms, a social behavior to the other subjects, etc. Such adaptive behaviors are the intelligent sensory-motor functions, and most essential and indispensable ones for animals to survive.

It is known that the function of such adaptive behaviors is disturbed in patients with neurological disorders. Parkinson disease is a typical example of disorders on adaptive motor function, and autism or depression can also be considered as a disorder on social adaptive function.

Recently, due to aging or environmental change of society, the population of people who are suffering from these diseases is growing rapidly, and it is urgent to cope with this problem. However, the mechanisms for the generation of intelligent adaptive behaviors are not thoroughly understood. Such an adaptive function is considered to emerge from the interaction of the body, brain, and environment, which requires that a subject acts or moves. Base on the consideration, we call the intelligence for generating adaptive motor function *mobiligence*.

The present project is designed to investigate the mechanisms of *mobiligence* by closely collaborative research of biology and engineering. In the course of this collaborative project, the following processes will be carried out:

1. Biological and physiological examinations of animals;
2. Modeling of biological systems;
3. Construction and experiments on artificial systems by utilizing robotic technologies; and
4. Creation of a hypothesis and its verification.

The final goal of this project is to establish the common principle underlying the emergence of *mobiligence*.

3. Research Approach of the *Mobiligence* Project

In this project, the *mobiligence* mechanism is to be elucidated by the constructive and systematic approaches, through the collaboration of biologists and engineering scientists who developed biological models by integrating physiological data and kinetic modeling technologies as shown in figure 1. In other words, the *Mobiligence* Project is pursued by integrating biology and engineering, i.e., physiological analysis (biology), modeling and experiments on artificial systems (engineering), verification of models (biology), and discovery and application of principles (engineering).

In the following discussion, the focus is on three adaptive mechanisms:

1. Mechanism whereby animals adapt to recognize environmental changes;
2. Mechanism whereby animals adapt physically to environmental changes; and
3. Mechanism whereby animals adapt to society.

Research groups for each of the categories listed above are organized. The three groups conduct their respective research and clarify the universal, common principle underlying the mechanism of *mobiligence*. The Planned Research Team studies the following specific subjects: analysis of the environmental cognition and the adaptive mechanism in reaching movements; analysis of the physical adaptive mechanism in walking; and analysis of the adaptive mechanism observed in the social behaviors of insects. In addition, the Planned Research Team clarifies the common principle underlying *mobiligence* from a dynamic viewpoint. Furthermore, we study adaptive mechanisms relating to various objects by publicly inviting proposed topics and clarify the universal, common principle therein.

4. Research Activities till the *Mobiligence* Project

The *Mobiligence* project is highly motivated by the previous project on emergent systems, which was carried out from 1995 to 1997 and directed by Prof. Shinzo Kitamura of Kobe University. Although the system theory on emergent function formation was actively discussed in the project, the principle it couldn't be revealed enough how to design the emergent systems. After the project on emergent systems, a special interest group on System Principle on Emergence of *Mobiligence* and Its Engineering Realization was organized in the System and Information Division of the Society of Instrument and Control Engineers (SICE) in 2003, and the research activities have been continued.

We held a workshop sponsored by the Tohoku University Nation-wide Cooperative Research Project from 2001, and a workshop on the development of the emergence system of *mobiligence* and its control system under the sponsorship of the Nissan Science Foundation.

Before starting the *mobiligence* project, we planned and held organized sessions in international conferences and in lecture meetings of academic societies

- IFAC Intelligent Autonomous Vehicles (IAV)
- International Symposium on Distributed Autonomous Robotic Systems (DARS)
- International Symposium on Adaptive Motion of Animals and Machines (AMAM)
- IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
- SICE Annual Conference
- SICE System and Information Division Annual Conference (SSI)
- SICE System Integration Division Annual Conference (SI)
- SICE Symposium on Decentralized Autonomous Systems

5. Expected Impact of the *Mobiligence* Project

Various types of adaptive motor function mechanisms performed by animals are expected to be elucidates. In the medical field, the results of our research will contribute to the discovery of a method to improve motor impairment and develop rehabilitation systems. In addition, in the engineering field, the results of our research will contribute to the derivation of the design principles of artificial intelligence systems. Furthermore, we will explore the new research field, *mobiligence*, establish a research organization that integrates biology and engineering, and implement programs to foster young engineering scientists and biologists to conduct collaborative and interdisciplinary research between biological and engineering research, respectively.

References

[1] http://www.arai.pe.u-tokyo.ac.jp/mobiligence/index_e.html

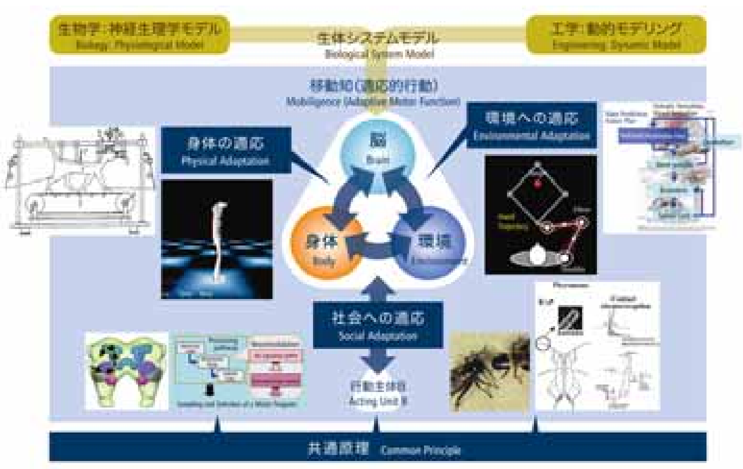

Fig. 1 Framework of the *Mobiligence* Project

Fig. 2 Expected Impact of the *Mobiligence* Project

Steering Committee Report on the *Mobiligence* Project

Hajime Asama*[1], Kazuo Tsuchiya*[2], Koji Ito*[3], Masafumi Yano*[4], Koichi Osuka*[5],
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*[5]Kobe University, *[6]Asahikawa Medical College, *[7]Hokkaido University, *[8]Nagoya University

1. Missions

The missions of the steering committee are as follows:

- Establish goals for the *Mobiligence* Project
- Plan and coordinate research
- Evaluate research results and consult
- Determine the procedures for the public invitation of proposed topics
- Organize symposia and research meetings for the purpose of developing related research
- Plan publicity of research results
- Encourage close collaboration among researchers, i.e., information exchange, mutual understanding, and communication
- Plan international research and lectures by members of academic societies and announce interim and ex post evaluations of progress
- Devise programs to encourage fused collaboration among biologists and engineering scientists and establish a research center and research organization

2. Steering Committee Meetings

The following Steering Committee meetings were held, and planning and coordination of the research subjects in the *Mobiligence* project and discussion on how to establish the research goals were made:

[1] 1st Steering Committee Meeting
Oct. 14th, 2005, 16:00-19:30
at the University of Tokyo, Tokyo

[2] 2nd Steering Committee Meeting
Dec. 5th, 2005, 13:00-15:30
at Hokkaido University, Sapporo, Hokkaido

[3] 3rd Steering Committee Meeting
Mar. 6th, 2006, 14:00-17:30
at the University of Tokyo, Kashiwa, Chiba

3. Planning, Coordination, and Consultation

The research policy of the total project was established. For planned research groups, research subjects were coordinated in each group to facilitate the fused collaboration between biologists and engineering scientists, which characterizes this project, and joint group meetings and open group meetings were organized to promote the inter-group collaboration effectively. The subjects to be complemented were analyzed, which could be covered by accepting proper applied research, and the coordination and consultation of research subjects were made to make the total project consistent between the planned research groups and the applied research groups.

4. International Symposium

The 1st International Symposium on *Mobiligence* (*Mobiligence* ’06) was organized and held in Dec. 4th, 2005 in Sapporo. The abstract of the *Mobiligence* project was introduced by Prof. Hajime Asama (The University of Tokyo), the director of the project, followed by the presentation on research plan of each planned research group by group leaders, who are Prof. Koji Ito (Tokyo Institute of Technology) for group A, Prof. Kazuo Tsuchiya (Kyoto University) for group B, Prof. Hitoshi Aonuma (Hokkaido University) for group C, and Prof. Koichi Osuka (Kobe University) for group D. In the symposium, three distinguished guests, Prof. Sten Grillner (Karolinska Institute, Sweden), Prof. Rolf Pfeifer (University of Zurich, Switzerland), and Prof. Avis H. Cohen (University of Maryland, USA), gave invited talks, who are also the members of reviewers of the *mobiligence* projects. The discussion on research related to *mobiligence* was made intensively. The concept of the *mobiligence* research was shared, and the importance of the *mobiligence* project was recognized. The number of attendees was 80. Figure 1 shows the circumstance of the symposium.

Fig. 1 *Mobiligence* ‘05

5. Tutorials

To accelerate the fused collaboration and to foster young scientists and students who are doing *mobiligence* research, the following tutorial programs including practice and experiments were arranged and held:

[1] 1st Experimental Practice Program
Introduction of research methodology of neuroethology and demonstration of experiments

Nov. 22nd, 2005, 13:00-16:00 at Kanzaki-Takahashi Laboratory of the University of Tokyo, Tokyo

[2] 1st Tutorial Program
Tutorial lectures on biology for young scientists and students majoring in engineering
Mar. 14th-17th, 2006, at Aonuma Laboratory of Hokkaido University, Sapporo, and at Takakusaki Laboratory of Asahikawa Medical College, Asahikawa, Hokkaido

6. Review

At the symposium mentioned above, in addition to the three foreign reviewers, three domestic members of reviewers, Prof. Shinzo Kitamura (Kobe University), Prof. Shigemi Mori (National Institute for Physiological Sciences), and Prof. Ryoji Suzuki (Kanazawa Institute of Technology) participated in the symposium, and the review on directivity and research progress of the project was made by the six reviewers. The comments of the review were highly positive, which are attached in the appendix.

At the end of academic year of 2005, interview to the group leaders was carried by the project director and secretary, and the research progress and the advancement of collaboration between biologists and engineering scientists in each group was recognized.

7. Arrangement of Special Issue and Organized Sessions

A special issue on “Emergence of Intelligence through Mobility” in the Journal of the Society of Instrument and Control Engineers was arranged and published in September 2005[1], in which the outline of the *Mobiligence* project and some of research activities of the planned research groups were introduced.

Following organized sessions in international and domestic conferences were arranged:

[1] 2005 SICE Symposium on Systems and Information (SSI ’05) (Domestic), Nov. 28th-30th, 2005, Fukuoka, Japan
[2] 2005 SICE Symposium on System Integration (SI ’05) (Domestic), Dec. 16th-18th, 2005, Kumamoto, Japan
[3] 2006 SICE Symposium on Autonomous Decentralized Systems (Domestic), Jan. 26th-27th, 2006, Fukui, Japan
[4] 9th International Conference on Intelligent Autonomous Systems 9 (IAS-9) (International), Mar. 7th-9th, 2006, Kashiwa, Japan

8. Publicity and Others

For publicity, a home page of the *Mobiligence* project was established[2], which was shown in figure 2, database on research achievements[3] and activity records was constructed and presented on the web site.

The brochure of the *Mobiligence* project was published and distributed as well as call for proposals for the applied research. The report, this volume, on the research activities of the *Mobiligence* project in 2005 was edited and published.

References

[1]Journal of the Society of Instrument and Control Engineers, vol. 44, no. 9, (2005).
[2]http://www.arai.pe.u-tokyo.ac.jp/mobiligence/index_e.html
[3]http://www.arai.pe.u-tokyo.ac.jp/mobiligence/act/index_e.html

Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Culture, Sports, Science and Technology, Scientific Research on Priority Areas (Area No. 454)
Mobiligence Project

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- A Constructive Approach to the Understanding of Mobiligence -

Fig. 2 Web Site of the *Mobiligence* Project

Group A: Adaptation to Environment
Annual Report

Koji ITO

Department of Computational Intelligence and Systems Science
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1. INTRODUCTION

Motor control system consists of <Body> with various action outputs and sensory inputs, <Brain> as the central controller, and <environment>. The body includes large number of sensors and actuators, and connects the brain with the environment. The interaction between the body and environment imposes some constraints on the redundant degree of freedom in the total dynamical system. Then, as shown in Fig.1, the body and environment are the controlled object and builds up the external dynamics to the brain. On the other hand, the body connects with the brain, which builds up the internal dynamics. Accordingly, it is essential in the motor control to self-adjust the dynamic relations among the brain, body and environment corresponding to the purpose of his/her action or movement under an infinite variety of environments. That is, in the dynamical system with the redundant degree of freedom composed of the brain, body and environment, it is the most important problem in the adaptation to environment to find some constraints from the spatiotemporal contexts and to create the internal dynamics appropriate to the forthcoming environment.

Group A is composed of two subgroups on the voluntary motor control in order to tackle these problems.

2. RESEARCH REPORTS

Subgroup A01:

Voluntary Movements Controlled by “Mi-Nashi” created in the Motor Cortices.

(Masafumi YANO, Research Institute of Electrical Communication, Tohoku University).

Since it is impossible to know all situations of the environment, the biological system has to tentatively suppose a relationship between the system itself and the environment. We call this relationship as “Mi-Nashi”. An aim of the movement can be acquired by the system having “Mi-Nashi”. Carrying out an aim with adapting to unpredictable environments is a voluntary movement. Because the problem controlling the voluntary movement is generally ill-posed, “Mi-Nashi” can be thought to a higher constraint for resolving the ill-posedness and will generate practical constraints for motor control in various levels.

Furthermore, for adapting to unpredictable changes in the system and environment, “Mi-Nashi” should emerge from the system itself depending on the interactions between the system and environment, and the system has to evaluate whether the assigned “Mi-Nashi” would be satisfied every moment. This is the computational problem that has to be solved by motor control system, i.e., motor cortex during voluntary movements in the real world. For examining this hypothesis, it is required to construct a model for voluntary movements based on the physiological knowledge and evaluate its ability for adapting to changes of environments in the real world.

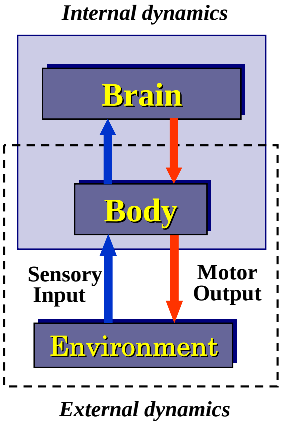


Fig.1 Brain-Body-Environment systems.

Fig.2 “Mi-Nashi” information

This year we focused on the arm reaching movement and bipedal locomotion based on the physiological and psychophysical studies.

(1) Arm reaching movement

We hypothesized that the higher constraints, “Mi-Nashi” in the reaching movement are both of the target position and arrival time to the target. This builds up the hand velocity vector as the practical constraint that should be satisfied.

Under the hypothesis that “Mi-Nashi” is given in advance, we proposed the control system that satisfied the practical constraints in real-time corresponding to the changing environment dynamics.

(2) Bipedal locomotion

Bipedal locomotion is the body movement carried out by cyclical and dynamical interactions of the legs with the ground. During the bipedal locomotion in the real world, the body will receive unpredictable forces depending on various factors, e.g., changes of the ground conditions, changes of the wind conditions and etc. Perturbations to the environment caused by these external forces depend on the condition of the system itself, that is, dynamical properties of the body. For example, the body posture will be directly affected by the external forces if the body stiffness is high and will be less affected if it is low.

Muscle tone is one of the important parameters to determine the body properties, such as the stiffness and viscosity. Recent physiological studies have revealed that appropriate setting of the muscle tone before and during movements is essentially important to carrying out various movements, including locomotion. Thus, as one of “Mi-Nashi” for the bipedal locomotion, the muscle tone should be appropriately set before the movement depending on an aim supposed by the system itself, and should be controlled during the movement depending on the environmental conditions. We demonstrated by the dynamical model simulation that the flexible and robust bipedal locomotion could emerge from appropriate control of the muscle tone depending on the ground reaction force.

Subgroup A02:

Understanding of Intra-cerebral Mechanisms for the Motor Adaptation to Unknown Environments.

(Koji Ito and Toshiyuki KONDO, Tokyo Institute of Technology).

As has been described, the biological system has the ability of appropriately and rapidly constraining their sensorimotor mapping in real-time, even though they are situated in unknown environments. There are at least three different levels in the sensorimotor coordination mechanism.

First, there should be an innate (i.e. genetically-determined) relationship, like spinal reflex or central pattern generator (CPG). These innate sensorimotor connections are mainly distributed in spinal cord, and utilized as a basic circuit for generating some more complicated motions.

Just like we can walk unconsciously, the second level sensorimotor coordination is automated through iterative learning. This is known as the automatic movement, which corresponds to periodic motions such as walking, swimming, breathing, etc. According to walking experiments of decerebrate cats, these periodic motions are basically generated in the brain stem by selectively evoking the innate level motor circuits. It should be noted that the brain stem and spinal cord are strongly supported by both the basal ganglia and cerebellum.

Finally, the third level is voluntary movement, in the case where all the brain regions, i.e. cerebral cortex, cerebellum, basal ganglia, and so on are interdependently concerned for the complicated motor control.

Based on the biological evidences, we proposed a computational motor adaptation model with a context-based environmental cognition, which is called CPG-CM (Central Pattern Generators with Constraints Modulation) shown in Fig.3. It is basically consists of three components, Brain nervous system, Body and Environments. Here, the body and environment correspond to the dynamics of musculo-skeletal system and external worlds, respectively. We built up the brain nervous system (RNN and CPG) which can generate an appropriate motion pattern based on a time-series of the proprioceptive feedbacks (i.e. context-based cognition). As an example, it was applied to a redundant manipulator control for a crank rotation as shown Fig.3. It was demonstrated that the proposed model could recognize the change of external environment through the time-series observation of the system state variables and evoke CPG parameters to maintain the crank rotation.

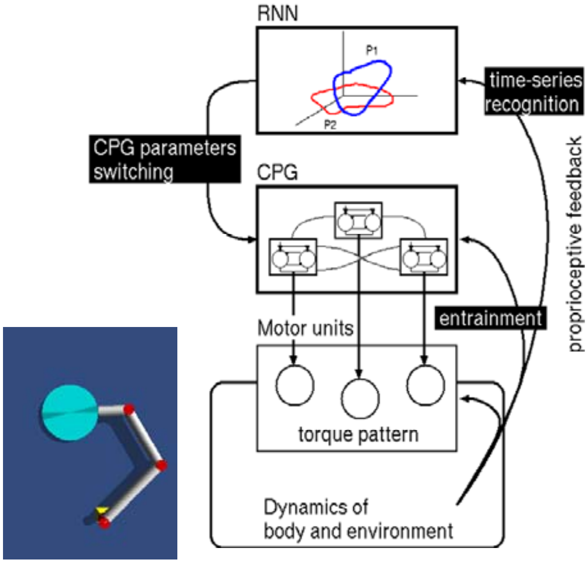


Fig.3 CPG-CM (Central Pattern Generators with Constraints Modulation)

3. MEETING AND OTHERS

- Joint meeting by Group A & B.

  Date: 10:00-16:30, 11 February, 2006.

  Place: Room 315, Building 2, Faculty of Science, Kyoto University.

  Attendee: 16 members.

  Contents: Report on research plans and results by all members of Group A, and frank and fruitful discussions on “Mi-Nashi”

- Invited lecture 1

  Date: 15:30-17:00, 14 March, 2006.

  Place: University of Catania (Italy)

  Attendee: about 80 students and researchers.

  Lecturer: Koji ITO.

  Title: Adaptive Motor Functions through Dynamic Interactions among the Body, Brain and Environment

- Invited lecture 2

  Date: 16:30-17:45, 21 March, 2006.

  Place: University of Napoli (Italy)

  Attendee: about 15 students and researchers.

  Lecturer: Koji ITO.

  Title: Adaptive Motor Functions through Dynamic Interactions among the Body, Brain and Environment -Understanding of Motor Intelligence by Constructive Approaches –

Voluntary Movements Controlled by “Mi-Nashi” created in the Motor Cortices.

Masafumi Yano, Research Institute of Electrical Communication, Tohoku University

I. INTRODUCTION

Environments around biological systems are continuously changing. In such environments, the biological systems can control their own bodies appropriately and flexibly for carrying out various kinds of purposes. In conventional approaches to a problem of motor control, the environment is separated from the system and all conditions of the environments and the system are postulated to be completely observable. However, because conditions of the environment and the system will change unpredictably during any of actions in the real world, all changes of these conditions cannot be modeled in advance. To accomplish the emergence of the flexible and divergent motor actions in the real world, there must be a new method dealing with interactions between the environments and the biological system in the real world.

To address this, it is important to have a new viewpoint for the biological system, that is, “Various faculties of the biological system, i.e., cognitive functions and motor functions, are the functions of yielding appropriate relationships with unpredictable environments”. Since it is impossible to know all conditions of the environment, the biological system has to tentatively suppose a relationship between the system-itself and the environment. We call this relationship supposed by the system as “Mi-Nashi”. An aim of the movement can be acquired by the system having “Mi-Nashi”. Carrying out an aim with adapting unpredictable environments is a voluntary movement. Because a problem controlling the voluntary movement is generally ill-posed, “Mi-Nashi” can be thought to a higher constraint for resolving the ill-posedness and will set practical constraints for motor control in various levels. Furthermore, for adapting unpredictable changes in conditions of the system and the environment, “Mi-Nashi” should emerge from the system-itself depending on interactions between the system and the environment, and the system have to evaluate whether the emerged “Mi-Nashi” would be satisfied every moments. These are computational problems that the motor control system, i.e., the motor cortices, has to solve during the voluntary movement control in the real world. For examine this hypothesis, we have to construct a model for voluntary movements based on physiological knowledge and evaluate its ability for adapting changes of environments in the real world.

II. THE MECHANISM OF CONSTRAINTS EMERGENCE / SATISFACTION IN ARM REACHING MOVEMENT

To study voluntary movements, we focus on arm reaching movement based on physiological and psychophysical studies[1], [2], [3]. We hypothesized that the higher constraint, the “Mi-Nashi”, of reaching movement are a target position and arrival time to the target and it sets hand velocity vector as practical constraint, which arm movement satisfies. In this section, we report about control systems that satisfy the practical constraint, where the “Mi-Nashi” is given.

A. *Hand velocity vector as practical constraint*

The arm must have redundant joints to reach a target in various environments. To control such redundant arm, constraint is necessary. And the constraint must be valid even when external force to the arm or dynamical property of the arm (inertia mass, joint viscosity) changes. Using hand velocity vector as practical constraint is reasonable because the velocity can be reset with any environmental change in real time. Our model determines angular velocity of each joint that satisfy the constraint in distributed autonomous way, and achieves robust control in unpredictable environment.

1) Setting hand velocity vector: Our model consists of 3-joints and 3-links. The target velocity $\boldsymbol{v}_d$ is set in real time, depending $\boldsymbol{x}_d$ (target point) and t_d (movement time gain that regulates movement speed);

$$\boldsymbol{v}_d \quad = (\boldsymbol{x}_d - \boldsymbol{x}_h)/t_d. \tag{1}$$

2) Constraints emergence at joint level, and interaction between joints: Each joint evaluate its efficiency and interact with other joints so that the more efficient joint can move faster.

$$\begin{aligned} \tilde{\boldsymbol{v}_{d1}} &= (1-k_2)\boldsymbol{v}^l_{d1} + k_2\boldsymbol{v}^{c2}_{d1} \\ \tilde{\boldsymbol{v}_{d2}} &= (1-k_1)(1-k_3)\boldsymbol{v}^l_{d2} + k_1\boldsymbol{v}^{c1}_{d2} + k_3\boldsymbol{v}^{c3}_{d2} \\ \tilde{\boldsymbol{v}_{d3}} &= (1-k_2)\boldsymbol{v}^l_{d3} + k_2\boldsymbol{v}^{c2}_{d3}, \end{aligned} \tag{2}$$

where $\boldsymbol{v}^l_{di}$, $\boldsymbol{v}^r_{di}$, and $\boldsymbol{v}^{cj}_{di}$ are local target of each joint, residual target of each joint, interaction between neighboring joints, respectively.

3) Autonomous evaluation of efficiency: Each joint evaluate its efficiency autonomously by the following equation;

$$k_i = \exp[-\ln 2 \|\boldsymbol{v}^l_{di} - \boldsymbol{v}_i\|^2 / (\|\boldsymbol{a}_i\|/2)^2], \tag{3}$$

where $\boldsymbol{v}_i$ is hand velocity component contributed by rotation of joint i, and $\boldsymbol{a}_i$ is moment arm from joint to hand.

4) Constraint emergence at torque level: The target joint velocity $\tilde{v_d}$ determined by equation (2) is transformed to target joint angle and target joint torque by the following equations;

$$\dot{\theta_{di}} \quad = \mathrm{Dir}(\boldsymbol{e}_{x_i}, \tilde{\boldsymbol{v}_{di}}) \cdot \|\tilde{\boldsymbol{v}_{di}}\| / \|\boldsymbol{a}_i\| \tag{4}$$

$$\tau_{di} \quad = \tilde{I}_i(\boldsymbol{\theta}) \cdot (\dot{\theta_{di}} - \dot{\theta}_i)/T_n, \tag{5}$$

where $\tilde{I}_i(\boldsymbol{\theta})$ is an estimate of inertial mass of joint i and T_n is a time constant of the nervous system.

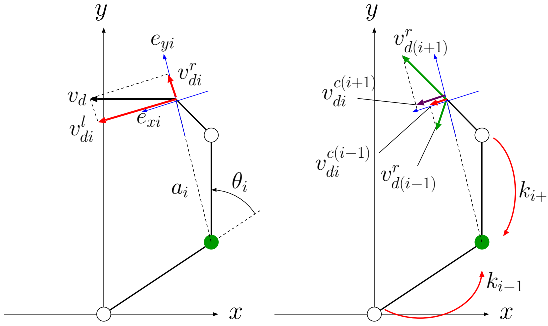
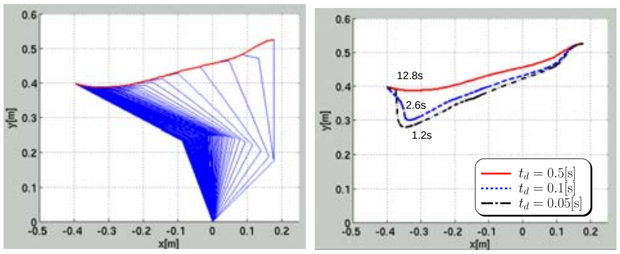


Fig. 1. A local purpose v^l_{di} and its residual v^r_{di} for joint i(left). A coupling term v^{cj}_{di}(right)



(a) $t_d = 0.5$[s]

(b) t_d changed.

Fig. 2. Typical reaching trajectory. In the left, sticks are traced every 0.1[s], and in the right, values represent convergence time(when a hand reaches 1[cm] around the end point).

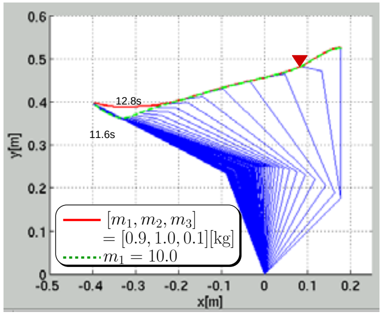


Fig. 3. Reaching trajectory($t_d = 0.5$[s]) when the mass of link 1 changed after $t = 0.2$[s](depicted by filled triangle). Other notations are same as in Fig.2.

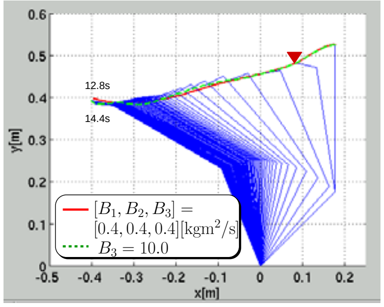


Fig. 4. Reaching trajectory($t_d = 0.5$[s]) when viscosity in joint 3 changed after $t = 0.2$[s].

B. Results

1) Representative reaching trajectory: Fig.2 shows reaching trajectory when initial arm configuration $\boldsymbol{\theta}(0) = (45, 45, 0)^T$[deg] and target position $\boldsymbol{X}_d = (-0.4, 0.4)$[m]. The hand converges to the target position with smooth trajectory.

2) Influence of arm mass change during movement: Fig.3 shows reaching trajectory when the mass of link 1 changes from $m_1 = 0.9$ to 10[kg] at 0.2 [s] after start. The hand reaches to the target position without winding, though it needs more time to converge.

3) Influence of viscosity change in joint during movement: Fig.4 shows reaching trajectory when the viscosity in joint 3 changes from $B_3 = 0.4$ to 10.0[kgm^2/s] at 0.2 [s] after start. After the viscosity increases, the inefficient joint 3 would not work.

III. THE MECHANISM OF CONSTRAINTS EMERGENCE/SATISFACTION IN BIPEDAL WALKING

Bipedal locomotion is a movement of the body carried out by cyclical and dynamical interactions of the legs with the ground. During the bipedal locomotion in the real world, the body will receive unpredictable forces depending on various factors, e.g., changes of the ground-conditions, changes of the wind-conditions (such as a tail or head wind) and etc. Perturbations to the movement of the body caused by these forces depend on the condition of the system-itself, that is, dynamical properties of the body. For example, the posture of the body will be directly affected by the forces if the stiffness of the body is high and will not be affected if the stiffness is low. Because the biological system has an ability to change various dynamical properties of its own body, an appropriate control of those properties is important for the system to maintain the locomotion in the real world.

Muscle-tone is one of important parameters to determine the properties of the body, such as the stiffness and the viscosity. To adapt unpredictable changes of the environment, controlling the muscle-tone seems to be one of useful ways. Indeed, recent physiological studies have revealed that appropriate setting of the muscle-tone before and during movements is essentially important to carrying out various movements, including locomotion[4], [5]. Thus, as one of "Mi-Nashi" for the bipedal locomotion, the muscle-tone should be appropriately set before the movement depending on an aim supposed by the system-itself, and should be controlled during the movement depending on conditions of the environment.

In this section, we show results of model simulations, indicating that flexible and robust bipedal locomotion can emerge from appropriate control of the muscle-tone depending on the ground reaction force.

A. Model

The musculo-skeletal models in the sagittal plane are shown in Fig.5 The model has a total of 14 muscles, five in each leg, four in lumber part. The range of motion of

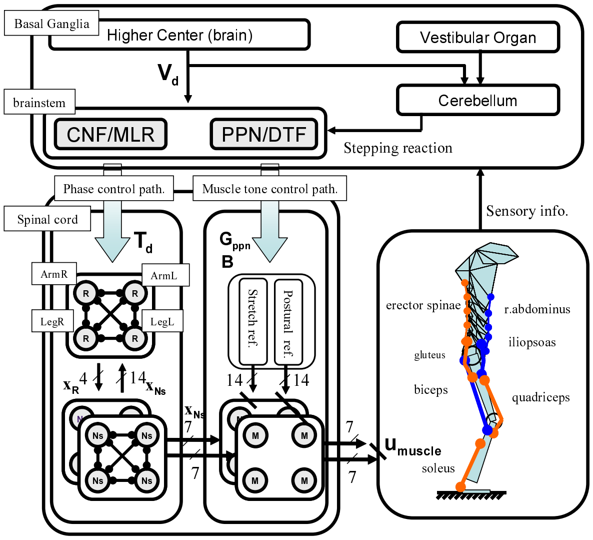


Fig. 5. Information flow diagram

each joints are determined according to the observed data of human. The mass ratio of each part to the whole body weight, the length ratio of each part to the height and radius rotational ratio are determined according to the average of Japanese athletes.

1) Muscle Model: The dynamical properties of muscle contraction plays essential role for bipedal walking. We adopt muscle model proposed by Hill[6], which has most widely accepted and represent a quite precise relationship between the tension development and the shortening velocity, known as force-velocity (P-V) relation. The P-V relation is denoted by

$$P\left(u, v(t)\right) \;=\; \begin{cases} \frac{bP_0 - av}{v+b} u, & v \geq 0 \\ \frac{P_0 v + av - bP_0}{27v^3 - b} u, & v < 0, \end{cases} \tag{6}$$

where v, P_0, a, b and $u(t)$ are the shortening velocity, the maximum tension development, the isometric proportional constant, the constant of energy release and the degree of activation of muscle, respectively. Using the natural length of muscle L_n, the constants a, b are given by $a = 0.25, P_0, b = 0.9L_n$, respectively.

2) Body stiffness control: In this model, the stiffness and the compliance of the body is adjusted to external forces in real time. This adjustment reduces impact shock at stepping on the ground, and consequently increases postural stability and efficiency. The stiffness $B_k(t)$ works as a gain of the stretch reflex and is adjusted side-independently. When the walking system get floor reaction force(GRF) on either leg, $grf_k(t)$, $B_k(t)$ is given by

$$B_k(t) = St\left(grf_k(t), GW(grf_k(t), \gamma_m)\right), \tag{7}$$

where St is the saturate function denoted by

$$St(x, x_s) = \begin{cases} 0, & x < 0 \\ \frac{1}{2} - \frac{1}{2}\cos(\frac{x}{x_s}\pi), & 0 \leq x < x_s \\ 1, & x \geq x_s. \end{cases} \tag{8}$$

GW denotes the corresponds to the integral

$$GW(f(t), \sigma) = \frac{2}{5\sigma}\int_{t-\sigma}^{t} GF(\tau, \sigma) f(t-\tau) d\tau, \tag{9}$$

$$GF(x, \sigma) = \frac{e^{-\frac{x^2}{2}\sigma^2}}{\sqrt{2\pi\sigma^2}}. \tag{10}$$

where γ_m is the response time of the afferent fiber, $\gamma_m = 50ms$. $B(t)$ is the gain of the phasic stretch reflex(psr).

3) Muscle tone control: Muscle tone level is adaptively controlled by the force feedback loops and determines amount of locomotor movements depending on various external loads. The muscle tone level, $G_{ppn}(t)$, which is the gain of descending tract from the PPN to the motoneuron pool in the spinal cord, is given by

$$G_{ppn}(t) = \frac{GW(\sum_k^2 grf_k(t), \gamma_m)}{GW(\sum_k^2 grf(T^0_{stride})_k, T^0_{stride})}, \tag{11}$$

where T^0_{stride} is walking period during one stride. The numerator is a total ground reaction of both legs, and the denominator is a substantial body weight at the time of a simulation start. Normally, $G_{ppn}(t)$ is 1.0 in a standing posture.

4) The posture control by mechanical interaction: Since the optimal antigravity posture depends on the situation, setting the hip height to a fixed value prevents flexible walking. In this model, posture controller controls antigravity muscles so that total of each muscular external work rate is set to zero. Postural control is automatically performed by balancing gravity force and reaction force by muscle contraction forces. Time average of the normalized external work rate, $\overline{\dot{W}}$, is given by

$$\overline{\dot{W}} = GW\left(\frac{P(v(t))v(t)}{P(v_{W max})v_{W max}}, \gamma_{tsr}\right), \tag{12}$$

$$v_{W_{max}} = \frac{-\sqrt{a}b + b\sqrt{a + P_0}}{\sqrt{a}}, \tag{13}$$

where γ_{tsr} and $v_{W_{max}}$ are the response time of the tonic stretch reflex(tsr), muscle contraction velocity in case external work rate becomes the maximum.

B. Control of Muscle Contraction by Motoneuron

In our model, each non-spiking neuron is connected to each muscle by one to one through each corresponding motoneuron. The muscle tone level affects on the whole body muscles as a value $G_{ppn}(t)$, which is the gain of the descending tract from the PPN to the motoneuron pools in the spinal cord. The output of motoneuron $u(t)$, which determines the activation level of muscle contraction, is given by

$$\begin{aligned} u_i(t) &= k_{Ns}G_{ppn}(t)H(x^i_{Ns}) - k_{v1}H(x^i_{Ns})v_i \\ &\quad -k_{psr}G_{ppn}(t)B_k(t)v_i - k_{tsr}G_{ppn}(t)\overline{\dot{W}}_i \\ &\quad +G_{ppn}(t)\textstyle\sum_c k^c_i Cont_c(t). \end{aligned} \tag{14}$$

where H, v_i and k denote the heaviside function, the shortening velocity of the corresponding muscle and the gain coefficients, respectively. Each terms of the right side denote phase pattern from CPG, viscosity of muscle, phasic stretch reflex, tonic stretch reflex and controller output of balance and desired body velocity, respectively. Fig.5 shows the neural networks.

C. Result

Fig.6 shows a example of walking movement on the level ground. The stick figure was traced every 0.1 second. 20kg load was added to the waist during the steady walk when body velocity was kept to 1.5m/s. Allow at the top and broken line indicate onset of load-adding. The value of G_{ppn} indicated 1.0 in a standing posture, 1.1 in a natural walk. And it increased immediately after adding a load and the body velocity was maintained. Furthermore, a walk was maintained even if adding a load of the same weight as body weight, 60kg. Thus, by determining the properties of body dynamics with adapting unpredictable environments using ground reaction forces, model could be adapted to various loads without needing an explicit posture control.

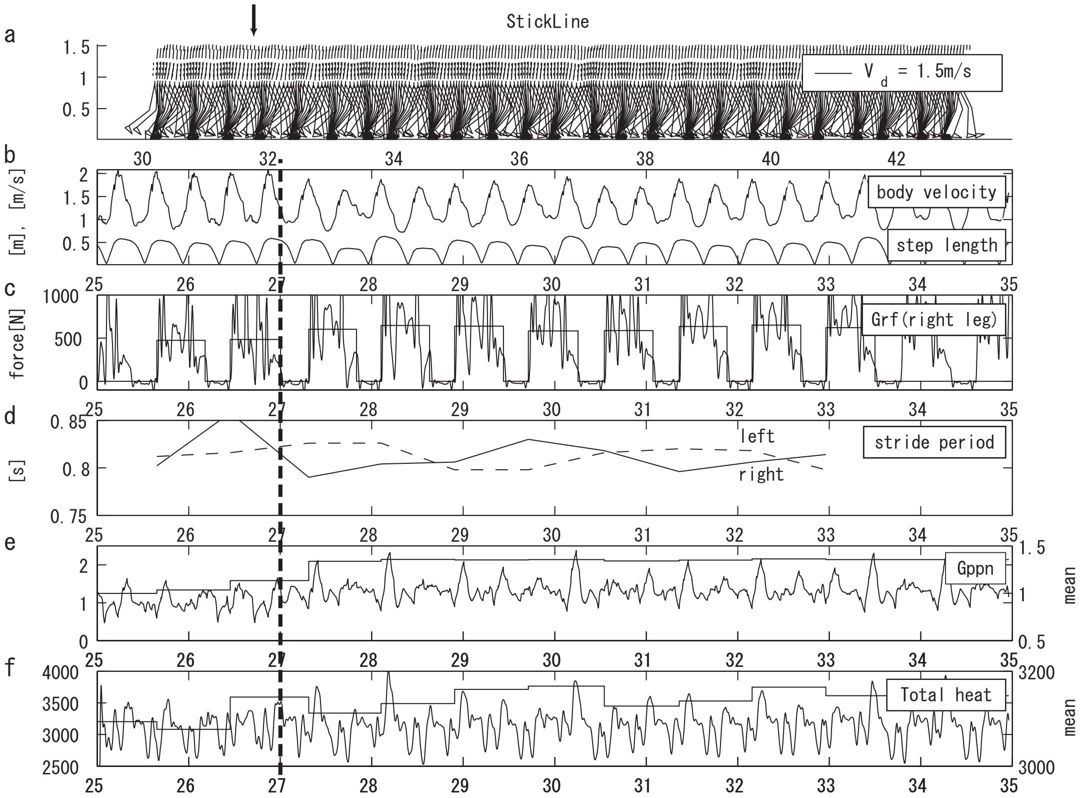


Fig. 6. 20kg weight is added to the waist during a walk.

IV. CONCLUSION

In our reaching-movement model, the target position and the arrival time to the target were given as the higher constraints. In order to satisfy these, the model set the velocity vector of the hand (i.e., an end-effecter of the arm) as the practical constraint for movement. Without monitoring dynamical parameters of the arm such as torque, our model was able to adapt to unpredictable changes in environment or to perturbations to the arm. Our bipedal-walking model also showed high adaptability and robustness to unpredictable changes of environment. These were accomplished by controlling the muscle-tone as “Mi-Nashi” depending on the ground reaction forces, which is available only when the body and the environment are interacting during actual walk.

Voluntary movements are classified into two types, i.e., one is the active movement mediated by intention including the reaching movements, and the other is the automatic voluntary movement including the bipedal locomotion. So, both of our model simulations indicate that the emergence of “Mi-Nashi” and the practical constraints for motor control is necessary to carrying out robust and flexible voluntary movements. We hypothesize that “Mi-Nashi” will be generated in the higher center of the motor-control system, and the practical constraints are automatically generated and satisfied in its lower center with interacting with the environment. Based on physiological knowledge, the higher center of the motor-control system can be thought to correspond to the motor cortices, and the lower center to the cerebellar cortex, the basal ganglia, the brain stem and the spinal cord.

Our future work is to clarify how “Mi-Nashi” itself is generated in the higher center thorough interactions between the motor areas and the sensory areas (especially the visual areas) based on behavioral, physiological and computational studies.

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Annual Report of Research Group A02 —Understanding of Intra-cerebral Mechanisms for the Motor Adaptation to Unknown Environments—

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***Abstract*— Regardless of complex, diverse, unknown, and dynamically-changing environments, animals can recognize situated environments and behave adaptively by theirselves. In research group A02, we aim to clarify the adaptation mechanism to recognize unknown environments and generate suitable motor behaviors through constructive and synthetic approaches. The key concept for realizing environmental cognition and motor adaptation is a context-based elicitation of sensorimotor constraints which are canalizing suitable motions. In the present paper, we report a preliminary result of our conceptual motor adaptation model and describe ongoing works.**

I. INTRODUCTION

Living creatures are information structuring systems which have enormous sensorimotor degrees of freedom. As shown in Fig.1, external world can be recognized on the spatiotemporal integration of their sensorimotor information e.g. vision, tactile and somatosensory stimulus, etc. Giving a task goal in addition to the environmental cognition, smooth limb movements can be realized immediately in spite of huge DOF of our musculoskeletal systems. However the mechanisms of the cognition and motor adaptation are still open question.

Due to this, not a few computational models for cognition and motor adaptation have been proposed. Most of them are based on *internal model* theory in which an adequate inverse model (i.e. controller) would be selected according to the prediction generated by forward models (e.g. [1]). In these *localist* models, a novel pattern can be incrementally learned by allocating an additional module. But in other words, they have less ability for dealing with unknown environments.

In contrast, recently, much attention has been focused on *dynamical systems* (or *distributed*) approach to cognition and motor adaptation[2], [3], [4], [5]. In this approach, the prediction and generation of motor patterns are represented in accordance with the concept of attractors in dynamical systems theory. Thus, degenerating the coupled dynamics of the system and environments using appropriate sensorimotor constraints, real-time cognition and motor adaptation to unknown situations can be expected.

Accordingly emergence of adaptive motor function through interaction among the body, brain, and environment has become a hot topic in the society of brain science, cognitive psychology, artificial intelligence, robotics, an so forth. Especially in the present project, the intelligence for generating adaptive motor function is called *mobiligence*[6] since it will stem from active movements. Based on the concept, our research group A02 hypothesizes that *active movement with abduction* brings about the key for the environmental cognition and motor adaptation. In particular, the following functions would be required for the conceptual motor adaptation model.

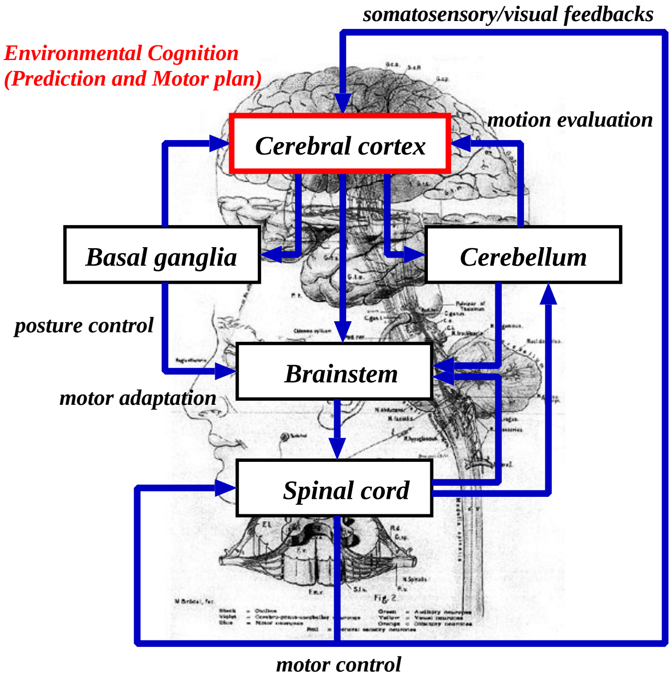

Fig. 1. Intra-cerebral loops for environmental cognition.

First, the model should have the ability to find/extract sensorimotor constraints which are canalizing suitable motion patterns, through continuous interactions with the environments. Secondly, the obtained constraints should be stored in a dynamical memory (e.g. associative memory) by linking with the context, so that they can be appropriately evoked when needed. Herewith, improvising motion generation is expected in analogous context. And third, in order to keep updating the repertoire of constraints, a novel sensorimotor constraint should be explored if generated motion is unsuitable. In that case, it should be taken care of preventing the dynamical memory from forgetting the previously memorized ones.

II. A Computational Motor Adaptation Model with a Context-based Environmental Cognition

As has been described, any living creatures have the ability of appropriately and rapidly constraining their sensorimotor DOF in real-time, even though they are situated in unknown environments. Although the details have not yet been clarified, there are at least three different levels in the sensorimotor coordination mechanism.

First, there should be an innate (i.e. genetically-determined) relationship, like *spinal reflex* or *central pattern generator* (CPG). These innate sensorimotor connections are mainly distributed in *spinal cord*, and utilized as a *motor primitive* for generating some more complicated motions[7].

Just like we can walk unconsciously, the second level sensorimotor coordination is automated through posteriori iterative learning. This is known as *automatic movement*, which corresponds to a periodic motion such as walking, swimming, breathing, etc. In most cases it plays an essential role for life-sustaining. According to walking experiments of decerebrate cats, these periodic motions are basically generated at *brain stem* by selectively evoking the innate level motor primitives (i.e. spinal reflex or CPG)[8].

On the contrary, it is widely accepted that the higher brain regions, especially *basal ganglia*, are highly concerned with the context-dependent elicitation of the motor primitives[9]. Interestingly, it is also reported that the decerebrate cats with *cerebellum* were able to learn a novel gait pattern even in unknown environments[10]. It should be noted that brain stem and spinal cord are strongly supported by both basal ganglia and cerebellum.

Finally, the third level is *voluntary movement*, in the case where all the brain regions, i.e. *cerebral cortex*, cerebellum, basal ganglia, and so on are interdependently concerned for the complicated motor control.

To sum up, in the developmental processes of animals' motor adaptation, a frequent motion would be automated by associating the context and evoking patterns of the motor primitives, while repeating it voluntarily.

Based on the biological evidences, we had proposed a computational motor adaptation model with a context-based environmental cognition, that is called CPG-CM shown in Fig.2[11]. It basically consists of three components, *Brain-Nervous system*, *Body*, and *Environments*, same as the concept of *mobiligence*. Here, the Body and the Environments correspond to the dynamics of musculo-skeletal system and external worlds, respectively. Since these dynamics are given as systems specification (and sometimes they are unknown), what we can do is to design the Brain-Nervous system which can generate an appropriate motion pattern based on a time-series of the proprioceptive feedbacks (i.e. context-based cognition).

The Brain-Nervous system has two processing layers named *Dynamical memory* and *CPG*. Likewise biological central pattern generators, the CPG layer plays a role in generating periodic motion patterns and it is implemented by using a neural oscillator model[12]. Thanks to the entrainment feature, the generated motions have self-stabilizing ability with respect to environmental perturbations[13]. On the other hand, the Dynamical memory layer is a time-series pattern discriminator implemented by recurrent neural networks (RNN)[14], and it associates time-series inputs with the optimized CPG parameters. After the training, it can conduct appropriate motion patterns by evoking well-suited CPG parameters according to the observations.

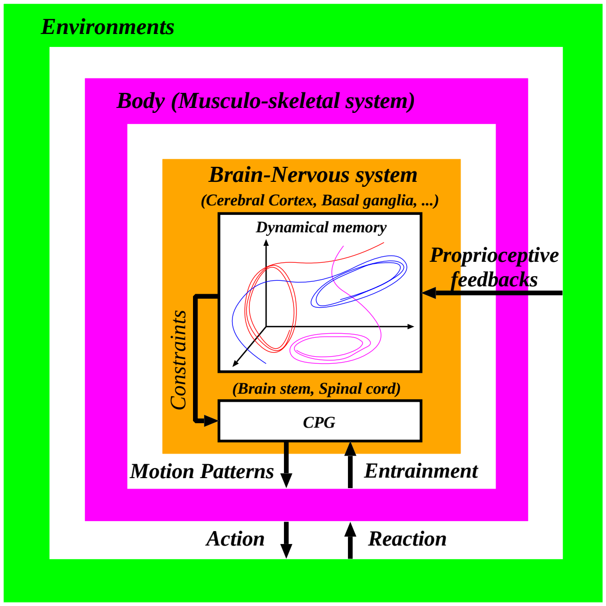

Fig. 2. A motor adaptation with a context-based environmental cognition.

III. A Redundant Manipulator Control for a Crank Rotation

The proposed model was applied to a redundant manipulator control for a crank rotation. The aim of the task is rotating the crank-handle as many times as possible by controlling a three link manipulator during a given time period. Each joint of the manipulator is controlled based on the joint torque generated by a corresponding CPG model. Because the crank has a rotational viscous friction in which the friction coefficient can be varied by an experimenter as an environmental change, the proposed model should be able to recognize the changes through the time-series observations of system states (i.e. joint angles, angular velocities and torques) and evoke corresponding CPG parameters to maintain the rotation.

Based on the above explained conditions, appropriate CPG parameters had been optimized by using simulated annealing (SA) method[15]. As illustrated in Fig.3, the manipulator with the optimized CPG parameters can appropriately rotate the crank. Here, each snap was captured in every 200 [ms]. During the first 1000[ms] (i.e. depicted *A* in the figure), the manipulator adjusted its posture to rotate the crank, and after the preparation, it started periodic/sequence movements continuously (i.e. *B*).

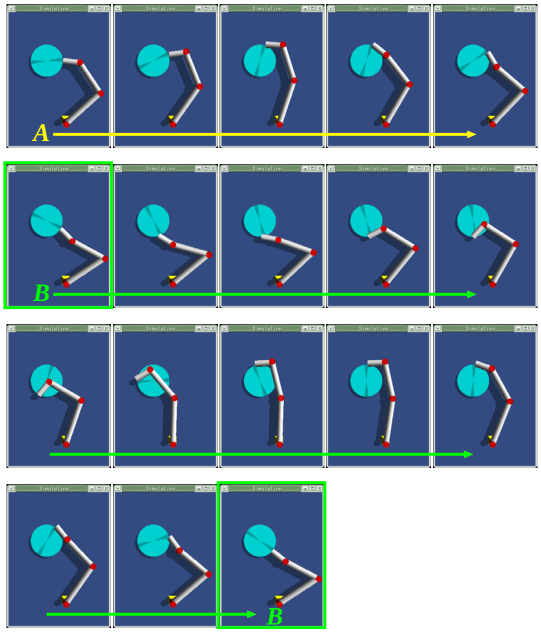

Fig. 3. Snapshots of an optimized trajectory for a crank rotation.

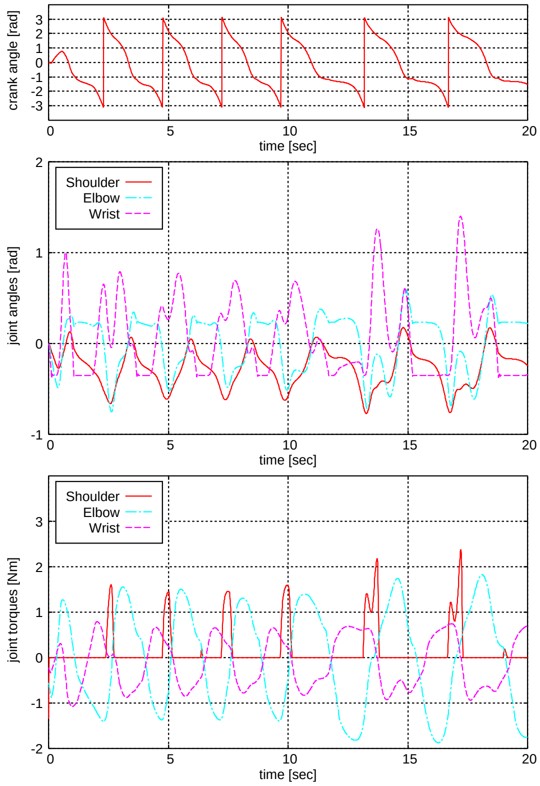

Fig. 4. A real-time joint angles/torques adaptation to environmental change.

On the other hand, Fig.4 illustrates a dynamical cognition and motor adaptation, i.e. the trajectories of three joints angles and torques (i.e. shoulder, elbow and wrist) against a sudden change of viscous friction coefficient (i.e. μ_v=0.10[Nm/(rad/s)] for 0-10[sec] and μ_v=0.15 for 10-20[sec]). According to this, it can be seen that the proposed model could recognize the environmental change through the perceived context and immediately generate suitable motion patterns by evoking appropriate CPG parameters.

IV. CONCLUSIONS AND FUTURE PROSPECTS

Because of limited computational resources, higher brain regions should not directly store motion trajectories rather elicit certain sensorimotor constraints which conduct reasonable motions in lower motor systems. According to the hypothesis, we proposed a computational model for environmental cognition and motor adaptation based on the concept of dynamical systems approach.

The proposed model was investigated through simulation experiments with respect to a redundant manipulator control for a crank rotation. The simulation results clarify that the cognitive system (i.e. Brain-Nervous system in the model) learns to discriminate the situated external environments based on a time-series of proprioceptive feedbacks and appropriate motion patterns are generated in real-time by selectively constraining its redundant sensorimotor DOF.

In the proposed model, however we have acknowledged that there are various points to be improved. First applicable scope of the present model is restricted to periodic motion generation since it is represented as coupled nonlinear oscillator model. As described in [7] living creatures innately have non-periodic motor primitives in their peripheral nervous system, e.g. spinal reflex. These motor primitives should be highly associated with their embodiment[16], as they are sophisticated through the continuous interactions with diverse environments in the process of evolution and development. However in case of artificial systems, it is impossible to arrange appropriate repertories of primitives in advance. Hence a developmental learning algorithm, where a number of dynamical modules are self organized through iterative design processes, should be incorporated in the present model.

On the contrary, in the proposed environmental cognition model, RNN is adopted as a time-series pattern discriminator. In general, the RNN is a promising time-series learning model but it has to be taken care of avoiding it from forgetting the previously memorized patterns when an additional pattern is trained. In regard to the problem, Freeman showed an interesting physiological experiment concerning olfactory bulb responses of rabbit to various odor stimuli[17]. In other words, it shows chaotic responses when unknown odor stimuli are given, while it expresses periodic patterns in the case of known stimuli. Based on this phenomena, Kojima et al. proposed a dynamical memory network model constructed from coupled chaotic dynamics modules[18], and it is also reported that the proposed associative memory model has robustness in the incremental learning. Interestingly similar conceptual models have been proposed in recent studies of brain science based on complex systems[19].

Meanwhile living creatures seem to be able to instantaneously generate remarkable motor commands in spite of being placed in unknown environments. At any time observing this motor adaptation processes in unknown environments reminds us that there is an additional intelligence beyond reinforcement learning. It likely corresponds to "knacks for adaptation" which would be extracted and self-organized from prior trained sensorimotor mappings, and this would be meta-level principle for the emergence of *mobiligence*. In the future study, we aim to reveal the relationship between this meta-level principle for motor adaptation/cognition and active movements in the level of computational theory. In addition, it must be clarified how these functions are represented in real the brain.

At the moment we have been studying environmental cognition and motor adaptation models for a biped robot control in unexperienced environments. In the example, the biped locomotion is fundamentally dominated by coupled phase oscillators. Consequently motor adaptation is represented as adjustment of phase difference among these oscillators in accordance with environmental changes. And the environmental change is simulated as perturbations of floor elevation and it can be arbitrarily varied by an experimenter. Compared with the crank rotation task, it should be more difficult since the biped locomotion is essentially unstable. Furthermore, we begin to analyze humans adaptation processes through the learning experiments of reaching and manipulation movements in unexperienced dynamical environments.

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Group B: Research Report

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I. RESEARCH PROJECT

This group studies the locomotion of animals. Specifically, this group's study aims are to elucidate how the mechanisms of the selection and realtime generation of motion patterns adapt themselves to environmental variations. This group is working on the following research projects:

A. *Physiological Study on Locomotion*

The purpose of this research is to establish the neuronal mechanisms of adaptive behaviors. We use three types of mammals: monkeys; cats; and mice. First, we systematically investigate the neuronal mechanisms of automatic postural adjustments that precede the initiation of locomotor behaviors. This investigation is particularly focused on the prominent role of signal flows from the cerebral cortex basal ganglia, limbic system, and cerebellum to the brainstem, which includes the basic neuronal systems involved in the control of posture and locomotion. Second, we elucidate the role of the cerebral cortex in the planning and programming of task-related and goal-directed locomotor behaviors. Our focus is concentrated on determining how cortical neurons are involved in integrating posture and locomotion during the transition from quadrupedal to bipedal locomotion. Following this, we try to establish how animals unconsciously select volitionally-initiated and emotionally-triggered behaviors. Our study focuses on the interaction between cortical and subcortical structures, such as the limbic system, basal ganglia, cerebellum and the brainstem.

B. *Biomechanical Study on Locomotion*

Animal locomotion is highly coordinated and involves dynamic motion that emerges through the complicated musculoskeletal system. The shape of the skeletal system is formed and maintained using the muscles. Furthermore, the muscles activate the motion of the skeletal system. We construct a mathematical model for a whole body musculoskeletal system, called the 'biomechanical model'. This model is based on anatomical data obtained through computed tomography and the dissection of a fresh adult Japanese monkey cadaver (*Macaca fuscata*).

C. *System Study on Locomotion*

The motoneuron in the spinal cord and the group of the muscle fibers innervated by the spinal motoneuron are fundamental for movement and are called 'motor units'. A motor unit causes reflexes using sensory information from the sensory receptors. The feedback control system is composed of many fundamental reflexes that generate complex movements. Locomotion is controlled using a complex control system that incorporates a central pattern generator. The command signals from the basal ganglia-thalamocortical loops and the basal ganglia-brainstem pathways are transmitted to the control system through the descending spinal pathways and control the animal's locomotion. We derive a mathematical model for the hierarchical control system, the 'neural network model', based on these reflexes. We construct a mathematical model for the locomotion, the 'system model', by combining the biomechanical and neural network models. In particular, using a Japanese monkey that accomplished bipedal locomotion, we extract kinematic data such as posture and limb movements during upright standing and quadrupedal and bipedal locomotion, physiological data such as energy consumption, and anatomical data about the skeletal system. Then, we investigate the control mechanism of the movement selection during locomotion by comparing the kinematic, physiological, and anatomical data and the simulation results based on the system model.

In order to extract the essential principles of locomotion, it is necessary to conduct a constructive investigation from a functional viewpoint. This study uses a simplified mathematical model for locomotion that is driven by rhythmic signals, and which analyzes movement to illustrate the dynamic principles of locomotion.

D. *Biorobotics*

Recently, many locomotion robots have been developed, although in general they are based on control theory. This means that they are manipulated with model-based controls using kinematics and kinetics. This control approach is unable to achieve adaptive locomotion in various environments. We develop many kinds of robots including biped, quadruped, and snake-like robots to clarify the guiding principles in designing robots that accomplish adaptive locomotion an the engineering viewpoint.

II. RESEARCH RESULTS

The research results are described in detail in the research reports completed by each subgroup. The main results are as follows:

A. *Physiological Study on Locomotion*

In the first year of this research program, we started research on the most fundamental mechanisms of postural control, which consisted of studying the brainstem and spinal cord mechanisms that controlled the level of postural muscle

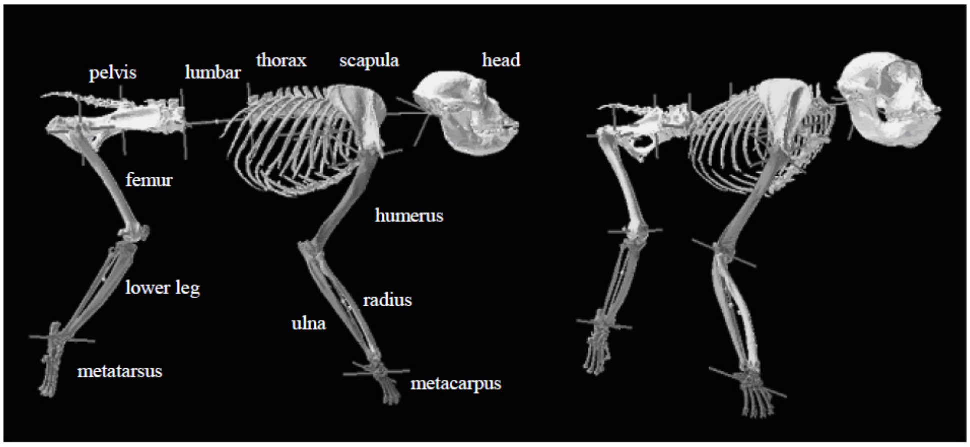

Fig. 2. Kinematic description of the whole body skeleton of a Japanse monkey as a chain of links. Only right fore- and hindlimb are shown.

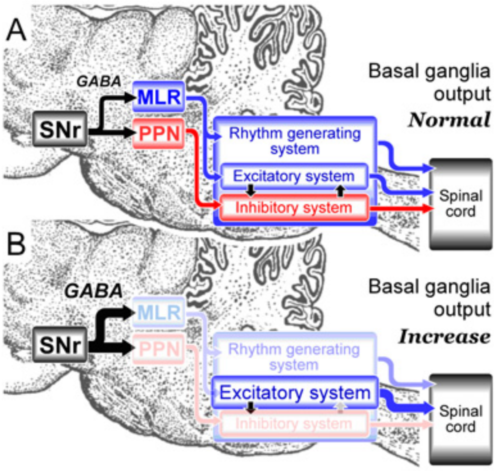

Fig. 1. Summary of the present findings.

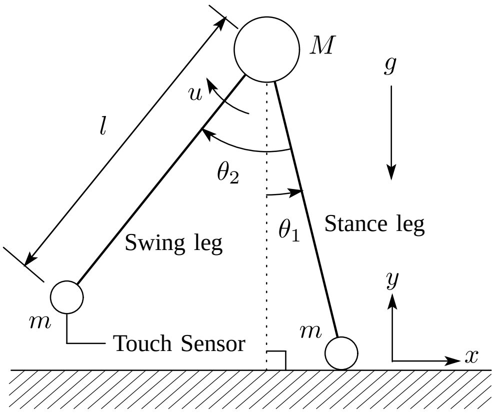

Fig. 3. Schematic model of a simple walking model.

tone in decerebrate cats. We first examined the excitability of both the pontomedullary reticulospinal neurons and spinal interneurons at the lower lumbar segments. Second, we examined how these brainstem-spinal cord systems modulated the excitability of the spinal reflex arcs in each state. The findings revealed that the reticulospinal system may: 1) reduce the amount of sensory input from the periphery, 2) inhibit the activity of the spinal interneuronal networks that compose the locomotor central pattern generators, and 3) suppress the excitability of the motoneuron, a final common path (Fig. 1).

B. Biomechanical Study on Locomotion

This year, we constructed an anatomically-based whole body musculo-skeletal model of a Japanese monkey. We conducted whole-body computed tomography on the fresh cadaver of an adult Japanese monkey (*Macaca fuscata*) and constructed three-dimensional surface models of the entire body surface and the skeletal system. We approximated the shape of each joint surface using a quadric surface to determine the rotation axis and joint location. We articulated the joint surfaces adjacent to each other based on these approximations and were then able to mathematically describe the kinematic skeleton of the Japanese monkey as a chain of 20 links (four links for the trunk segments, five links for each forelimb, and three links for each hindlimb) connected by revolute joints, as illustrated in Fig. 2. To mathematically describe the path of each muscle and the associated capacity to generate force, we dissected the fresh cadaver of a Japanese monkey. We observed the points of origin and insertion for each muscle, and systematically recorded the mass and fascicle lengths to calculate the physiological cross-sectional area. Presently, we are deriving the equations of motion for this model and are developing a simulator to achieve these dynamics in a virtual space.

C. System Study on Locomotion

In the past year, we used a simple planar model for bipedal locomotion and analyzed the essential characteristics of a walking motion driven by rhythmic signals. The model consists of one body and two legs and each leg is composed of one link (see Fig. 3). Each leg is driven by a nonlinear oscillator using its phase and generates periodic movement. This study revealed that this model achieves stable walking motion under appropriate conditions and has self-stabilization properties. Furthermore, stability is improved by intermittently using the sensory signals from the touch sensors attached to the tips of the legs.

Basal Ganglia & Gait Control
- with special reference to the synaptic mechanisms acting on spinal motoneurons -

K. Takakusaki, MD., PhD

Abstract - **Locomotion requires appropriate level of postural muscle tone. Gail failure and muscular rigidity (sustained increase in muscle tone) are major symptoms in Parkinson disease, one of the basal ganglia disorders. It has been shown that efferents from the basal ganglia project toward to the brainstem in addition to the cerebral cortex via thalamocortical loops. Because basic structures respon- sible for the generation of locomotion and the regulation of the level of postural muscle tone are located in the brainstem, the present study was designed to understand how basal ganglia efferents to the brainstem contribute to the modulation of locomotion. To under- stand the synaptic mechanisms acting on spinal motoneurons during gait control by the basal ganglia, intracellular activity of hindlimb motoneurons was examined in decerebrate cats. Electrical stimula- tion applied to the midbrain locomotor region (MLR) generated rhythmic membrane oscillations in motoneurons. Although stimula- tion of the substantia nigra reticulata, one of the basal ganglia output nuclei, did not alter the excitability of motoneurons, it greatly attenuated MLR-induced rhythmic oscillations and generated tonic firing of motoneurons innervating extensor and flexor muscles. Particularly, amplitude of hyperpolarizing phases of oscillations was greatly reduced. These results suggest that an increase in the basal ganglia output to the brainstem terminate locomotion by attenuation of the activity of central pattern generators and by enhancement of postural muscle tone.**

I. INTRODUCTION

THE basal ganglia are considered to be necessary for voluntary control of body movements [1]. Gait disturbance is one of the cardinal symptoms in patients with Parkinson disease. Typically, Parkinsonian patients hesitate to start walking (frozen gait) and walk slowly with shuffling and dragging steps, diminished arm swing and flexed forward posture. The progressive gait disturbance is associated with postural instability finally deprives the patients of locomotor ability and yields medical as well as social problems.

A basic hypothesis to explain hypokinesia in Parkinson disease is that thalamocortical projections fail to facilitate the motor-related cortical areas due to overactivity of the inhibitory projections from the basal ganglia to the thalamus [2, 3]. On the other hand, the basal ganglia have direct projections to the brainstem where fundamental structures involved in the control of locomotion and postural muscle tone are located [4, 5]. These are the midbrain locomotor region (MLR) and muscle tone inhibitory region in the pedunculopontine tegmental nucleus (PPN). We have shown in decerebrate cat preparations, repetitive electrical stimuli applied to the MLR and the PPN generated locomotion and abolished postural muscle tone, respectively. An activation of GABAergic neurons in the substantia nigra pars reticulata (SNr), one of the basal ganglia output nuclei, disturbed the MLR-induced locomotion and PPN-induced muscle tone suppression, respectively [4, 5]. Based on the above findings we have postulated that Parkinsonian gait deficiency would be also due to the excessive output from the basal ganglia to the brainstem neural networks.

The present study designed to understand mechanisms of the basal ganglia control of locomotion. Particular emphasis was placed on the examination how signals from the basal ganglia to the brainstem modulate the excitability of spinal motoneurons so that locomotion could be appropriately controlled. The present results may verify whether the latter hypothesis can be justified.

II. MATERIALS AND METHODS

The experiments were performed with laboratory-raised 11 cats of either sex weighing from 2.8 to 3.5 kg. All of the procedures were approved in the Guide for the Care and Use of Laboratory Animals (NIH Guide), revised 1996. During the investigation every effort was made to minimize animal suffering and to reduce the number of animals used.

A. *Surgical Procedures*

Under halothane-nitrous oxide gas anesthesia with oxygen, each cat was surgically decerebrated at precollicular-post-mammilary level. Surface of the lumbosacral spinal segments were exposed by laminectomy. The head and the vertebrae of the lumbar segments were fixed in a stereotaxic apparatus.

B. *Stimulation and Recording*

Stimulating electrodes were inserted into the mesopontine tegmentum of the brainstem. Repetitive stimuli (20-50 μA, 50 Hz) were delivered to the SNr, MLR, the PPN and the locus coeruleus (LC) for 5 to 10 s so that changes in the activity of motoneurons were induced. Short trains of stimuli (20-50 μA, 3 trains with 5 ms intervals) were applied to each site to evoke postsynaptic potentials (PSPs) in motoneurons.

Intracellular recordings were obtained from hindlimb motoneurons innervating extensor and flexor muscles at the level of L6 to S1 levels. Motoneurons were identified by the presence of antidromic action potentials which were evoked by stimulating peripheral muscle nerves of hindlimb.

C. *Framework*

Figure 1 shows a framework for this study. The MLR and muscle tone inhibitory region in the PPN are in close

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proximity to each other in the lateral part of the midbrain [4]. Activation of the MLR induces locomotor movements via activation of central pattern generators in the spinal cord through the medullary reticulospinal tract. Activation of the MLR may also activate muscle tone excitatory systems, including the coerulospinal and the raphespinal tracts. In contrast, activation of the PPN neurons suppresses postural muscle tone. The PPN-induced muscular atonia is mediated through the pontomedullary reticulospinal tract (inhibitory system. Moreover activities of neurons in the MLR and PPN were under the control of GABAergic inhibitory projections from the SNr [4, 5]. Among the basal ganglia nuclei, only SNr was preserved in decerebrate cats. Therefore we could examine how stimulation of the SNr altered the MLR/PPN-effects

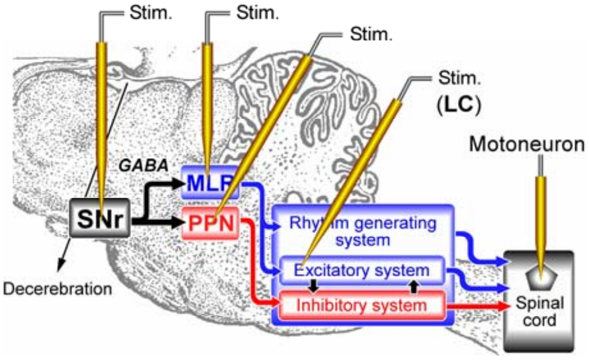

Fig.1. Framework of this study. Intracellular recording was made from hindlimb motoneurons. Stimulation of the MLR activates rhythm generating system and muscle tone excitatory system. Stimulation of the PPN activates inhibitory reticulospinal tract. To activate muscle tone excitatory system, stimulation was applied to the locus coeruleus (LC). SNr stimulation was applied to determine how basal ganglia efferent modulates locomotion and muscle tone.

III. RESULTS

A. Intracellular activities in spinal motoneurons following brainstem stimulations

Intracellular activities were examined in 47 motoneurons Representative example is shown in Fig.2 where lateral gastrocnemius soleus (LG-S) motoneuron was recorded. Repetitive stimulation applied to the MLR first depolarized membrane and generated membrane oscillations which were associated with burst firing (fictive locomotion; Fig.2Ba). Stimulation of the LC resulted in membrane depolarization along with tonic firing (Fig.2Bb). Such a tonic firing of the motoneuron reflected an increase in the postural muscle tone. On the other hand, stimulation of the PPN ceased the firing and hyperpolarized the membrane of the motoneuron (Fig.2 Bc), reflecting suppression of postural muscle tone.

Short trains of stimuli were delivered to each site to evoke postsynaptic potentials in the same motoneuron (Fig.2C). Stimulation of the MLR and the LC evoked excitatory postsynaptic potentials (EPSPs) followed by small amplitude of inhibitory postsynaptic potentials (IPSPs) on the declining phase of the EPSPs (Fig,2 Ca and Cb). Stimulation of the PPN evoked small EPSPs followed by IPSPs with large amplitude (Fig.2Cc). Accordingly, membrane depolarization and hyper- polarization induced by repetitive stimulation of the LC and PPN can be due to the temporal and spatial summation of these EPSPs and IPSPs, respectively. Therefore, amplitude of the LC-induced EPSPs and the PPN-induced IPSPs may respectively reflect the excitabilities of muscle tone excitatory system and inhibitory system.

B. Postsynaptic effects of stimulating the SNr upon MLR-induced fictive locomotion in hindlimb motoneurons

Then we examined the effects of stimulating the SNr upon fictive locomotion evoked from the MLR. Figure 3A and B are intracellular recordings obtained from plantaris (Pl) and posterior-biceps semitendinosus (PBSt) motoneurons. In both motoneurons, fictive locomotion, which was induced by the stimulation of the MLR, was greatly disturbed during SNr stimulation. Particularly, hyperpolarizing phase of membrane oscillation was reduced in size (Fig.3A and 3C, Table 1).

Such phenomenon was reflected in PSPs time-locked to the MLR stimulus pulse. There was an alternation of EPSPs and

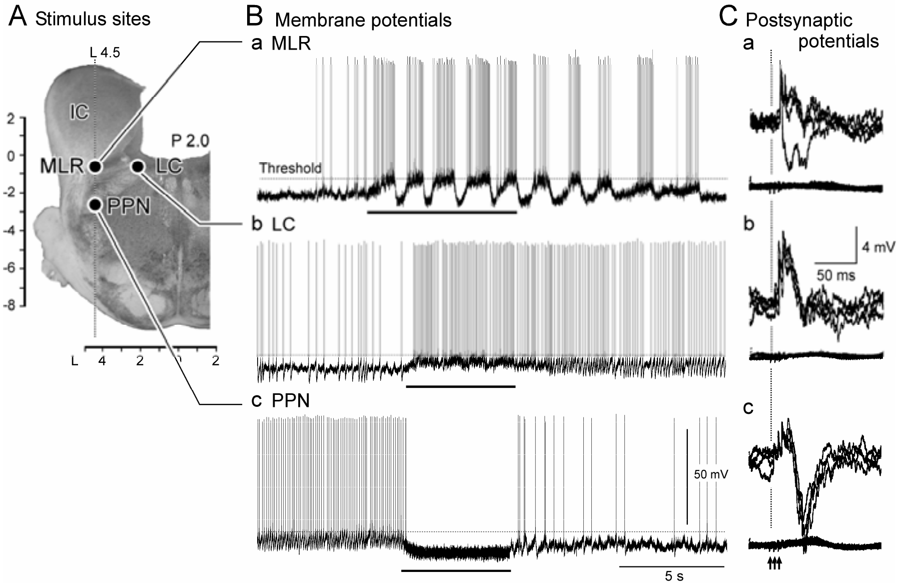

Fig.2. Activities of locomotor system and muscle tone control systems. A; Stimulus sites are shown on the coronal plane of brainstem B; Intracellular recording was made from a lateral gastrocnemius motoneuron. Stimulation of the MLR evoked fictive locomotion (a). Stimulation of the LC and the PPN depolarized (b) and hyperpolarized (c) membrane potentials, respectively. A dashed line in each record indicates threshold potentials. A period of stimulation is denoted by a solid line under each record. Each stimulation consisted of 50Hz and 40μA lasting for 4-7 seconds. C; Postsynaptic potentials evoked from each site. Stimulation of the MLR (a) and the LC (b) mainly evoked EPSPs, while that applied to the PPN evoked large IPSPs (b). Upward arrows indicate stimulus pulses consisted of 40 μA and 3 trains with 5 ms intervals.

IPSPs during fictive locomotion (Fig.3Ba). However, such an alternation was not observed during SNr stimulation, and only EPSPs were left (Fig.3Bb). It should be mentioned that SNr stimulation alone did not modulate the firing state of motoneurons, which was induced by intracellular injection of depolarizing current, as shown in Fig. 3Ac. These findings suggest that SNr stimulation suppressed the rhythmogenicity, possibly by the reduction of the activity of central pattern generators, of locomotion by removal of inhibitory drives acting on motoneurons. Because SNr stimulation, which was combined with MLR stimulation, induced depolarizing state with tonic firing in both extensor (Pl) and flexor (PBSt) motoneurons, muscle tone of both extensor and flexor muscles can be increased.

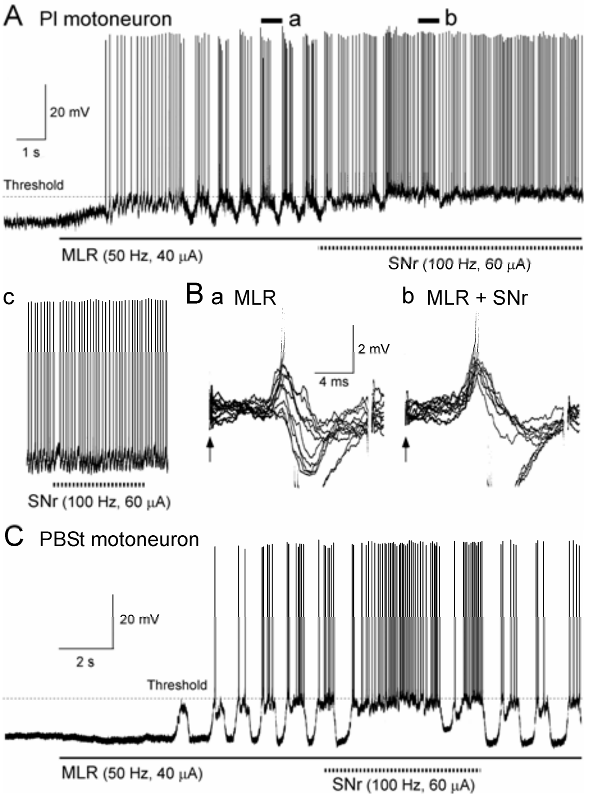

Fig.3. Nigral stimulus effects upon fictive locomotion. A; MLR-induced fictive locomotion in a Pl motoneuron was removed by SNr stimulation. Tonic firing induced by inward (5 nA) current injection was not affected by the SNr stimulation (c). B; Postsynaptic potentials which was time-locked to the MLR stimulation. During fictive locomotion (a), there was an alternation of EPSPs and IPSPs. However, tonic firing state during SNr stimulation, IPSPs were removed and only EPSPs were left (b). C; MLR-induced fictive locomotion in a PBSt motoneuron was attenuated during SNr stimulation. However rhythmic oscillations were reestablished after termination of the SNr stimulation. See text for further detail explanations.

C. Effects of SNr stimulation upon postsynaptic actions form muscle tone control systems

Because effects of SNr stimulation propagate to the activity of muscle tone control systems (Fig.1), we next examined the effects of SNr stimulation upon postsynaptic potentials from muscle tone excitatory system and inhibitory system. For this, stimuli were applied to the LC and the PPN to evoke EPSPs and IPSPs in motoneurons, respectively.

In Fig.4, although SNr stimulation alone did not alter input resistance of an LG-S motoneuron (Fig.4A), the identical stimulation greatly reduced the size of PPN-induced IPSPs (Fig.4B). Moreover, although the SNr stimulation did not change the amplitude of an LC-induced EPSP, dip of the declining phase of the EPSP was attenuated, indicating that IPSP components were removed by the SNr stimulation (Fig. 4C). Effects of SNr stimulation upon input resistance and EPSPs and IPSPs were summarized in Table 1. Because input resistance of motoneurons (n=7) was not modified by SNr stimulation, SNr stimulation itself may not evoke any post-synaptic effects. However, the amplitude of the IPSPs was significantly reduced. These findings suggest that excitability of muscle tone inhibitory system is reduced during SNr stimulation.

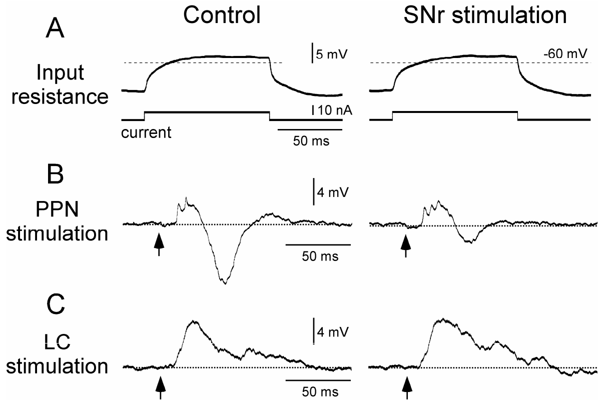

Fig.4. Effects of SNr stimulation upon input resistance (A) and postsynaptic potentials evoked from the PPN (B) and LC (C). Intracellular recording was obtained from an LG-S motoneuron. A; Changes in input resistance. To measure input resistance, inward current of 10 nA with 100 ms was injected into the motoneuron. B; Postsynaptic potentials evoked by stimulation of the PPN (3 pulses, 40 μA, 5 ms intervals). C; Postsynaptic potentials evoked by stimulation of the LC (3 pulses, 40 μA, 5 ms intervals). Upward arrows indicate the onset of the stimuli. Left and right panels are control and effects of SNr stimulation (100 Hz, 60 μA), respectively. Note that amplitude of PPN-induced IPSPs was greatly reduced during the PPN stimulation.

TABLE I
EFFECTS OF SNR STIMULATION

	Control (n)	SNr effect (n)
N-oscillations/10s (cycles)	10.2 ± 2.7 (43)	3.5 ± 1.2 (20)*
V-oscillations (mV)	9.1 ± 3.9 (43)	4.6 ± 1.9 (20)*
Input resistance (MΩ)	1.4 ± 0.4 (7)	1.4 ± 0.4 (7)
Brainstem EPSPs (mV)	2.4 ± 1.0 (37)	2.8 ± 1.0 (30)
Brainstem IPSPs (mV)	2.8 ± 1.0 (37)	1.6 ± 0.9 (30)*

Numbers (N) and amplitude (V) of oscillations during fictive locomotion, which was induced by stimulating the MLR was compared before (control) and after SNr stimulation (SNr effect). Mean and standard deviations and numbers of samples are shown. Significant difference ($p < 0.05$) was found in the numbers and amplitude of oscillations and the amplitude of IPSPs evoked from the brainstem.

IV. DISCUSSION

A. Mechanisms of basal ganglia control of locomotion

The present results support the previous findings that efferents from the basal ganglia to the brainstem modulate locomotion [5]. Moreover it is now clarified that the basal ganglia-brainstem system contributes to the gait control by modulating the activities of rhythm generating system and muscle tone control systems. Because SNr stimulation alone did not alter the excitability of motoneurons, these effects can be induced by the inhibition of descending systems having inhibitory actions on motoneurons. Such mechanisms can be critically important following two points. First, removal of IPSPs during MLR-induced fictive locomotion may disturb rhythmic membrane oscillations and leave only excitatory actions, resulting in tonic depolarization in both extensor and flexor motoneurons. Second, a decrease in the amplitude of PPN-induced IPSPs may reflect reduced activity of the inhibitory system. Because there are mutual inhibitory interactions between the inhibitory and the excitatory systems [4], the activity of the excitatory systems is disinhibited during SNr stimulation, leading to the enhancement of excitatory LC actions. As a result, an increase in the basal ganglia output to the brainstem may help terminating locomotion, which is associated with an increase in the level of extensor and flexor muscle tone. Co-contractions of extensor and flexor muscles can be beneficial to fix joint movements so that one can maintain a steady balance in the presence of gravity.

Based on above considerations, present findings can be summarized as shown in Fig.5. Locomotion is produced by an activation of rhythm generating system which requires the co-activations of excitatory and inhibitory systems (Fig.5A). When basal ganglia output increases, the activities of the rhythm generating system and the inhibitory system are reduced, but the activity of excitatory system is enhanced to terminate walking (Fig.5B). A decrease in the basal ganglia output initiate locomotion. Consequently, basal ganglia control locomotion by modulating the activities of plural descending motor systems.

B. Role of basal ganglia inhibition of target motor systems

Because Parkinson disease complicate hypertonia and gait failure, the basal ganglia are involved in the control of postural muscle tone and locomotion [4, 6]. Voluntary movements are controlled by the basal ganglia via thalamocortical loops [2], and postural muscle tone and locomotion can be controlled via projections from the basal ganglia to the brainstem [4, 5]. These motor systems in the cerebral cortex and the brainstem are under sustained tonic inhibitory drives from the basal ganglia [1]. One of mechanisms would be an enhancement of “spatial-temporal contrasts” of the activity of the target motor systems [1]. This function would be achieved by the combinations of sequences of the enhancement of sustained inhibition and a release from the inhibition (disinhibition). Timing of when to start and to stop walking may be determined by this process. Second, basal ganglia may determine the degree of freedom” of the activities of the target motor systems by increasing and decreasing the sustained inhibitory drives. This process would be important in the steady-state control of the target motor systems during on-going movements such as the maintenance of postural muscle tone and rhythmic limb movements during walking. [4]. Therefore the basal ganglia may provide template of “spatial-temporal contrasts” and “degree of freedom” for the target motor systems. Because the basal ganglia receive cognitive and volitional signals from the cerebral cortex and emotional signals from the limbic system, the basal ganglia would convert volitional and emotional signals to motor behaviors that enable context-dependent adaptation.

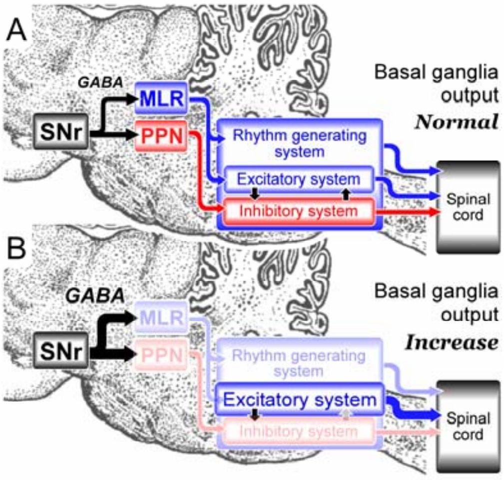

Fig.5. Summary of the present findings.

V. CONCLUSION

Basal ganglia output controls locomotion by modulating the activity of rhythm generating system as well as that of muscle tone control systems. An increase in the basal ganglia output may result in stop walking and increase the level of muscle tone. Disturbance of this mechanism may underlie as the basis of gait failure and rigidity in Parkinson disease when output from the basal ganglia is excessively increased.

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Exploration of the principle mechanism for generating adaptive locomotion on the basis of neurophysiological findings

Naomichi Ogihara, Yasuhiro Sugimoto, Shinya Aoi, Katsuyoshi Tsujita, and Kazuo Tsuchiya

I. INTRODUCTION

Animals are capable of generating locomotion adaptive to diverse environments by coordinately controlling complex musculo-skeletal systems. To elucidate the mechanisms underlying such intelligent adaptive behavior in complex biological systems, neuro-physiologists have attempted to directly capture the activities of locomotor neuronal networks in animal locomotion, while engineering scientists have tried to artificially emulate locomotion using mathematical models and robots based on control theory. However, neuro-physiological study by itself does not clarify how the nervous system adaptively functions as a dynamic system and coordinately interacts with the musculo-skeletal system during locomotion. Conversely, successful locomotor control of a simulation model or robot does not lead to an understanding of biological locomotor mechanisms, as the control laws are artificially constructed solely based on an engineering perspective independent of actual biological mechanisms. To truly understand the principles of adaptive behavior in animal locomotion, launching a new constructive locomotor study by integrating both of these approaches is indispensable.

The present study constructs a biologically plausible computer simulation model of animal locomotion by integrating physiological findings from the locomotor nervous system and the anatomy and the biomechanics of the musculo-skeletal system, with the aim of illuminating the dynamic principles underlying the emergence of adaptive locomotion in animals. Particular focus is placed on modeling quadrupedal and bipedal locomotion in Japanese monkeys, as Japanese monkeys are recently used for neurophysiological studies on adaptive locomotor mechanism [1-3]; thus direct comparisons between experimental data and simulation results are possible. Moreover, the transition from quadrupedalism to bipedalism in Japanese monkeys is regarded to some extent as a modern analogue of the evolution of bipedal locomotion and therefore is an interesting subject of research in the field of physical anthropology [4-8]. Furthermore, inferences gained by analyses of phylogenetically close animals such as primates might be more directly extensible to understanding of the human locomotor mechanisms [9,10].

In the current year, we construct a anatomically based whole body musculo-skeletal model of a Japanese monkey and conduct a basic study into prospect for mathematical modeling of the neuronal control mechanism of locomotion.

II. BIOMECHANICAL MODEL OF JAPANESE MONKEY

For a realistic representation of body motion, a fresh cadaver of an adult Japanese monkey (*Macaca fuscata*) underwent whole-body computed tomography, and a total of 1935 cross-sectional images with a pixel size of 0.75 mm and a slice interval of 0.5 mm were acquired. Some joints and segments such as hand and foot were re-scanned at a higher resolution (0.2mm) in order to obtain more detailed morphological information. Three-dimensional (3D) surface models of the

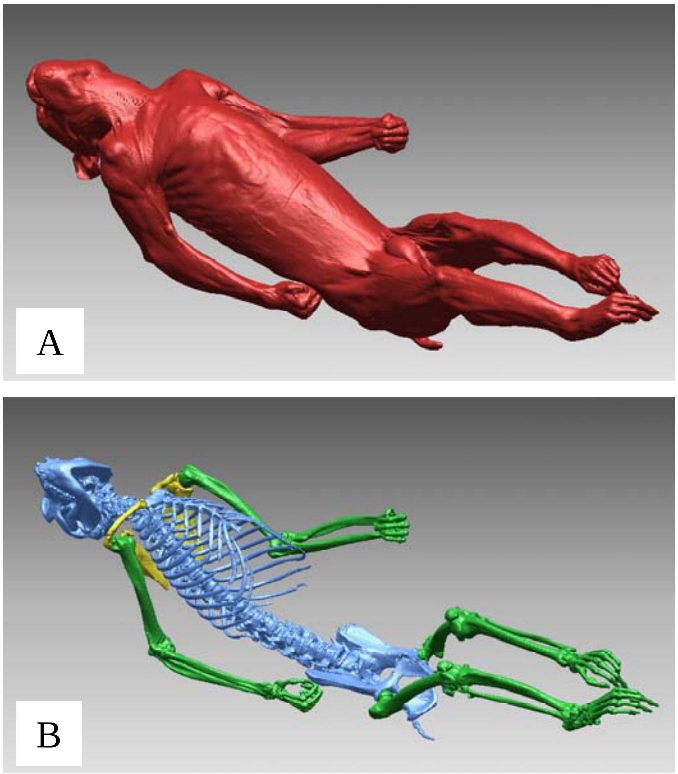

Fig 1. 3D representation of the musculo-skeletal system of a Japanese monkey. (A) 3D body surface data to calculate inertial parameters of each segment, (B) 3D skeletal data to define link configuration and muscle disposition.

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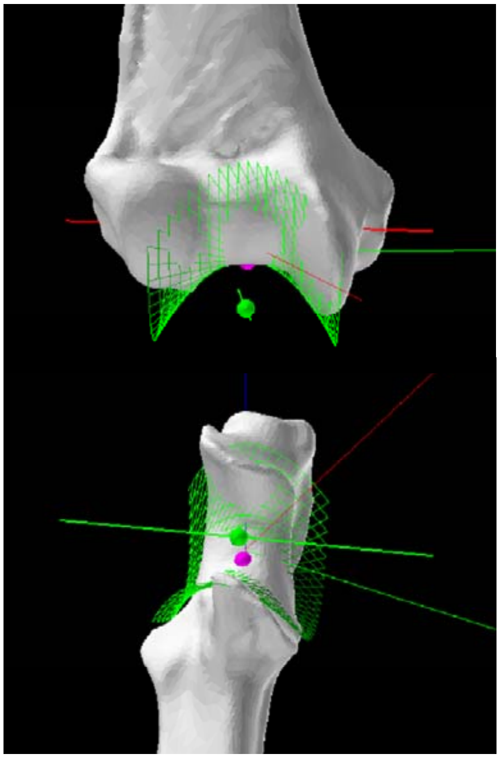

Fig 2. Approximation of joint articular surfaces using a quadric function. Distal end of the humerus and proximal end of ulna were both approximated by a hyperbolic paraboloid to estimate the joint location and rotational axes.

entire body surface and the skeletal system were then constructed (Fig. 1). For construction of the surface models, a biomedical image analysis software, Analyze 5.0, and a 3D modeling software, RapidForm2004, were used.

Bone coordinate system embedded in each of the bones was defined by principal axes. Shape of each joint surface was then approximated using a quadric surface to determine the axis of rotation and joint location as in Figure 2. Joint surfaces adjacent to each other were articulated based on this approximation.

The kinematic skeleton of the Japanese monkey was thus mathematically described as a chain of 20 links connected by revolute joints as illustrated in Figure 3. Joints connecting trunk segments (head, thorax, lumbar, and pelvis) were represented as a 3 degree-of-freedom (DOF) joint. The scapula is usually modeled to be immobile with respect to the thorax, although the relationship between the scapula and forelimb is functionally equivalent to that of the femur and hindlimb, thus representing an important element for propulsion [11,12]. A new approach was thus used to mathematically model translational motion of the scapula along the rib cage guided by the clavicle and muscles using 3 revolute joints (Fig. 3). Shoulder (glenohumeral), elbow, radioulnar, and wrist joints were modeled as 2, 1, 1, and 2 DOF joints, respectively. Hip, knee and ankle joints were represented as 3, 1, and 2 DOF joints, respectively. Therefore, total number of DOF of the skeletal system was 45. As a result of morphologically accurate description of the joint kinematics based on the quadric function approximation, rotational axes of the joints do not coincide with the bone coordinate axes.

In order to obtain inertial parameters of each segment, such as mass, position of the center of mass, and inertia tensor, the 3D body surface was divided into segments. A 3D CAD software, Autodesk Inventor 10, was used to calculate the inertial parameters. The density of the body composition was assumed to be 1 g/cm^3. This resulted in the body mass of 10.0 kg, nearly equal to the average body mass of adult male Japanese monkey.

The equation of motion of the model is derived as

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{h}(\dot{\boldsymbol{q}},\boldsymbol{q}) + \boldsymbol{g} - \boldsymbol{\alpha}(\boldsymbol{q}) + \boldsymbol{\beta}(\dot{\boldsymbol{q}}) = \boldsymbol{T} + \boldsymbol{\Phi} \tag{1}$$

where $\boldsymbol{q}$ is a vector of translational and angular displacement of the middle trunk segment and joint angles, $\boldsymbol{T}$ is a vector of joint torques, $\boldsymbol{M}$ is an inertia matrix, $\boldsymbol{h}$ is a vector of torque component depending on Coriolis and centrifugal force, $\boldsymbol{g}$ is a vector of torque component depending on gravity, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$

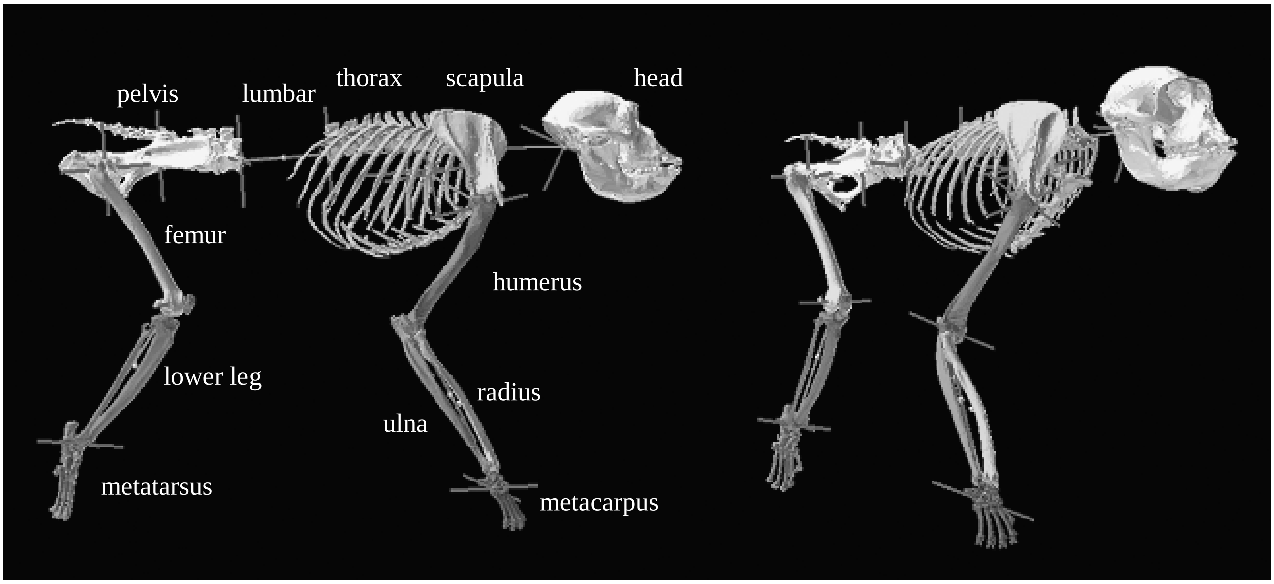

Fig 3. Kinematic description of the whole body skeleton of a Japanse monkey as a chain of links. Only right fore- and hindlimb are shown.

Fig. 4. Dissected forelimb of a Japanese monkey

are vectors of elastic and viscous elements due to joint capsules and ligaments (passive joint structure) which restrict ranges of joint motions, and $\boldsymbol{\Phi}$ is a vector of torque component depending of the ground reaction forces acting on the limbs, respectively.

III. MUSCLE MODEL

To mathematically describe the path of each muscle and the associated capacity to generate force, the fresh cadaver of a Japanese monkey was dissected (Fig. 4). The points of origin and insertion for each muscle were observed, and mass and fascicle length were systematically recorded to calculate physiological cross-sectional area (PCSA). From this dissection, the path of each muscle was defined using a series of points connected by line segments. Joint torque $\boldsymbol{T}$ generated by a vector of muscular forces $\boldsymbol{f}$ is given by:

$$\boldsymbol{T} = \boldsymbol{G}^T \boldsymbol{f} \tag{2}$$

where $\boldsymbol{G}$ is a moment arm matrix, element of which is determined by geometrical relationship between the direction of a muscular force and the corresponding joint rotational axis. Each muscle generates force by receiving a stimulus signal from a corresponding motoneuron to generate motion. Maximum force for each muscle is assumed to be proportional to the PCSA. Mechanical properties of muscle such as force-length and force-velocity relationships are also taken into consideration, as these intrinsic properties of muscle seem to facilitate autonomous self-stabilization of cyclic motions in the musculo-skeletal system [13].

IV. NEURO-CONTROL MODEL

Animal locomotion, including that of primates, is generally accepted as being generated by a rhythm-generating neuronal network in the spinal cord known as the central pattern generator (CPG), with locomotion evoked by stimulus input from the mesencephalic locomotor region (MLR) in the brainstem [14-16]. However, the rhythmic signals produced by the CPG alone do not generate adaptive locomotion. Afferent proprioceptive information is also essential for generating locomotion, and must be mutually coordinated in the spinal cord to construct appropriate intra- and interlimb coordination [17].

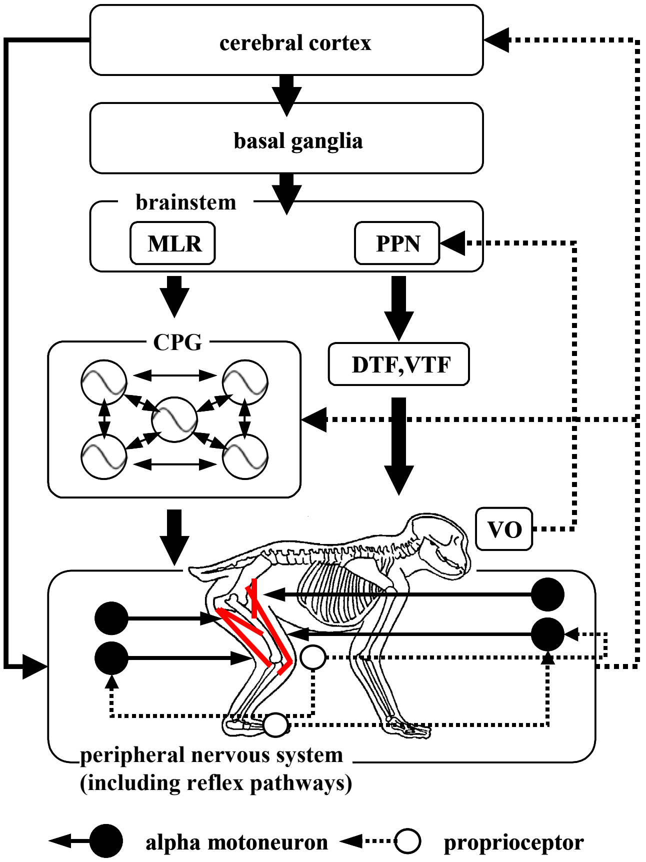

Fig. 5. Schematic diagram of the neuro-musculo-skeletal model of Japanese monkey to be constructed. See text for abbreviations. Solid line = efferent signal, dotted line = afferent signal.

It has been recently reported from neurophysiological studies on spinocerebellar neurons that sensory feedback signals from proprioceptors in muscles and joints are integrated in the spinal circuitry to encode global parameters of the limb movement, i.e., the orientation and length of the axis connecting most proximal joint and distal position of a limb (limb axis) [18-20]. This finding implies that the global parameters describing limb kinematics, along with individual local proprioceptive inputs, are actually utilized as important sensory inputs for locomotion. In addition, muscle activation pattern is also suggested to be generated primarily based on global kinematic parameters. Grasso et al. showed that kinematic pattern of human forward and backward locomotion was basically the same while muscle activation is quite different [21].

These results suggest that (1) state variables of the CPG may represent the global limb kinematics, i.e., the orientation and length of the limb axis and muscle activation patterns are generated based on them, and (2) phase dynamics of the CPG network is autonomously regulated by the mutual interaction among the CPGs as well as the global sensory information, in order to adapt to various environments and cope with external perturbations. Therefore, in this study, the CPG is hypothesized to be an oscillator that generates the orientation and length of the corresponding limb axis, and the spinal circuitry of interneurons somehow generate muscle activation patterns based on the output signal of the CPG.

Moreover, the neuronal mechanisms controlling body posture play an important role in the generation of robust locomotion. Basically, body orientation and force equilibrium are controlled by tone in the limb muscles, and this tone is regulated by the pedunculopontine tegmental nucleus (PPN) in the brainstem through the dorsal tegmental field (DTF) and ventral tegmental field (VTF) (Fig. 5). In this study, this tone system is also hypothesized to utilize the global kinematic parameters for control; DTF/VTF encodes degree of stiffness of the limb axis and the spinal circuitry of internurons generates muscle activation patterns according to its activity.

Both the PPN and MLR receive inputs from the basal ganglia to integrate posture and locomotion and to initiate and terminate locomotion in a coordinated manner [22,23]. The cerebellum also seems to play a crucial role in this process, as this region is where multi-modal sensory information from the vestibular organ (VO), proprioceptors and exteroceptors is integrated, and balance and locomotion are greatly disturbed in decerebellate animals [24]. Therefore, integrated control of posture and locomotion in the basal ganglia-brainstem-cerebello-spinal system is envisaged as providing the basis of adaptive locomotion. Such neuro-control model of adaptive locomotion is constructed based on these physiological findings, and the model is verified by reproducing some experimental data on mesencephalic and decerebellate cats using simulation techniques.

V. CONCLUSION

Based on the anatomical data obtained by the computed tomography and dissection, a whole-body musculo-skeletal model of a Japanese monkey was constructed. In addition, we conducted a basic study for mathematical modeling of the neuronal control mechanism of locomotion. Such a physically realistic musculo-skeletal model may reproduce actual mechanics and dynamics of the body system during locomotion.

We hope to reach the dynamic principles underlying the emergence of adaptive locomotion in animals by analyzing the behavior of the neuro-musculo-skeletal dynamics recreated in a computer from a system engineering point of view.

ACKNOWLEDGMENT

The authors sincerely thank Prof. Hideki Endo, Primate Research Institute, Kyoto University for allowing us to dissect the specimen.

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

Koh Hosoda, Hiroshi Kimura, and Kousuke Inoue

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. In this report, we discuss on the lower control architecture for realizing reactive adaptive locomotion for each 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.

We investigate robots that have many degrees of freedom, snake-like robots, quadruped robots, and biped robots. 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. In this report, we discuss on research results in 2005, which mainly focus on the lower control system for each modality.

II. SERPENTINE LOCOMOTION

Snakes has long and narrow bodies and, by curving the bodies, they generate physical interaction between bottom and side of their bodies and surrounding environments to realize purposive movement. Living snakes exhibit locomotion in various environments including hard ground, sandy ground, underwater and tree branches (Fig. 2). The mechanism of such locomotion is essentially different from legged animals. Therefore, new knowledge about the distinction between mobiligene dependent on locomotion form and one independent, by revealing what part is common in different locomotion forms.

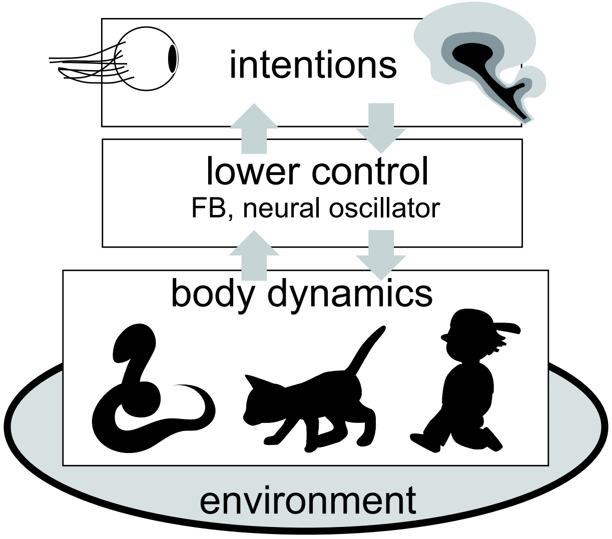

Fig. 1. Overall architecture for adaptive locomotive agents

Fig. 2. Locomotion in various environments in living snakes

A. Generation of adaptive meandering locomotion by CPG

Until this research project started, using existing snake-like robot (Fig. 3), we realized decentralized controller (Fig. 4) of meandering locomotion by implementing a decentralized control system mimicking locomotion pattern generation with CPG in spinal cord in living creatures[1]. In the current year, we focus on physical interaction between the bottom of the robot and the ground as the sensory information given to CPG controller. We developed sensors to measure this interaction (Fig. 5) and aimed at adaptation by CPG controller by the use of force information obtained by the sensors.

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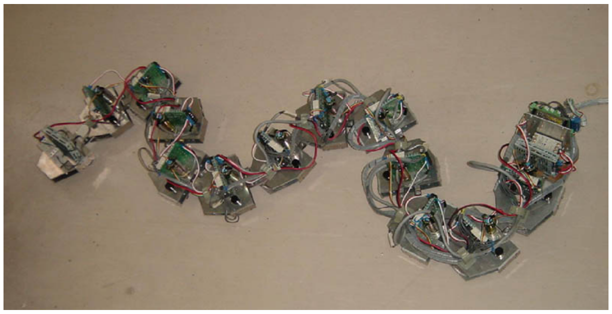

Fig. 3. Snake-like robot

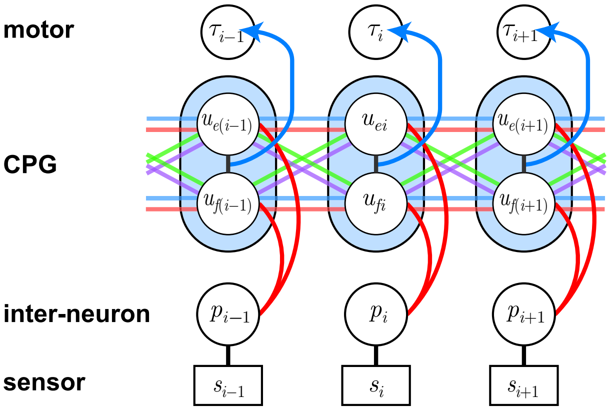

Fig. 4. Decentralized controller based on CPG

So far, we made clear that the characteristics of the sensory input during meandering locomotion of the robot is different from simulation based on Coulomb friction model (Fig. 6). Presently, we are modeling this characteristics and obtaining adaptive controller parameters according to realistic sensor model.

B. Investigations about snake biology

From this year to the next year, we are investigating anatomy and neuron-physiology relating with snake locomotion. In this year, through participation in biology seminars sponsored by this priority area, we investigated the state of basic physiologic studies concerning general animals. From now, we will start investigation about snakes by visiting researchers and laboratories specializing snakes.

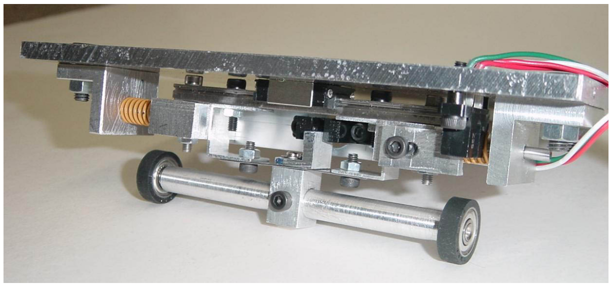

Fig. 5. Sensor to measure friction and normal force

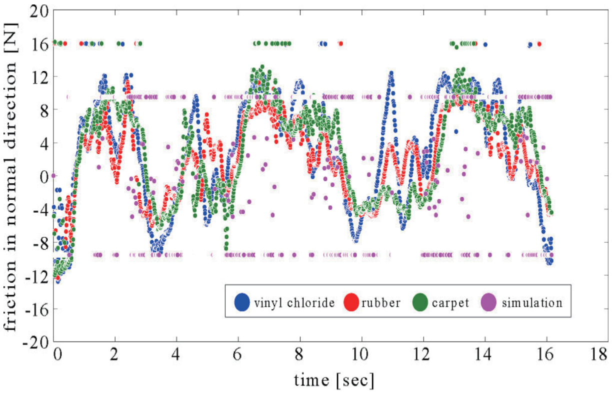

Fig. 6. Sensor pattern during meandering locomotion

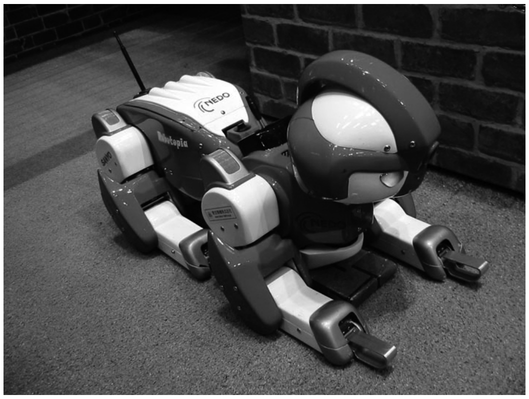

Fig. 7. Tekken 4: a dog-type servive robot exhibited at Aichi expo

C. Conceptual design of a robot mimicking musculoskeletal system of snakes

In the next year, we will develop a snake-like robot mimicking musculoskeletal structure and muscle characteristics of living snakes. In this year, we are conceptually designing the robot by physical simulations with parallel computers and preliminary experiments of actuators bought using the fund.

III. QUADRUPED LOCOMOTION

Quadruped locomotion is the normal mode for mammals. Not like Serpentine locomotion, it relies on dynamics of the phisical robot as well as friction. 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

Intending a dog-type service robot in future, we developed a self-contained quadruped robot named "Tekken3&4"(Fig. 7). 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[2].

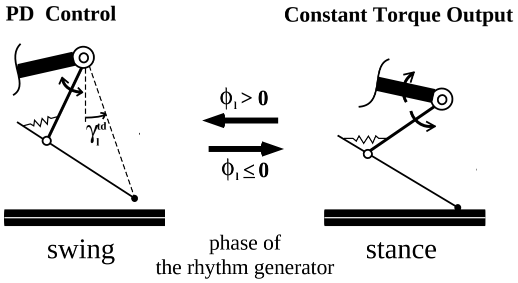

Fig. 8. Control diagram for running. $_i$ means the output phase of the rhythm generator of the i-th leg.

B. *Running on irregular terrain*

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

Since it is difficult to accurately measure the total energy of the system in a practical application, we use 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.8). The DFC is applied to both the rhythm generator and the torque generator. The DFC method not only stabilizes the running around a fixed point, but also results in the transition from standing to steady running and stabilization in running up a small step.

The effectiveness of the proposed control method is validated by simulations and experiments using a quadruped named "Rush". 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.

IV. 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], [3], [4].

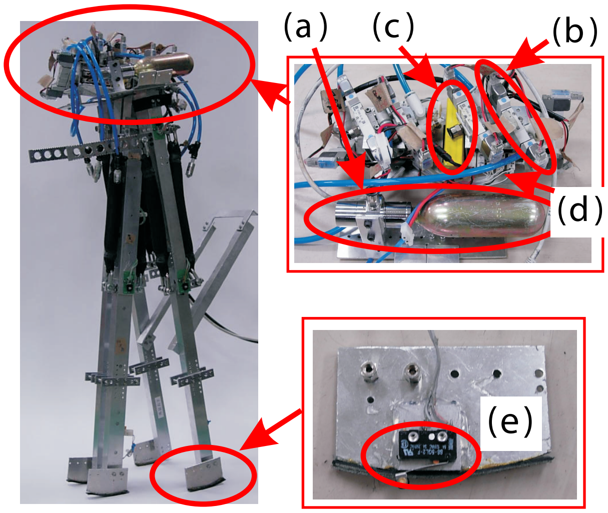

Fig. 9. A biped robot "Que-Kaku" driven by McKibben artificial muscles. (a) CO2 bottles, (b) electromagnetic valves, (c) electric cell, (d) micro computer with amplifier, and (e) round foot and touch sensor

A. *Stabilization of Biped Walking with Pneumatic Actuators against Terrain Changes*

Humans are supposed to utilize its joint elasticity to realize smooth and adaptive walking. Although such human-like biped walking is strongly affected by the terrain dynamics, it was not taken into account in robotic bipedalism since it is very difficult to model the dynamics formally. Instead of modeling the dynamics formally, we propose to estimate the relationship between actuation (air valve opening duration) and sensing (touch sensor information) by real walking trials, and to stabilize walking cycle by utilizing it. In Fig. 9, we show a biped robot used for the experiemtns. It has 3 DOF: one for the hip and two for knees. All joints are antagonistically driven by a pair of pneumatic actuators. In Fig. 10, we show the outline of the ballistic control for the pneumatic actuated biped. Fig. 11 shows the obtained relation between the valve oepning duration and swing duration observed by the touch sensor information. As indicated in the figure, the relation on linoleum is linear, and that on carpet is also linear, but these two are different. This observation indicates that the robot can distinguish linoleum or carpet while walking on a terrain. The resultant behavior of the robot changes depending on the material of the terrain. This obviously shows that the resultant behavior of the robot emerges from interaciton between the body (robot dynamics), the controller (valve opening duration), and the environment (material of the terrain).

B. *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. 12, we show photos of the biped robot. The sketch Fig. 13 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. The leg has a 1-DOF hip joint, a 1-DOF knee

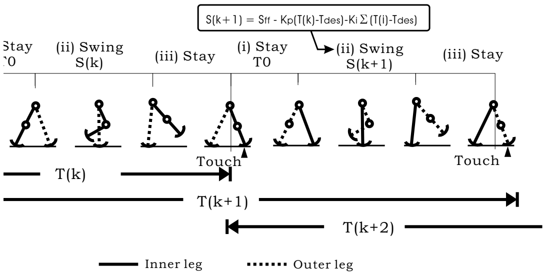

Fig. 10. Walking pattern and basic idea of a controller

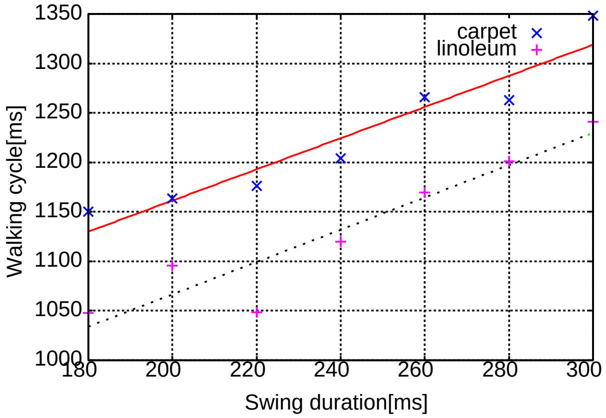

Fig. 11. Relation between the valve oepning duration and swing duration observed by the touch sensor information

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.

V. 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.

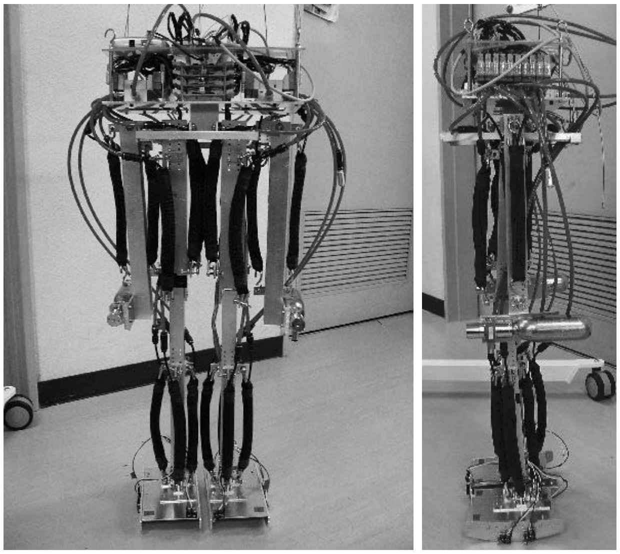

Fig. 12. A 3D pneumatic actuated walker “Pneu–Man”. It has 10 joints with 10 pairs of McKibben artificial muscles, totally 20 muscles. CO_2 bottles are attached to tips of arms for balancing.

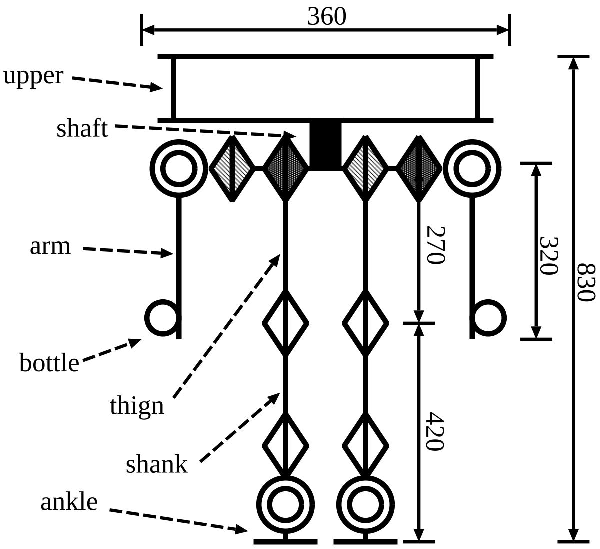

Fig. 13. A sketch of the 3D walker “Pneu–Man”. The swing joint of left arm is physically connected to the right hip joint, and that of right arm to the left hip joint.

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Group C: Elucidation of mechanisms underlying social adaptation

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1. Introduction

All animals on the earth adapt to survive in changing environment. They have acquired nervous systems through the evolutional process as a function to respond to changes of their surroundings. The nervous system consists of the following three parts, that is, a sensory system to search the environment, a central nervous system to integrate and process information, and a motor system to elicit a coordinated motion of the body. In that sense, the nervous system can be described as an organ dealing with communication and control. It is important to understand the mechanism underlying adaptive behaviors for getting some insights into the evolution of animals. Moreover, it also gives us a possibility to clarify the mechanism for information processing and network design in the animals' nervous system, and apply that knowledge to the future information sciences and engineering sciences. For this purpose, we are trying to extract a common design principle for various functions of the animal.

2. Aims

Society has an aspect as a part of their environment. Animals are capable to behave adaptively in their social environment as interacting with other individuals. Each species has survived by organizing their own "society" based on interaction, cooperation and competition with others. Group C is trying to uncover the mechanism to make such adaptive social behaviors possible.

Group C01: Systematic understanding of real time selection of behavior pattern (Hitoshi Aonuma, Hokkaido University; Ryohei Kanzaki, The University of Tokyo)

The aim of Group C01 is to clarify the neural mechanism underlying animals' social behaviors, such as recognition, interaction and communication among individuals, and organization of a society.

Group C02: Constructive understanding of the mechanism for formation of sociality in insect (Jun Ota, The University of Tokyo; Hajime Asama, The University of Tokyo; Kuniaki Kawabata, RIKEN)

Animals can be considered as a multiagent system acquiring very sophisticated functions for adaptation and adjustment to their environments. The aim of Group C02 is to elucidate mechanisms for adaptation dealing with the animal behavior as a model system.

Group C03: Principle of the formation of insects' sociality under the different stages of complexity (Daisuke Kurabayashi, Tokyo institute of Technology)

The interaction among individuals or neuronal modules, which is closely related to a switching of the behavior, can be dealt as a network. The aim of Group C03 is to understand the adaptive behavior from the aspect of the structural and functional characteristics of the networks.

3. Achievements

Our ultimate goal is to elucidate the mechanism of social adaptation in animals. The term of "society" has a very wide meaning. We found that there is a difference between the meaning of "sociality" in biology and that in engineering. Thus, we first defined the "sociality" by the following three points. a) Existence of the individuals that can change their behavioral pattern depends on their own experiences of interaction between others: we call this ability as "sociality", here. b) More than one individual are existed at the same location, and inter-individual interactions among them change the behavioral pattern. c) An order in the group is formed as a result.

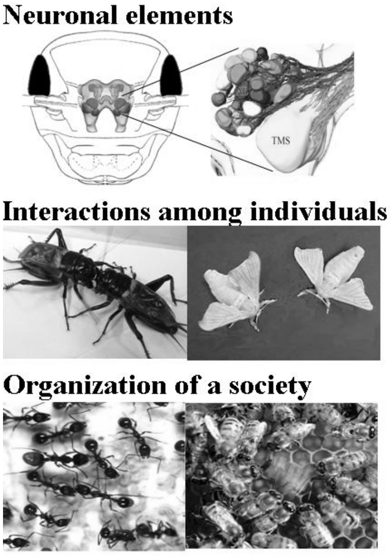

Fig. 1 Investigation of social behavior in insect from cellular level, individual behavior level and social community level.

From this standpoint, we are studying the mechanisms of adaptive behavior in the social environment using insects as model animals, whose neuronal function (cellular level) and behavior (behavioral level) are relatively easy to analyze (Fig. 1).

Since the nervous system in vertebrates consists of many numbers of neurons, it is quite difficult to discuss the relationship between their behaviors and neuronal functions. For example, a human brain consists of about 10^{12} neurons. On the other hand, insect nervous system has only 10^{6} neurons as a whole, and the numbers of the neuron in a brain is only about several tens of thousands. In the planned research group, the mechanism underlying inter-individual interactions and switching of the behavior are investigated in the cellular and behavioral level using insects, in which it is relatively easier to discuss the relationship between their behaviors and neuronal functions.

Social insects, such as ants or honeybees, have a society in which they have a clear division of labor and a social hierarchy (caste). On the other hand, solitary insects, such as crickets or silkworm moths, maintain their group by inter-individual interactions mediated by pheromones.

Group C01 has studied the neuronal mechanisms for pheromone behavior in crickets and silkworm moths, especially focused on the effect of the contact experiences with other individuals. In crickets it has been shown that a fighting behavior of males is one of pheromone behaviors, and a loser changes its aggressiveness in its second encounter to other males. Moreover, nitric oxide and biogenic amines are suggested to play a crucial role for neural mechanism underlying pheromonal information processing and the memory of fighting experiences. Group C01 is now trying to construct a simulation model for behavior of crickets together with Group C02 (Fig. 2, see below).

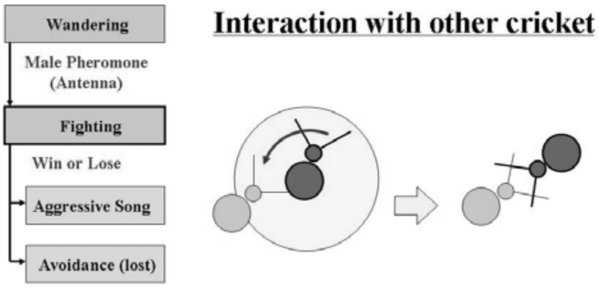

Fig. 2. Constructing of a simulation model of cricket behavior in a social population.

Group C02 is constructing models for cricket behavior based on the behavioral experiments using male crickets. A computer simulation model concerning about the relationship between behavior and density effect was suggested so far. Now Group C02 attempts a biological qualification and reasonable adjustment for the model together with Group C01. The model could mimic the establishment of a dominant individual depends on the density of the arena. The behavioral change by various disturbances, such as a new male, females and/or foods, should include the model as a next step. Besides, a construction of the model for brain function related with aggressiveness of the crickets is also planed for the future.

Group C03 is carrying out a research about the neural network and the inter-individual interaction from the aspect of network structures (Fig. 3). Especially, the performance of the network with several oscillators, each of which represents a region of insect brain, was examined. If a shortcut existed within the network of oscillators, the network performance changed from a limit cycle oscillation to a quasi-periodic oscillation. In fact, gaseous neurotransmitters such as nitric oxide have a function like a shortcut in the actual neural system. Group C01 has already showed that the nitric oxide in brain has an important role for the mechanism of switching of the behavior.

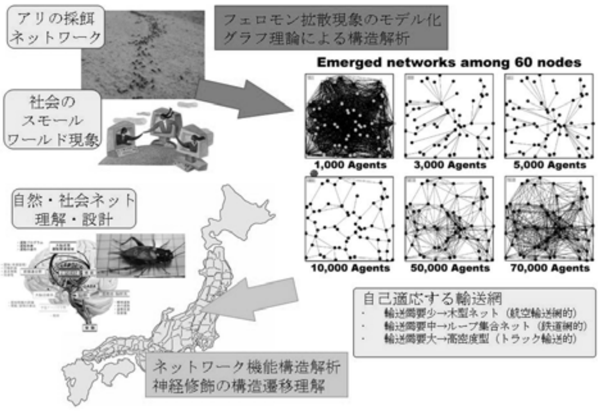

Fig. 3. Understanding of structural and functional characteristics of networks.

Future perspective

For understanding of socially adaptive behavior, it is important to clarify the switching mechanism of the behavior based on the recognition of others and/or interaction with others. Based on this idea, the planed research groups are studying the inter-individual interaction and its neural mechanism by biological and engineering approaches. To simplify the experimental system, solitary insects are used for the materials. However, for the better understanding of the social adaptation, we also need the knowledge about other factors of social behavior, such as division of labors, sharing of knowledge and organization of a society. From the next year, we will try to elucidate the mechanism of social adaptation by different level of approaches collaborating with the proposal research groups.

Systematic understanding of neuronal mechanisms for adaptive behavior in changing environment

Hitoshi AONUMA, Hokkaido University, Ryohei KANZAKI, The University of Tokyo

Abstract: **Formation of sociality and adaptation in a society are based on individual interactions. In this project, we focus on pheromone behavior in insect such as cricket and silkmoth to understand how animals show adaptive behaviors depending on changing circumstances including society. Insects use species specific pheromone as a communication signals. Neuronal mechanism of pheromone behaviors can be a good model system to investigate the neuronal mechanisms of adaptive behaviors in social interactions. We also focus on NO/cGMP cascade in insect brain. NO system must be one of the most important systems that mediate adaptive behaviors. Based on results from biological experiments, we collaborate with engineering groups to establish model systems to reveal mechanisms of adaptive behavior in society.**

I. Introduction

One of the common goals of biologists and engineering researchers seems to understand how nervous systems adapt animal behaviors to changing external environments including society. Animals have evolved nervous systems as an adaptation mechanism throuogh long history of the life. Animals perceive several kinds of signals from external world and adjust behavior to their environments by choosing and switching program in the central nervous system. Animals do not always respond same way to the same external stimuli. The state of central nervous system must be dependent on their experiences as well as internal and/or external conditions.

Insects have rather simple and identical nervous systems. Mammalians have about 10^{12} neurons in a brain. On the other hand, insect brain has about 10^{6} neurons and so it is called “micro-brain”. The micro-brain allows us to access each neuron easily, which accelerate us to investigate how animals introduce adaptive behavior from cellular level to behavior level analysis. We have here investigated mechanisms for formation of social hierarchy and adaptation mechanisms for individuals to exist in a society, which are both, emerged from individual interactions. We will combine biological (neuronethological) approaches and engineering approaches to understand how animals form social communities, how they learn and retain previous experience and how they change their behavior depending on the situation, which will help us to unravel the universal design of central nervous systems.

II. Aim

The aim of our project is to unravel the mobiligence in a society by understanding how animals adapt themselves in a society. To understand how animals establish social communities, we have investigated 1) how animals show adaptive behavior in the changing environment, in particular, social communities, 2) how they recognize and distinguish each other (individual interaction), 3) how they divide labor and share knowledge. As a first step, we have focused on mechanisms that animals alter their behaviors in order to respond to the demands of changing circumstances.

Insects have identical nervous systems and provide us good model system to resolve our questions. Pheromone behavior must be one of the greatest model systems. Most of pheromone behaviors in insects have been thought to be hard-wired: a behavior that could be turn on and off but with no plasticity. For example, male moths respond with a highly stereotyped response when they detect a pheromone plume released by females. However, some of pheromone behaviors are revealed to be modified by their previous experiences. Cricket aggressive behavior is an example of such pheromone behaviors. The response of males to the pheromone can be modified by the previous fighting experiences. Aggressive behavior and avoidance behavior in male crickets must be a great model system to investigate the neuronal mechanisms how animals adapt their behavior in changing circumstances.

Our biology group has started to collaborate with engineering groups to understand how animals alter their behaviors depending on the circumstances by combining biological approaches and engineering approaches. Engineering modeling technique must have great potential to unravel biological events.

III. Achievements

We have investigated neuronal mechanisms of adaptive behavior using cricket and silkmoth. Pheromone processing system in insect brain has investigated by several approach such as electrophysiological, biochemical and histochemical experiments. Combination of behavioral and physiological experiments and engineering modeling has processed with engineering groups.

III-1 Aggressive and avoidance behavior in cricket

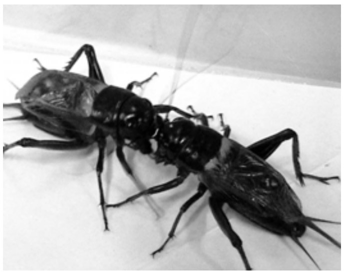

Fig. 1 Fighting behavior of male crickets.

Pheromones are chemical substances produced by animals to exchange individual information to evoke particular physiological event or to evoke particular behavior. Pheromone behavior of moth is one of the famous behaviors that are hard-wired behavior. Cricket aggressive behavior in males is also released by pheromones that are cuticular substances on the surface of male cricket bodies (Fig. 1). The aggressive behavior is found to be modified by previous fighting experience.

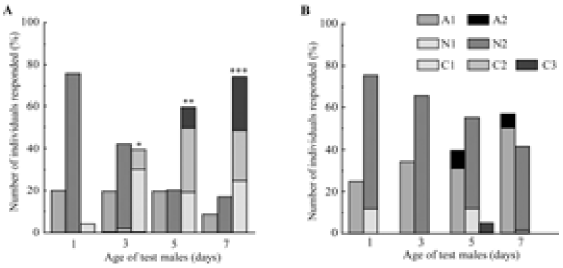

Fig. 2 Age dependent response of male crickets to cuticular substances. A: Response to female substances. B: Response to male substances. A1-A2: aggression N1-N2: no response or avoidance C1-C3: courtship. Nagamot et al (2005).

Major components of cuticular substances of cricket were hydrocarbons. Crickets perceive cuticular substances of opponent animals and distinguish their sex and state of their ages or condition etc. (Fig. 2). Antennae have receptors of cuticular substances. The pheromone information is first processed at antennal lobe and then the information will convey to mushroom bodies and lateral lobes (Fig. 3). Then motor program will be chosen to drive particular behavior. Male crickets respond with series of courtship behavior pattern to female substances. On the other hand, they respond with aggressive behavior to escalate fighting. These behavioral responses are found to be closely related with their ages after molting to be adult (Nagamoto et al. 2005). Pheromone processing system in the brain of crickets has not been clarified yet in detail, and so we are now trying to identify components of pheromone substances and neuronal circuits for the pheromone processing.

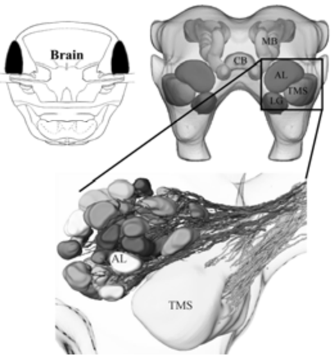

Fig. 3 Three dimensional reconstruction of cricket brain. AL: antennal lobe, CB: central body, LG: lobus glomerulatus, MB: mushroom body

III-2 Fighting experience and memory

Fighting behavior between male crickets escalate until opponents escape from them. Male crickets start antennal fencing if they contact to perceive cuticular substances each other. Then they open mandible to attack and bite each other. Once one of them is beaten, the dominant cricket starts aggressive song and subordinate one escapes from the dominant. The subordinate cricket retains beaten experience for 20-30min. If the inter-training interval of twice sequential fighting is more than 1hr, the subordinate crickets showed the aggressive behaviors again. However, most of subordinate crickets would not fight again if the inter-training interval was within 15min. This indicates that beaten experience remains as an aversion to fighting in subordinate. Furthermore, memory of beaten experience reinforce more than 12 hours if they are beaten several times in short time. The beaten experience of crickets changes their behavior from aggressive to avoidance. Subordinate crickets might learn to associate cuticular pheromone of opponents during the fighting. This suggests that beaten experiment is short term memory that can be shifted to be mid-term memory. This also strongly supports that pheromone behaviors of insects can be modulated by their experiences.

III-3 Pheromone processing and NO system in the brain

Neuroplasticity is one of important factors to elicit adaptive behavior. Motor program for a particular behavior must be selected while sensory information are processed and integrated. Thus mechanisms of neurotransmission and modulation during pheromone processing are necessary to be cleared. We have focused on functional roles of nitric oxide (NO) in nervous system. NO is a gaseous molecule produced from L-arginine by activation of NO synthase (NOS). NO diffuses three dimensionally at about 100 μm/sec through cell membrane. NO activates soluble guanylyl cyclase (sGC) in the target cells to increase second messenger cGMP level, which in turn regulates intracellular Ca^{2+} and modulates neurotransmission. NO has been thought to be closely linked with neuroplasticity and NO/cGMP signaling is demonstrated to be important factor of learning and memory.

NO/cGMP system is found in pheromone processing system in insect. NO-induced cGMP immunohistochemistry demonstrated neuronal circuit for pheromone processing in the silkmoth (Fig. 4). Silkmoth brain has macroglomerular that is a primary center of pheromone processing. Projection neurons from macroglomerular are strongly stained by NO-induced cGMP immunohistochemistry.

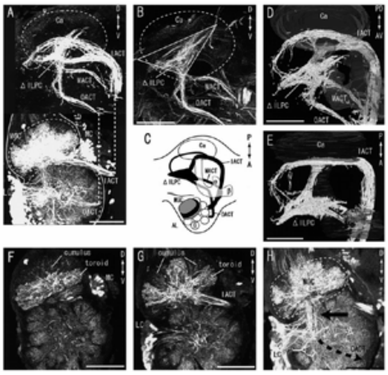

Fig.4 NO-induced cGMP immunohistochemistry revealed pheromone processing pathway of silk moth. (Seki et al. 2005)

Crickets also have NO producing neurons (Fig.5) and possible target cells (Fig. 6) in the brain. Cricket NOS is about 130kDa protein whose amino acid sequence has been partially determined (NCBI, AB245472). Universal NOS immunohistochemical experiment and NADPH-diaphorase histochemical experiment have demonstrated the distribution of NO releasing cells in the cricket brain (Fig. 5). Antennal lobe and mushroom bodies showed strong signals.

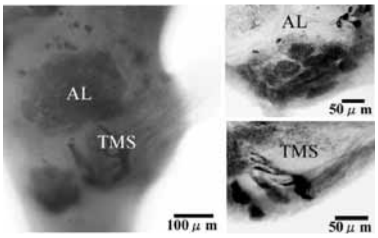

Fig. 5 NADPH-diaphorase histochemistry on cricket brain.

The possible target neurons in the cricket brain were also detected by immunohistochemistry by using antiserum against cGMP or sGC. SGC is heterodimer and its nucleotide sequence of α subunit and β subunit (NCBI, AB207897, AB207898) were determined. Biochemical experiment using ELISA and NO-induced cGMP immunohistochemistry demonstrated the accumulation of cGMP levels and distribution of possible targets of NO in the cricket brain.

Cricket antennal lobe does not have macroglomerular and pheromone processing pathway has not been cleared. Real time measurement of using NO-electrode suggests that antennal lobe continuously release NO about 150nM. Antennal stimulation using cuticular substances from male cricket increased NO level in the antennal lobe (not published) suggesting NO/cGMP system is involved in pheromone processing system in the cricket brain.

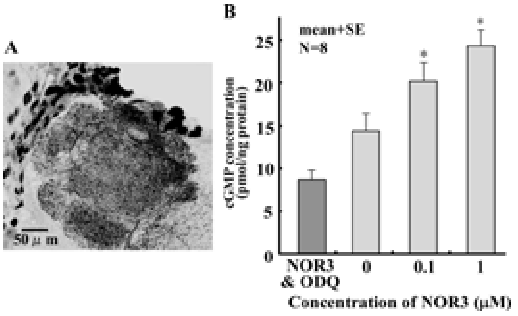

Fig. 6 Accumulation of NO-induced cGMP in the brain. A: NO-induced cGMP immunohistochemistry. B: Accumulation level of NO-induced cGMP in the brain.

III-4 Social hierarchy and NO/cGMP signaling

One of our major targets of our research is to understand how animals form social communities. Animal fighting establishes social hierarchy. Crickets also establish social hierarchy after fighting behavior. As a first step to investigate how animals establish social hierarchy, we have focused on how subordinate crickets retain previous beaten experience and change their behaviors.

Previous work demonstrates that NO signaling has important factor to retain associated memory (Matsumoto et al. 2006). Thus we examined the effects of NO signaling on evoking avoidance behavior in the subordinate crickets that was beaten at previous fighting. Head injection of NOS inhibitor L-NAME partly restrains retention of previous beaten memory in subordinate crickets (Fig. 7). However combination application of NO-donor NOR3 and L-NAME does not restrain the retention of memory. Furthermore, the effect of sGC inhibitor ODQ on the memory is similar to that of L-NAME. These results indicate that NO/cGMP signaling must be one of major factor to form memory of previous experiences and that this memory is closely link with to the formation of social hierarchy.

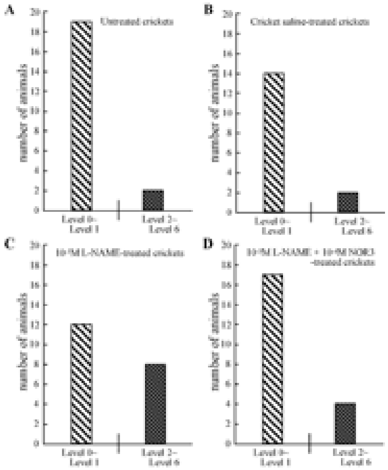

Fig. 7 Effect of NOS inhibitor on aggressive behavior of subordinate crickets. Aonuma et al. (2004)

III-5 Modulatory effect of NO

Morphological properties of insect antennal lobe are similar to that of olfactory lobe in mammalian. Therefore insect olfactory processing system and pheromone processing system provide us as ae experimental model system of mammalian olfaction. Our study shows NO/cGMP system has important role to mediate pheromone processing and olfactory processing. However, little has been known how NO modulate signal processing in the antennal lobe in insect. Pharmacological experiments demonstrated that NO donor and 8-br-cGMP increase activities of neurons in the antennal lobe of crickets (Fig. 8). NO scavenger PTIO and sGC inhibitor ODQ on the other hand decreased activities of antennal lobe.

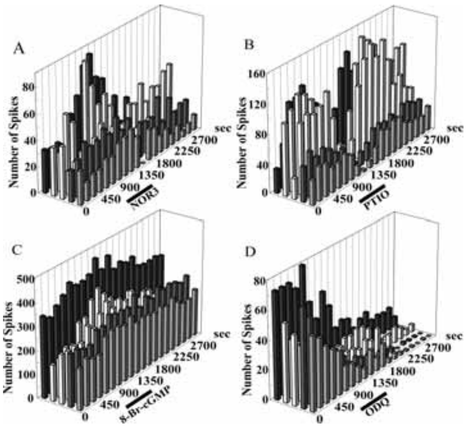

Fig. 8 Neuromodulatory effects of NO on the activities of antennal lobe. NO increased spontaneous spikes of neurons in the antennal lobe. A: Effect of NOR3. B: Effect of NO scavenger PTIO. C: Effect of cGMP homolog 8-br-cGMP. D: Effect of sGC inhibitor ODQ.

It is known that biogenic amine system is concern with animal behaviors. Aggressive and courtship behaviors in cricket are thought to be mediated by biogenic amine levels the central nervous system. Then we hypothesize that NO signaling system would drive biogenic amine system in the brain. To examine our hypothesis, we are investigating how NO regulate biogenic amines in the brain using pharmacological and biochemical technique. Biogenic amine levels in the insect brain are measured by HPLC-ECD. Head injection of NO-donor increases some kind of biogenic amines such as octopamine and serotonin but NOS inhibitor seems to decrease them in cricket brain (Aonuma and Murakami preparing). Biogenic amine levels in the silkmoth brain are also regulated by NO-donor and NOS inhibitor (Gatellier, Aonuma and Kanzaki, submitted). These results support our hypothesis although we need further experiments.

IV. Conclusion and future plan

Our study demonstrates that NO signaling system mediate insect pheromone behavior. Cricket fighting in males is released by cuticular pheromones and it has been demonstrated that released behavior can be modified after previous fighting experience. Cricket nervous system is thus good model system to investigate the mechanisms how animals change their behavior under changing circumstance of society.

Neuronal circuits for each behavior must be chosen in the central nervous system depending on the information they perceived from outer circumstances. Neuronal plasticity must be essential in the central nervous systems to introduce adaptive behaviors. Little is known about neuronal mechanisms how animals switch behavior. Aggressive and avoidance behavior in subordinate male crickets have a great potential to investigate the switching mechanisms of behavior program in the central nervous systems. This study is the first approach to investigate the functional role of NO-signaling in the switching mechanisms of nervous systems using insects. For further investigation, we now need to combine biological approaches and engineering approaches.

Behavioral modeling of crickets and multi-agent robot system design

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Abstract: Many studies have recently been made in the field of multi-agent robot systems. However, the design methodology of adaptive behavior of the multiple robots in the systems has not been thoroughly understood. In this report, we discuss how the adaptive behaviors were designed for the multi-agent robot systems in our former studies. Then, we discuss the importance of modeling of group behaviors of insects such as crickets. Finally, we present a plan for modeling of the crickets' behaviors.

Keywords: multi-agent robot systems, crickets, adaptive behavior

1. Research target of Group C02

Because various tasks are required of robots, cooperation becomes important. Currently, various studies have been undertaken on the issue of the accomplishment of tasks by multi-agent robots. The systems have been considered as a distributed autonomous system with two main characteristics: flexibility and adaptability. Although these characteristics have been the focus of many studies on multi-agent robot systems, design principle for assuring those characteristics has not been clarified yet.

On the other hand, most animate beings live through interacting with others. Those beings that scratch out lives in harsh environments can be called multi-agent systems that have advanced flexible and adaptive ability. It is important to study the adaptive mechanism of such kinds of living things.

In this study, we aim at modeling cricket’s behavior including a fighting behavior mainly among males or among females and a mating behavior among males and females, from the viewpoint of ecology and neuronal physiology. The reasons of selecting crickets as a model insect are (1) basic behavior-selecting mechanism causing the emergence of flexibility and adaptability is equipped with crickets. More concretely, programmed behavior with neuromodulation exists in crickets. (2) It is easy to analyze the cricket’s behavior because the mechanism of activating behaviors seems relatively simple. (3) The size of crickets is large enough to investigate neuronal structure. (4) Breeding of crickets is relatively easy.

This report summarizes the former multi-agent robot studies in Chapter 2. Research topic by utilizing crickets is explained in Chapter 3. The report is concluded in Chapter 4.

２．Overview of Multi-agent robot systems

２．１　General statement

Multi-agent robot systems can be useful for solving the problems that cannot be realized with single-robot systems or those that can be realized with single-robot systems but with tremendous costs (for example, huge task-realization time). The studies on the multi-agent robot systems have been made for several ten years. The concept of the systems is becoming important because of so many applications such as rescue systems, security systems, transport systems and production systems. This means that we need to consider robots not as single agents but as systems.

We define “construction of multi-agent robot systems that accomplish the given tasks” as a design problem of multi-agent robot systems. This design problem is very difficult to solve. The followings are the reasons: (1) we need to solve so many design outputs, they are, what kind of single robot functions are necessary to realize the given tasks, what kind of hardware devices are necessary such as sensors or actuators, what kind of behaviors should be embedded to the robots, what kind of learning or adaptive function is necessary, what kind of communication devices and contents are necessary among robots, whether some heterogeneity is necessary in the system or not, how many robots are necessary, and how much environmental design is needed for the robots to move efficiently. (2) In most cases, the relationship between the total system and the individual robot is not so simple because of the interaction between the individual robot. This makes the design problem very complicated and makes it difficult to discuss the robot’s motion from an analytical approach. This complicatedness is also caused by the fact that the robot exists in the real world with physical entity. The robots need to avoid each other in order to move to their own destinations. The function of multi-agent robot systems can be clarified when individual robots moves in a real world or at least with time-consuming simulations. The robot movement in a real world is very effective from the viewpoint of task realization because of expansion of active region, but on the other hand, it also makes it difficult to analyze the behavior. With the above discussion, general design principle for multi-agent robots has not still been established. In the almost same sense, we cannot have clarified how to emerge flexibility and adaptability in multi-agent robots. The present status of the studies on multi-agent robot systems are the followings: we are doing how to design interaction among robots with the simplified problem statement. This simplification is sometimes made by fixing some design parameters among huge ones.

２．２ Tasks of multi-agent robots

Multi-agent robots deal with many kinds of tasks. The task specification determines the level and kind of intelligence that robots need. Task classification of multi-agent robots is made in Table 1. It is natural to consider that behavior is essential for robots. Here, the robot tasks are categorized according to the various dimensions of the tasks and the numbers of tasks that are to be performed. (a) Dimension of the goal state: (a-1) point-reaching tasks are those in which the target is expressed with a specific goal configuration of the robot. The goal configuration is expressed as a specific point in the configuration space of the robots. (a-2) Region-sweeping tasks are those in which the target is expressed with a specific goal region. The target is to generate the trajectory of the robot covering the required region with the robot's sensing area, i.e., to generate a one-dimensional solution (trajectory) to complete a multi-dimensional goal. (a-3) Compound tasks are those tasks in which the above two types of tasks are combined. The second factor is the number of iterations of tasks, that is, (b-1) one time task, and (b-2) many time task. Ordinary tasks should be performed once only. Some tasks, however, must be performed many times. Here, "many times" means that we expect the effect of adaptation, learning, and self-organization to occur as a result of several trials.

Most multi-agent robotic tasks are included in Table 1. Tasks in the same class are similar in that the same behavior is required of the robots. Former studies in this field are surveyed based on these classes.

There are many studies of one-time tasks. Many of these studies in the categories assume the existence of perfect environmental model. One of the most fundamental topics is "motion planning of multi-agent robots," in which individual robots reach goal configurations from initial configurations while avoiding each other. The problem sometimes can be solved by utilizing a minimal distance problem solver in graph theory or the artificial potential field method. As for region-sweeping tasks, traveling salesman problem solver or generalized Chinese postman problem solver are frequently utilized.

Table 1: Task classification of multi-agent robots

	One-time	Many-times
point reaching	- motion planning -cooperative handling of a large object -pattern formation	coming and going between two positions
region sweeping	-sweeping -map generation	-periodical cooperative sweeping
compound	-cooperative transportation in unknown environments	-collecting objects/ foraging -robot soccer

As for the adaptable behavior that we are interested in, iteration of tasks becomes important. Some of our former studies will be introduced at the next section.

２．３ Iterative tasks

When a certain task should be executed many times, it becomes important to generate group formation of robots based on the learning capacity of individual robots. Several studies have been conducted on this topic.

Yoshimura et al. settled an iterative transportation task, as shown in Figure 1, in which the target of the task is to transport as many objects as possible from start to goal positions in an unknown environment [1]. All the robots should explore the environments efficiently and transport objects while avoiding recognized obstacles and other robots. The learning capacity of robots for generating adequate group formation was shown depending on both the characteristics of the objects (cost of handling over the object between two robots) and the disposition of obstacles. The final group formation of robots is determined with variation of the cost of handling over the object. When the cost is small, it converges to a "relay type," in which the objects are transported by the hand-to-hand delivery motions of individual robots. When the cost is large, the formation converges into a "loop," in which each robot transports an object from the start to the goal position within a loop.

Inoue et al. extended the above methodology to dynamically changing environments [2]. A three-phase methodology was propounded. It includes an environmental exploration phase, a path-generation phase, and a strategic phase. Here, they considered a trade-off between "searching for unknown environments" and "transport efficiency in the recognized environments" is considered.

An example in the class of "many-time" and "region-sweeping" tasks is patrolling of a dynamically changing environment (Fig. 2). This problem can be modeled as a Multiple Traveling Salesmen Problem (MTSP) by considering observation points as nodes in graph theory. Trevai et al. advanced a method to generate an exploration path in a restricted working environment [3]. The observation points are distributed in the environment, and they are

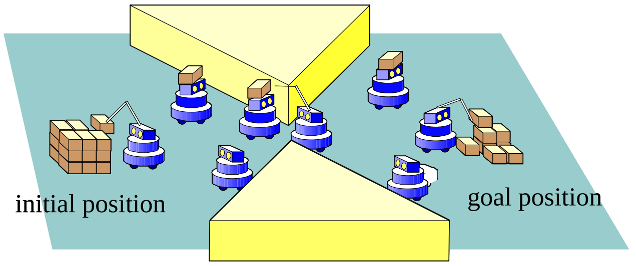

Fig.1 Iterative transport task by multi-agent robots

calculated by utilizing a reaction-diffusion equation on a graph proposed in [4]. Positions of these points can be moved in real time with respect to the recognized environmental information. By obtaining a result of the MTSP, robots can share their exploration regions efficiently within an environment. Because the derived solution is a set of closed-loop trajectories, the patrolling task is made continuously. In this study, adaptability is assured by changing the place of the observation points with the reaction-diffusion equation on a graph.

３． Future Research Plan

We aim at modeling cricket's behavior where several crickets exist in a certain bounded region. In this study, the focus is on clarifying of emerging principle of cricket's adaptive behavior. This means that we are going to model the behavioral transition of crickets, but aren't going to model more precise level, that is, locomotion of the cricket.

In concrete,

- Modeling of neuronal networks and neuronal network modules that realize the adaptive function
- Modeling of signal transmission among the modules and behavior generation mechanism that realize the above-mentioned function

As for the former topic, it is indispensable to introduce a neuromodulator model, which includes the effect of the geometrical placement of neurons in addition to the standard neural network model. It is important to evaluate the existing neuromodulator models and to select a good one. After that, the model will be improved by comparing the data of physiological experimental results of crickets (Fig. 3).

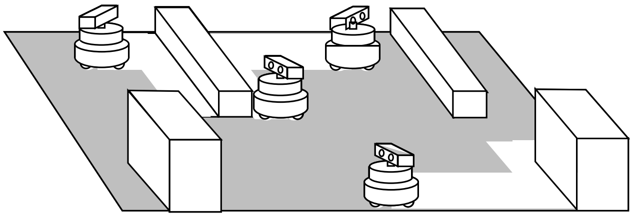

Fig.2 Iterative surveillance task of multi-agent robots

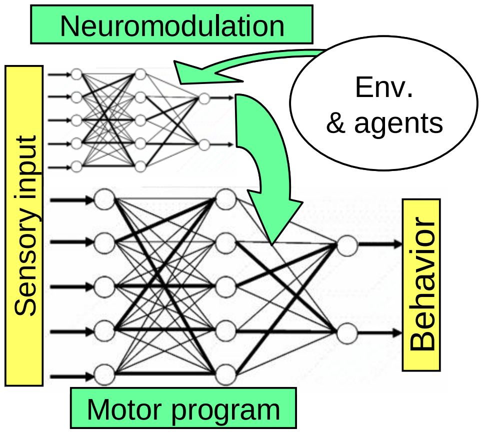

Fig.3 Neuronal modeling of a cricket

Especially, we are giving attention to the fighting behavior between the crickets and the function of NO (Nitric Oxide) as a major neuromodulator in the cricket's brain. Based on the hypothesis that adaptive behavior selection from behavior modules is realized by disinhibitory effect of NO, modeling such neural mechanism is being discussed. Here, disinhibition is to activate inhibitory neurons by inhibiting those neurons. In the central nerves, GABA (γ-amino acid) mainly works as a transmitter to inhibit synapse posterior-cells, and NO can inhibit GABA transmitting system. As a result, this means to inhibit synapse posterior-cells. Major program behaviors in the crickets' fighting behavior are aggressive behavior and avoidance behavior. We examined the basic architecture of the cricket's nervous system model based on the experimental knowledge of the relationship between those behaviors (Fig. 4).

As for the latter topic, we are going to create the simulator in which virtual crickets live. They introduce reactive behaviors that real crickets have and make physical interaction with other crickets. Fig. 5 and Fig. 6 show the real crickets. Fig. 7 (a) shows the behavioral model of the male crickets based on the observation results. Fig.7 (b) and (c) shows the snapshots of the created simulator. We are taking the following procedure:

1. Enumelate the cricket's behaviors that should be modeled in the virtual crickets.
2. Prepare the scalar function that expresses how the proposed model can reproduce the real cricket's behavior
3. Construct the behavioral of crickets in consideration of physiological knowledge about crickets and observation results.
4. Define several behavioral parameters that regulate the detailed behavior of the virtual crickets.
5. Derive the behavioral parameters that optimize the performance index in step 2 by utilizing an adequate optimization method.
6. Compare the behavior of virtual crickets and that of real crickets, and discuss the difference between them. Based on

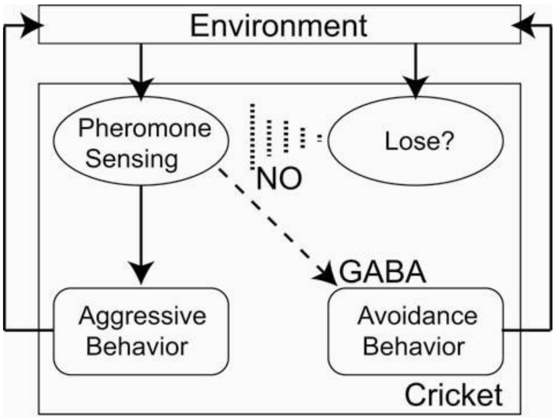

Fig.4 Overview of a basic behavior selection system by neuromodulator

the results, go back to step 1. In some cases, do additional observation of the cricket's behavior or additional behavioral experiments, and enhance the accuracy of the cricket's mode.

The above-mentioned procedure makes it possible to construct cricket's behavioral model. As for the performance index in step 2, we are thinking of the following things:

- We are going to check whether the behavior of the virtual crickets based on the proposed model includes some sense of rationality or not. That may be energy consumption of the crickets, or the quality or quantity of some resources in the working environments.
- We are going to evaluate the proposed behavioral model from the viewpoint of robustness to the disturbance such as environmental changes. For example, we can check whether the same situation can be maintained even if the number of the crickets has changed. One of the main difference between biological groups and artificial groups is robustness of the groups. Although the stability of the artificial groups is very low, that of biological ones is very adaptable and robust.

We may be able to obtain design methodology for adaptive multi-agent robot systems, by clarifying construction mechanism of cricket's groups.

4． Conclusion and Future Remarks

In this report, first we discuss the research direction of Group C02. Second, we discuss the former studies on adaptive behavior of artificial multi-robot systems. Last, we propose long-term research plan.

Fig.5 An actual cricket for the modeling

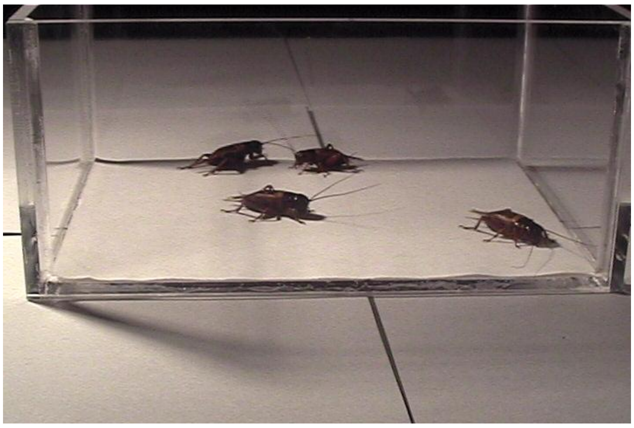

Fig.6 Four crickets in the cage

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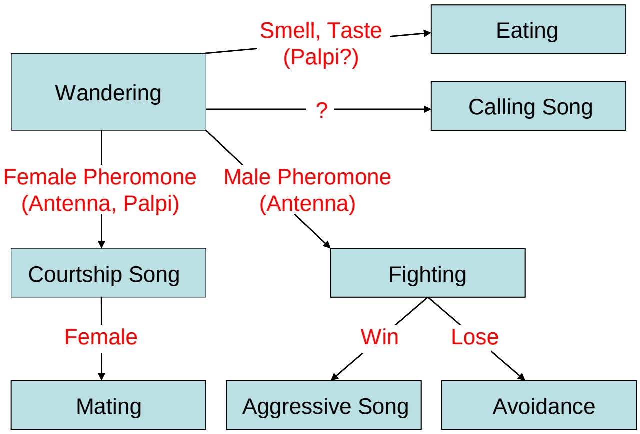
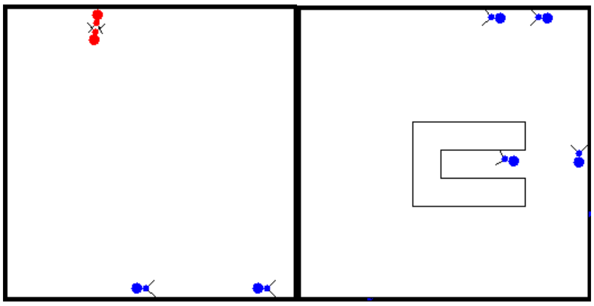


(a) Male cricket's behavioral model



(b) Four crickets in the simple environment

(c) Four crickets in the complicated environment

Fig. 7 Simulation environments

Analysis of Adaptive Behaviors Emerged by Functional Structures in Interaction Networks

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Abstract: Recent researches in animal brains showed an interesting explanation about transitions in crickets' attitude after fighting with other crickets. The result accounted that the changes in structures of neuron-network at crickets' brains controlled the attitudes. The structures of network have a strong effects for the behaviors like this. In this paper, a network built with nonlinear oscillators was dealt to study the effects of structure. The relationship between the characteristics of convergence about oscillators and the structure of network was confirmed. Then a concrete method for controlling the convergence states of oscillators was proposed.

Keywords: Graph Structure, Nonlinear Oscillator, Quasi-Periodic Oscillation

1. Introduction

Living creatures choose their behaviors adaptively depending on their surroundings and contexts. This accommodation is sometimes beyond individuals; the organs divide and share their functions to improve their yields, and moreover, they utilize environments as information source in order to govern the groups. The elements concerning this adaptation, such as organs, environments, functions, are strictly connected. In this paper, we deal with the interactions among these elements as networks and analyze the emergence of adaptive behavior from the perspective of network structure.

We can present three different levels of the interaction networks. (1) Networks inside the internal body; i.e., the interactions among neural cells and physical parts. (2) Networks among individuals; i.e., the interactions generated through moving and contacts. (3) Networks between groups and environments. We expect that the seeking common structural properties leads us enable to elucidate the emergent mechanism of adaptive behavior and re-construct natural systems into artificial systems.

In this paper, we analyze an elemental model of mechanisms for variating patterns in (1) networks inside the internal body.

2. Model and the Evaluation

2.1 Modeling of network structure

Resent researches have been reported that not only the effect of synapse connections, but also that of diffusion by gas substance has important roles for the function of neurons$^{1)}$.

We suppose this workings of gas substance as the changing of neural structure with a new connection of neuro-transmitter, and compose a graph with nonlinear oscillators as the mathematical model. Besides, we analyze the relationships of structure and convergence of this graph model to supply engineering interpretations of the function of the gas substance.

At first, we show the existence of relationship between structure and convergence by manipulating structural characteristic values in simulation. Moreover, by observing the behavior of the graph consists of two kinds of oscillators, we propose a concrete method to control convergent states via structural operation.

2.2 Oscillator and the model

In order to confirm that network structure affects the behaviors of system, we compose a graph allocating nonlinear oscillators to vertices, as a network model. We use well-handled, van der Pol (VDP) oscillators as nonlinear oscillators.

$$\ddot{x}_i - \epsilon_i(1 - x_i^2)\dot{x}_i + \omega_i^2 x_i = 0. \tag{1}$$

In addition, connected nonlinear oscillators cause forces for synchronization. We use the following equation to express this interaction force:

$$x_i(t+1) = \tilde{x}_i(t) + \lambda \left\{ \frac{1}{N_i(t)} \sum_{j=1}^{N_i(t)} x_j(t) - x_i(t) \right\}. \tag{2}$$

Here, $\tilde{x}_i(t)$ represents the renewed state by only eq.1 after time t.

2.3 Quasi-periodic oscillation

The phase of non-linear oscillator like a VDP has a certain stable orbit, called limit-cycle(fig.1(a)). However, the orbit of the oscillator that applied excessive forces draws an irregular periodic line as fig.1(b).

This unsteady motion is called quasi-periodic oscillation. In order to evaluate convergent tendency, we use the ratio of the number of quasi-periodic oscillators against the number of entire oscillators, named "quasi-periodic-ratio".

2.4 Characteristic values of graph structure

We analyze the values for evaluating graph structure and the manipulation methods for changing the character of topology.

CPL CPL is the size of graph: average of distances between any two points. We use the CPL as the parameter to characterize the graph structure.

If we express the number of vertices as N and the distance from a vertex v to any other vertices as $\bar{d_v}$, CPL becomes as following equation:

$$CPL = \frac{1}{N} \sum_{v=1}^{N} \bar{d_v}. \tag{3}$$

Shortcut In order to change the structural dispositions of oscillator graph, we use "shortcut" defined as follow:

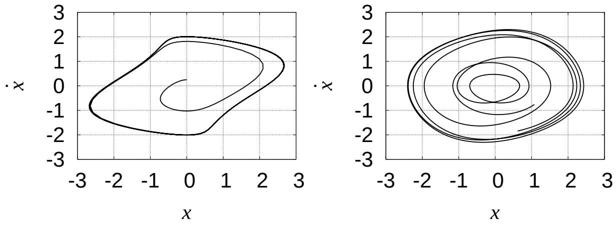
- Edge ij is shortcut if and only if the minimum distance of vertices i and j beyonds three, in occation that the edge ij is removed$^{2)}$.

In addition, we call the rate of current shortcut number against possible all shortcut number of graph as "shortcut-ratio".

3. Structural Transition and the Convergence

3.1 Shortcut additional ways and CPL

At first, we investigate the effect of several additional ways of shortcuts on structural properties. We compose oscillator network in the shape of first-order lattice as shown in fig.2, and provide shortcuts in the following three ways:



(a) Limit cycle (b) Quasi-periodic

Figure 1: Convergent states of oscillators

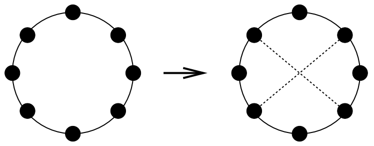


Figure 2: Addition of shortcuts

- **Random:** the random addition of shortcuts
- **Up-order:** the selecting addition of the nearest edge (CPL is the least sensitive.)
- **Down-order:** the selecting addition of the farthest edge (CPL is the most sensitive.)

In order to study the difference in convergence between additional ways of shortcuts, we carry out following simulation.

1. At first, we compose first-order lattice graph using 30, 60, 90 and 120 oscillators.

2. Next, we add shortcuts in the three ways of random, up-order and down-order on each oscillator networks.

3. Finally, we research the convergent states of oscillators comparing each graph structures, and count the quasi-periodic-ratio.

Here, ϵ and ω of each oscillators suppose to be 1.0, and we use oscillator states of 30000 step after simulation start as convergent states. Besides, initial phase of x and $\dot{x}$ are set randomly from -1 to 1.

We simulated 100 times and calculated the average of the rate of quasi-periodic oscillator number against entire oscillator number. Fig.3 shows the average of the quasi-periodic-ratio against shortcut-ratio. These figures suggest convergent states can change depending on the additional ways of shortcuts even their shortcut rates are same. Therefore, we can mention that structure of network dominates the convergent states together with the amount of shortcuts.

3.2 The effect of parameters of oscillator on convergence

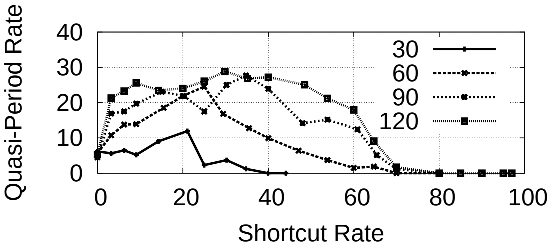
We look into the conditions that make oscillators quasi-periodic, to search for the control methods of convergent states by operation on structures.

The dynamics of ith connected oscillator is determined by following equation:

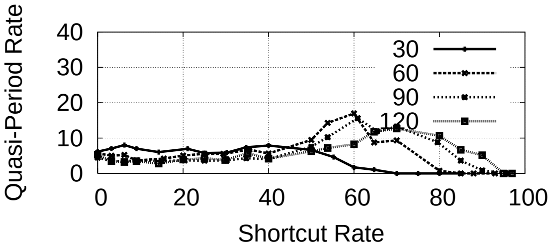
$$\ddot{x}_i - \epsilon_i(1 - x_i^2)\dot{x}_i + \omega_i^2 x_i = F(t). \tag{4}$$

Here, $F(t)$ represents the attracting force. If the frequency becomes Ω by this synchronize force, following relationship exists:

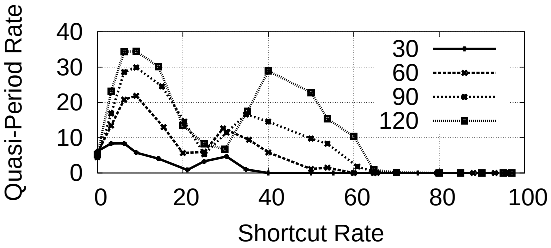
$$F(t) = a(t)\cos\Omega t + b(t)\sin\Omega t. \tag{5}$$



(a) Quasi-periodic-ratio (random-order)



(b) Quasi-periodic-ratio (up-order)



(c) Quasi-periodic-ratio (down-order)

Figure 3: The ratio of Quasi-periodic oscillation against shortcut-ratio

When vast oscillators are attracting each other, the motion of one oscillator can affect only slightly. Therefore, we can regard the motion of oscillators under attracting force as forced vibration with external force $F(t)$.

In the literature[3)], the convergent condition of VDP oscillators can be mentioned as follows. If the states of oscillators are decided by following equation:

$$\begin{aligned} x_i &= c_i(t)\cos\Omega t + d_i(t)\sin\Omega t \\ r_i^2 &= c_i^2 + d_i^2, \end{aligned} \tag{6}$$

and we use variables ρ and ζ,

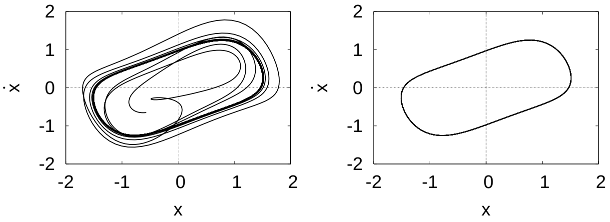
$$\rho(t) = \frac{r^2}{2} \tag{7}$$

$$\zeta^2(t) = \left(\frac{a}{2\epsilon_i\Omega}\right)^2 + \left(\frac{b}{2\epsilon_i\Omega}\right)^2 \tag{8}$$

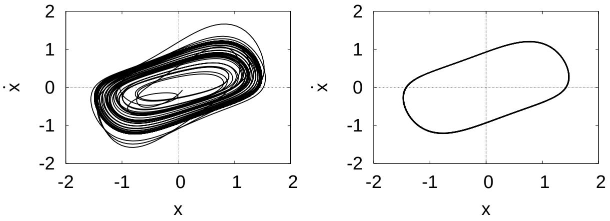
oscillators becomes quasi-periodic if ρ and ζ satisfy following conditions:

$$\begin{cases} \zeta^2 & > \frac{8}{27} \\ \rho & < \frac{1}{2}. \end{cases} \tag{9}$$

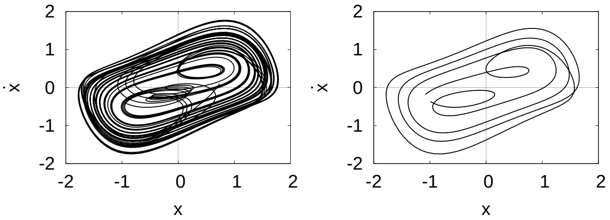
This condition shows that if we fix the variation ϵ, Ω dominantly affects on the convergent states.



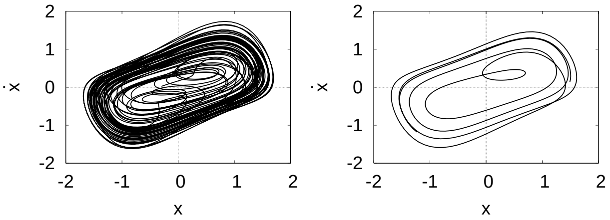
(1a) 0→30,000 step (1b) Last 3,000 step
(1) N=4 : Limit cycle



(2a) 0→30,000 step (2b) Last 3,000 step
(2) N=50 : Limit cycle



(3a) 0→30,000 step (3b) Last 3,000 step
(3) N=5 : Quasi-periodic



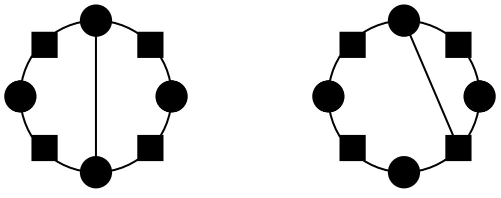
(4a) 0→30,000 step (4b) Last 3,000 step
(4) N=51 : Quasi-periodic

Figure 4: Oscillator numbers and convergent states

The primal factor to determine the value of Ω is frequency ω. Especially, we can mention that the value of Ω is between maximum and minimum ωs of all oscillators. Therefore, if we consider the case that only two kinds of oscillators, which differ in ω, exist, we may alter the convergences with simple operation.

3.3 Convergence disposition of two oscillators

We constructed a first-order lattice shaped oscillator network in which two types of oscillators are arranged mutually. Each oscillator differs by ω. We investigated the relation between the number of oscillators and the convergence state of this system. At



(a) Odd-structure (b) Even-structure

Figure 5: Two types of shortcuts

this time, ϵ is fixed at 1.0, and the initial value of each oscillator is set randomly from -1.0 to 1.0, and $\lambda = 0.5$.

Charts in fig.4 are the transitions of phase states under simulation. The parameters of the oscillators are as follows. If the number of oscillators i is odd, then ω is 0.8, and if i is even, then ω is 1.2. Figures (a) show the phase states of the entire time (30,000 steps), and Figures (b) show only the last 3,000 steps. These simulation results indicate that an oscillator network with two types of oscillators has the following characteristics:

- N: even → limit cycle (Fig.4(1)(2))
- N: odd → quasi-periodic oscillation (Fig.4(3)(4)).

3.4 Control of convergence

Next, we create a control method using the property between odd- and even-numbered oscillator networks. The system that consists of an odd number of oscillators has connections between oscillators, whereas the even-numbered system does not. We can assume that this difference affects the convergence states.

We consider a system composed of eight oscillators and one shortcut (Fig.5). The square and circle symbols in Fig.5 represent two different oscillators. This system has two types of structures, labeled “Odd-structure” and “Even-structure”, according to the connection style of the shortcut. Only the “Odd-structure” has connections between identical oscillators.

In order to study the convergence characteristics of this system, we perform simulation as follows:

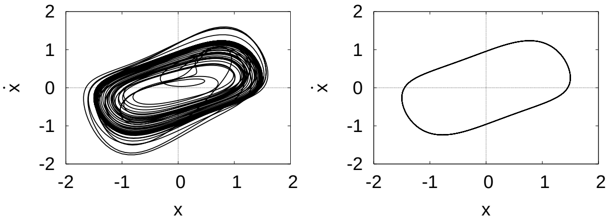
1. **0∼40,000 steps** : no shortcut
2. **40,000∼80,000 steps** : odd-structure
3. **80,000∼120,000 steps** : even-structure.

Here, $\epsilon = 1.0$ and initial values are chosen randomly from -1 to 1.

The simulation results are shown in fig.6. These figures indicate that the system with “Odd-structure” becomes quasi-periodic oscillation and that the system with “Even-structure” becomes limit cycle. Therefore, we can control convergence states as:

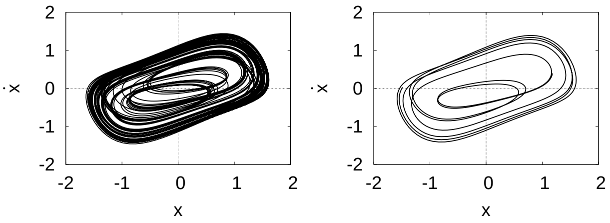
$$\text{limit cycle} \rightarrow \text{quasi-period} \rightarrow \text{limit cycle} \rightarrow \cdots$$

by structural manipulation using this system.



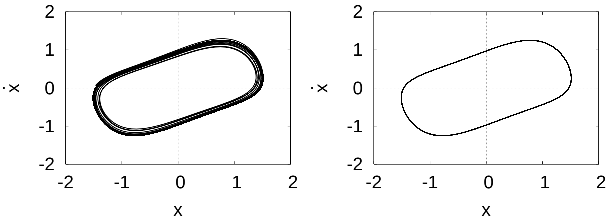
(1a) 0→40,000 step (1b) Last 4,000 step

(1) 0-40,000 step



(1a) 0→40,000 step (1b) Last 4,000 step

(2) 40,000-80,000 step



(1a) 0→40,000 step (1b) Last 4,000 step

(3) 80,000-120,000 step

Figure 6: Convergent control by structural change

4. Conclusion

In this study, we dealt with the adaptive behavior of organisms with oscillator network, inspired by the relationship of neuro-oscillators and gas substance, and investigated the changing method of synchronous states via only network structure.

We first constructed a graph that has oscillators in its vertices and confirmed that the convergent states of oscillators can change in accordance with the structure by simulation of gaining shortcuts. In addition, taking attention on eigen frequencies of oscillators, we clarified a simple characteristic to change convergence of the graph such as two kind of oscillators are connected alternatively. Finally, we proposed control method of convergence by operation on structure.

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Group Ｄ : Report on Common Principle of Mobiligence

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Abstract: In this note, the activity report of the Group D in 2005 is shown. The group has been organized for searching the common principle of Mobiligence. Concretely speaking, we show the considerations from the following three points. A. Walking principle in passive dynamic walking. B.Realtime shape control of the modular robot whose degree of freedom is big. C. Well-balance between control and mechanizm.

1. Introduction

In Group D, we mainly consider the concept of Balance as a common principle in Mobiligence. That is to say, we think that there exists some kind of feedback structure in Mobiligence of many situations (for example, GroupA, GroupB and GroupC). The result is expected to be reduced to the design principle of movement wisdom in the robot including the living thing.

In this year, we tried to approach Mobiligence fromt the following three approaches.

２．Approach Method to The Common Principle of Mobiligence

In this chapter, the report of the each group is shown.

A. Principle in Passive Dynamic Walking

We adopt the concept of "Delection of factor" as a key word for searching the common principle of Mobiligence. That is, as an effective method for understanding the complecated phenomenon, the approach adopted here is useful. Such method often called as "minimul design". Let us consider the minimul designhn in malking. As a start point, we consider the passive dynamic walking. Fig.1 shows the passive dynamic walker Quartet II (upper side of the figure.) and it"s model (law sides of the figure). The reasons why we try to treat the simple biped are the following.

(1) The movement of walking can be seen in not only robot but also human.

(2) Sice the passive walking phenomenon is stable, this must play an important part of walking mechanism.

We expect that a principle of Mobiligence must exist in the core of the principle of dynamic walking.

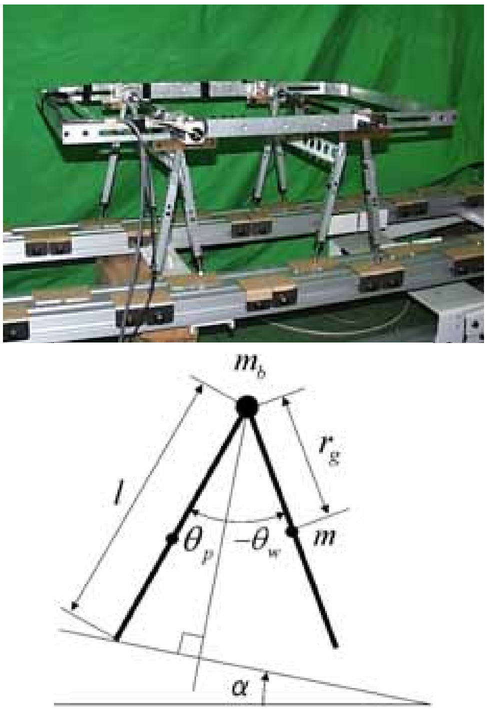


Fig. 1 Passive dynamic walking machine
(up QuartetII, down model)

We begin to walk by controlling all joints of our body in a few years. Then after a few years, we acquire a walking manner which is relaxed and has high energy efficiency. We can regard that the realization of the above situation is the passive walking machine. Passive walking machine is one of the realizations of the above situation. We think that in the passive dynamics walking there must be existed the principle of walking. The reason why we think in this way is the fact that the passive walking is stable. That is, we think that when we learn to walk we naturally refer the passive walking manner. Because, the passive walking has a high energy efficiency and stability. And we have the following hypothesis. That is, the natural does not like to hard work.

The interesting point here is to understand the stabilization mechanism of the passive walking phenomenon. As the partial answer, we had one results as follows. See Fig. 2. The block diagram in the upper part of the figure is a representation of the passive walking formulated as a discrete dynamical system. The lower figure in the same figure is the most important job in this sub-theme. That is, we found that the feedback structure in the Poincare map.

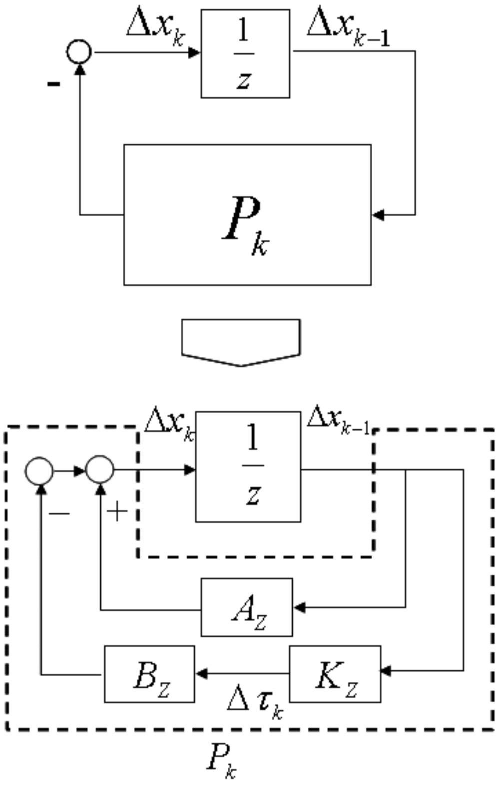


Fig. 2 Feedback structure in P.D.W.

For the feature works, we are going to construct a four-legged passive dynamic work We expect that this research

B. A Robotic Case Study with a Modular Robot

Traditionally, robot control has been done typically by "highly precise control algorithms": the position of each movable body part is accurately determined at any time with vast amount of computation. This, however, causes serious problems, particularly in terms of adaptability and energy efficiency. Despite such undeniable drawbacks, this approach seems to be still dominant in robotics.

On the other hand, an extreme alternative approach has been gaining a lot of attention recently. A good instantiation is the passive dynamic walker, driven only by exploiting the intrinsic dynamics of its mechanical system. However, mechanical system is not everything, just as control system is not everything. This will automatically lead to the following conclusion: control and mechanical systems cannot be designed separately due to their tight interdependency; "well-balanced" coupling between control and mechanical systems should be considered.

Based on the consideration above, this study is intended to deal with the interplay between control and mechanical systems, and to investigate *emergent phenomena* expected, stemming from this interplay. More specifically, we intend to clearly answer the following questions:

- How should control and mechanical systems be coupled?
- Does a "well-balanced coupling" between control and mechanical systems exist?
- What does the coupling between control and mechanical systems "appropriately" designed bring to resulting behavior?

Since this research field is still in its infancy, it is of great worth to accumulate various case studies at present.

In light of these facts, we have intensively dealt with a two-dimensional modular robot -called "Slimebot"- consisting of many identical mechanical modules, as a practical example. A significant feature of this study is that we have focused on one of the most primitive yet flexible locomotion, *amoebic locomotion*, in the hope that this "primitiveness" and the large number of system components allow us to consider the questions above effectively.

In order to realize an emergent control method that enables Slimebot to change its morphology in real time according to the situation encountered, the coupling between its control and mechanical systems should be carefully designed. To this end, we have particularly focused on a "functional material" and a "mutual entrainment", the former of which is used as a spontaneous connectivity control mechanism between the modules, and the latter of which plays as the core control mechanism for the generation of locomotion and ensures the scalability. Simulation results indicate that the proposed algorithm can induce amoebic locomotion, which allows us to successfully control the morphology of the modular robot in real time according to the situation without losing the coherence of the entire system.

Fig.3 shows representative simulation results obtained under the condition of 100 modules (left) and 500 modules (right). Here, the task of Slimebot was to move upward. The thick circles in the figures are obstacles. Interestingly, the way of negotiation with the environment seems significantly different according to the number of modules: Slimebot consisting of 100 modules passes though the obstacles by narrowing the width of the entire system, whilst the one consisting of 500 modules negotiates its environment by enclosing the obstacles. Note that these behaviours are not pre-programmed, but are totally emergent.

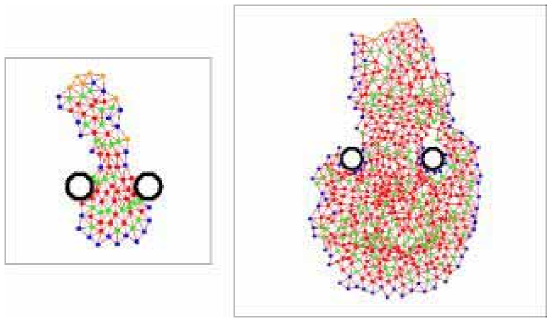


Fig.3: Snapshots of the representative simulation results. Left: 100 modules. Right: 500 modules.

Fig.4: A photo of the prototype of Slimebot (two physically-connected modules are shown).

In order to verify the feasibility of our proposed method, experiment performed with real physical modular robot is significantly important. A prototype of a module for Slimebot is represented in Fig.4 (two physically-connected modules are shown). We are planning to construct more than 20 modules for the experimental verification. We also plan to intensively investigate the interaction dynamics between the control system, the mechanical system, and the environment, by exploiting a continuum approximation technique.

C. The Well-Balance between Control and Mechanisms

Yet another approach to understanding the Mobiligence is through well-balanced utilization among the intended control efforts in and the physical naturalness of the motor systems. Task examples given in Figure 1 are a Japanese-style tea whisking and a stone mill grinding. These two tasks are performed through similar and circular basic movement while the human exhibit dissimilarity of task strategies in the each which results from human’s task/environment adaptation in muscle tonus around the joints of the arm.

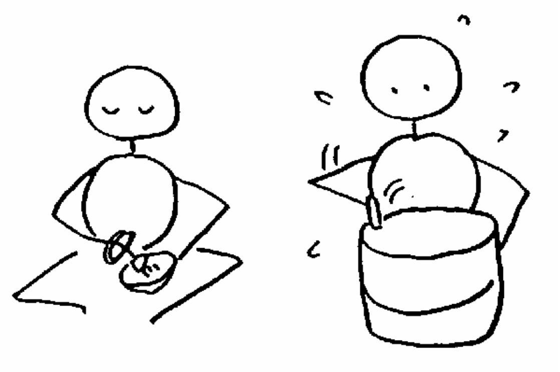


Fig.5. A *Tea Whisking* and a *Stone Mill Grinding*.

Simulation examples obtained by using manipulator model can exhibit the same as humans. In the simulations, the upper arm, the forearm, and the hand of human are modeled as a three-link manipulator as in Figure 2, and the

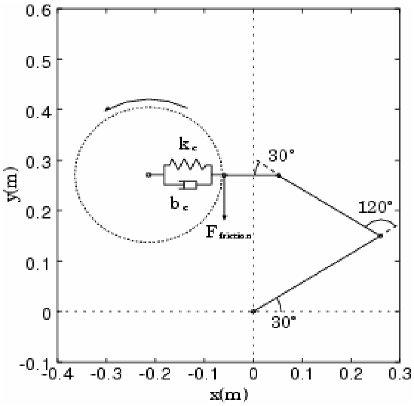
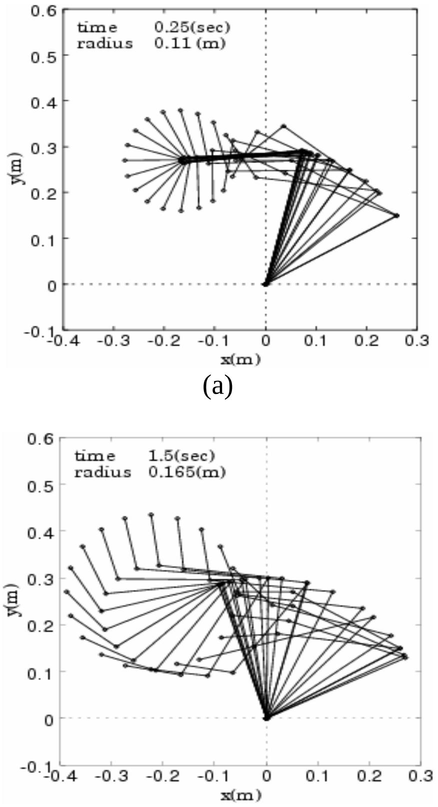


Fig. 6. Task Model.

different type two tasks, tea whisking and stone mill grinding, are both modeled as a circular movement of the tip of hand.

Then the “arm” motions in the two types of task can be seen as in Figure 3 (a) and (b), which both are quite close to human’s one.



(a)

(b)

Fig. 7. Loci of arm motion.

Such motion strategies have been previously understood in such a way that, letting q_e denote the joint equilibrium positions, K and B denote the viscoelasticities around the joints, and the joint driving torques of a arm be expressed by

$$\tau = K(q_e - q) - B\dot{q} \qquad (1)$$

the dissimilarity of the task strategies are simply the results of an proper adjustment of q_e, K, and B to meet the geometrical and statics characteristics of the tasks and to obtain the arm motion with least energy consumption in dependence on its dynamical property. This understanding is, therefore, from some optimization/embodiment viewpoints, and expressed sort of necessary conditions only in development of such motion strategies.

Meanwhile, expression of such motion strategies is also suggesting that, taking a well-balanced adjustment among q_e, the motor control from upper-level central nervous system, and K and B, an expression of the muscle tonus, as well as taking well-balanced relation with the utilization of the intrinsic physical naturalness of the motor systems through interaction with the task environment, dissimilar motion strategies can be developed for similar but different tasks/environments. This also suggests that Equation (1) as an expression of muscle-tonus-motor-control model may give one of the sufficient conditions for such motion strategies.

3. Conclusion

In this note, we report the activities of Group D in the 2004. The points are the following.

P1) We try to consider the two extreme problems. One is the simplest problem, and the other is the most complicated. The example of the former one is the passive dynamic walk, and the example of the later one is the modular robots. If we could understand the two extreme problems, we can realize reasonable robots in the real world.

P2) We set a basic principle. That is, “the nature does not like a hard work”. Say the other words, many varieties of motions can not be unnatural. Because, the living thing has evolved putting many years. This is a concept of Dynamics Based Control.

P3) It is very important to think as the following. Mechanism suited for control is important. But, in the same time Control suited for mechanism. When the two factors meet at a nice meeting point, the highest performance of the controlled system can be obtained. This is the concept of Well-Balance.

Members

■=Director 🟦=Planned Research Groups

	Name	Organization	
Director	Hajime Asama	The University of Tokyo	■
A01	Masafumi Yano	Tohoku University	🟦
A01	Kazuhiro Sakamoto	Tohoku University	🟦
A01	Yoshinari Makino	Tohoku University	🟦
A02	Koji Ito	Tokyo Institute of Technology	🟦
A02	Toshiyuki Kondo	Tokyo Institute of Technology	🟦
B01	Kaoru Takakusaki	Asahikawa Medical College	🟦
B01	Masahiko Inase	Kinki University	🟦
B01	Shigeru Kitazawa	Juntendo University	🟦
B01	Kazuya Saito	Asahikawa Medical College	🟦
B01	Taizo Nakazato	Juntendo University	🟦
B01	Katsumi Nakajima	Kinki University	🟦
B01	Futoshi Mori	Yamaguchi University	🟦
B01	Dai Yanagihara	The University of Tokyo	🟦
B02	Naomichi Ogihara	Kyoto University	🟦
B02	Kazuo Tsuchiya	Kyoto University	🟦
B02	Yasuhiro Sugimoto	Kyoto University	🟦
B02	Shinya Aoi	Kyoto University	🟦
B03	Koh Hosoda	Osaka University	🟦
B03	Kousuke Inoue	Ibaraki University	🟦
B03	Hiroshi Kimura	The University of Electro-Communications	🟦
B03	Katsuyoshi Tsujita	Osaka Institute of Technology	🟦
C01	Hitoshi Aonuma	Hokkaido University	🟦
C01	Ryohei Kanzaki	The University of Tokyo	🟦
C02	Jun Ota	The University of Tokyo	🟦
C02	Hajime Asama	The University of Tokyo	🟦
C02	Kuniaki Kawabata	RIKEN	🟦
C03	Daisuke Kurabayashi	Tokyo Institute of Technology	🟦
D01	Koichi Osuka	Kobe University	🟦
D01	Akio Ishiguro	Nagoya University	🟦
D01	Xin-Zhi Zheng	ASTEM	🟦
Evaluation	Shinzo Kitamura	Kobe University	🟦
Evaluation	Ryoji Suzuki	Kanazawa Institute of Technology	🟦
Evaluation	Shigemi Mori	National Institute for Physiological Sciences	🟦
Evaluation	Rolf Pfeifer	University of Zürich	🟦
Evaluation	Sten Grillner	Karolinska Institutet	🟦
Evaluation	Avis H. Cohen	University of Maryland	🟦

Publications, Awards

Publications

1. Naohiro Saito, Hajime Mushiake, Kazuhiro Sakamoto, Yasuto Itoyama, Jun Tanji, Representation of Immediate and Final Behavioral Goals in the Monkey Prefrontal Cortex during an Instructed Delay Period, Cerebral Cortex, 15, 10, 1535 - 1546, 2005
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Awards

1. 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems Best Paper Award: “Don't Try to Control Everything!: An Emergent Morphology Control of a Modular Robot”, Akio Ishiguro, Masahiro Shimizu, and Toshihiro Kawakatsu
2. Best Paper Award to the IEEE International Workshop on Robot and Human Interactive Communication 2004 (RO-MAN 2004) in Kurashiki, Japan (Awarded on 14th, August, 2005) : “Deskwork Support System Based on the Estimation of Human Intentions,” Yusuke Tamura, Masao Sugi, Jun Ota and Tamio Arai

Activity Record

Date	March 8th, 2006
Place	Kashiwa New Campus, The University of Tokyo
Title	IAS-9 (Intelligent Autonomous Systems-9) Organized Session
Schedule	OS:Mobiligence1 Session Chair: Prof. Hajime Asama WE2C-1 13:30-14:00 A Modular Robot That Self-assembles "Akio Ishiguro, Hiroaki Matsuba, Tomoki Maegawa, and Masahiro Shimizu" WE2C-2 14:00-14:30 Autonomous Robust Execution of Complex Robotic Missions "Paul Robertson, Robert Effinger, and Brian Williams" WE2C-3 14:30-15:00 Emergence of Small-world in Ad-hoc Communication Network among Individual Agents "Daisuke Kurabayashi, Tomohiro Inoue, Akira Yajima, and Tetsuro Funato" WE2C-4 15:00-15:30 Parametric Path Planning for a Car-like Robot Using CC Steers "Yossawee Weerakamhaeng, Takashi Tsubouchi, Masamitsu Kurisu, and Shigeru Sarata" OS:Mobiligence2 Session Chair: Prof. Jun Ota WE3C-1 15:50-16:20 Self-organizing Planner for Multiple Mobile Robot Exploration and Patrol "Chomchana Trevai, Jun Ota, and Tamio Arai" WE3C-2 16:20-16:50 Adaptive Action Selection of Body Expansion Behavior in Multi-robot

	System Using Communication "Tomohisa Fujiki, Kuniaki Kawabata, and Hajime Asama" WE3C-3 16:50-17:20 From Mobility to Autopoiesis: Acquiring Environmental Information to Deliver Commands to the Effectors Antonio D'Angelo and Enrico Pagello

Date	December 4th, 2005
Place	Conference Hall, Hokkaido University
Title	Mobiligence'05 (Internatinal Symposium)
Schedule	9:30- 9:45 Opening Session I (Chair: Prof. Masafumi Yano, Tohoku University, Japan) 9:50-10:10 Emergence of Adaptive Motor Function through Interaction among the Body, Brain and Environment Prof. Hajime Asama (The University of Tokyo, Japan) 10:10-10:40 Research Activities and Plan in Group A: Environmental Adaptation Prof. Koji Ito (Tokyo Institute of Technology, Japan) 10:40-11:10 Research Activities and Plan in Group B: Physical Adaptation Prof. Kazuo Tsuchiya (Kyoto University, Japan） 11:10-11:20 Coffee Break Session II (Chair: Prof. Ryokei Kanzaki, The University of Tokyo, Japan) 11:20-11:50 Research Activities and Plan in Group C: Social Adaptation Prof. Hitoshi Aonuma (Hokkaido University, Japan) 11:50-12:20 Research Activities and Plan in Group D: Common Principle Prof. Koichi Osuka (Kobe University, Japan) 12:20-14:00 Lunch Invited Talk I (Chair: Prof. Kaoru Takakusaki, Asahikawa Medical College, Japan) 14:00-15:00 Mechanisms for selection of basic motor programs - a role for striatum and pallidum (tentative) Prof. Sten Grillner (Karolinska Institute, Sweden) Invited Talk II (Chair: Prof. Akio Ishiguro, Nagoya University, Japan) 15:00-16:00 Morphological computation: connecting brain, body, and

	environment Prof. Rolf Pfeifer (University of Zurich, Switzerland) 16:00-16:15 Coffee Break Invited Talk III (Chair: Prof. Hiroshi Kimura, University of Electro-Communications, Japan) 16:15-17:15 Implementation of learning in intelligent motor systems Prof. Avis H. Cohen (University of Maryland, USA) 18:00-20:00 Banquet (Sapporo Century Royal Hotel)

Review comments of six steering committee members

Prof. Avis H. Cohen
Prof. Rolf Pfeifer
Prof. Sten Grillner
Prof. Shinzo Kitamura
Prof. Ryoji Suzuki
Prof. Shigemi Mori

Review Comments of

Prof. Avis H. Cohen
(University of Maryland, USA)

Report by Avis H. Cohen:

The ideas of the group are very ambitious and look toward enormous gains by the community over the 5 years. The groups are well conceived, and full of creative individuals who have already proven themselves. In summary, this is an incredibly exciting group, with wonderful ideas, and goals, with a good chance of success.

The group will generate AND will require, as emphasized by Prof. Shimozawa: non-linearity of interaction – they will gain more than the sum of their parts: IF they do what they/he said – have strong collaborations, regular meetings, good educational programs to give everyone the necessary background (don't need to all have the same depth, but should at least know each other's words and meanings and constraints). Need at least one biologist in each group to keep the group "honest" and pointing to problems and bringing up new ideas from the biology. (I recommend he be kept as part of the group, if willing!).

Currently, the group consists of many wonderful ideas, good organization, and already has made substantial progress in many directions. This was clearly exemplified in the presentations. No need to itemize, as all were up to very high standard. All are currently interacting well, apparently, and have clear goals and directions.

One challenge is in the physical distances among the groups. It is necessary to bring a sense of cohesiveness to the whole, and allow all the members to gain from discussing with the others.

Another challenge is in the intellectual development of the individuals, to guarantee that the different disciplines do, in fact, bring the power to each other that is required to achieve what they have set out to accomplish. This will be especially important as the group gets larger.

Recommendation:

1. Set up a regular educational program for their students, so all have common background. Have biology at core, as recommended by Shimozawa, perhaps at some central place, but not necessarily.
    a. But this must be taken seriously. The students must be aware that this is not fluff, but important component.
    b. The courses should be taught be individuals who are either part of the program or who share the goals of the project, to guarantee that the spirit of the courses carries the message of Mobiligence.
    c. Should include in this, seminars with speakers from their campuses, but also outsiders. Students should be required to hear the lectures by everyone, especially those outside their particular fields.
    d. Students should be encouraged to have a common meeting program to build a sense of comraderie among them. This will give the next generation easy collaborations, and will help them learn a common language. It will also be a source of new ideas, and new collaborations.

2. Have regular meetings of the parts and the whole. Have, perhaps, a regular “retreat” or nice meeting where they report progress and discuss new directions, but also can get help and ideas for their projects, and can share ideas.
3. A challenge will be for all to ask “dumb questions” to learn from each other. This will require the older, more secure members to ask the questions first. They must set the tone. It MUST be permissible, indeed, advisable for the group members to be able to show they don’t understand. The ideas MUST be understood by the researchers across the disciplines. THIS IS THE CHALLENGE, and this is the only way to accomplish this very difficult task.
4. There is clearly the intention of including a social benefit, but there was little in the presentations that emphasized it. I believe this should be enlarged and made more explicit.

Review Comments of

Prof. Rolf Pfeifer
(University of Zurich, Switzerland)

Mobiligence, Sapporo, 5 December 2005

Comments by Rolf Pfeifer

1, Overall project and strategic goals

The project is right on target, both in terms of basic research and potential applications. Targeting medical applications is useful and strategically important to get the support of the funding agencies and the population at large.

The way the program is set up it bears the potential for breakthroughs in two ways: First for understanding the principles underlying motion/locomotion and engineering respective systems. Second, it also represents a first step in a long-term quest for high-level cognition, where cognition is fully grounded in sensory-motor interactions. At this point, this may not be so important, but it shows the long-term strategic potential of the project.

2. A note on the cooperation between biology and engineering

The question is always: “What can you learn?” (e.g. by building a robot)

The transfer should not only be from biology to engineering, but both ways, which can best be achieved in everyday close collaboration. There should not be a “naïve” transfer from biology to engineering. It is important to note that biological systems have their own intrinsic dynamics of the joint neural/body system. That is, the neural systems are matched to their specific body dynamics. Transfer to an engineering system only makes sense at the level of principles since the artificial system, because of its completely different morphology and material properties, will have a very different intrinsic dynamics.

Close cooperation will beneficial even if it is hard to quantify exactly what is gained. Often it is hard to pin down precisely what the transfer precisely comprises.

3. Materials

One might want to put materials more explicitly onto the research agenda. Recent work in the physiology and biomechanics of locomotion has demonstrated the importance of materials for movement/locomotion. Of particular interest are muscle-tendon systems and artificial skin with haptic sensors.

4. Group C: Social adaptation

Currently, the project is focused on elucidating the brain mechanisms underlying certain types of social interaction. It might be of interest to also look at embodiment, e.g. to experiment with different types of morphologies for the pheromone receptors.

Morphology is an enabler of social interaction and interesting results might be achieved because various morphologies can be studied with robots.

5. International visibility

Achieving visibility not only at the national but at the international level will be very important for the success and the acceptance of the project. If international recognition is given, it will be easy to defend the project and the apply for additional funding.

Sapporo, 5 December 2005 Rolf Pfeifer

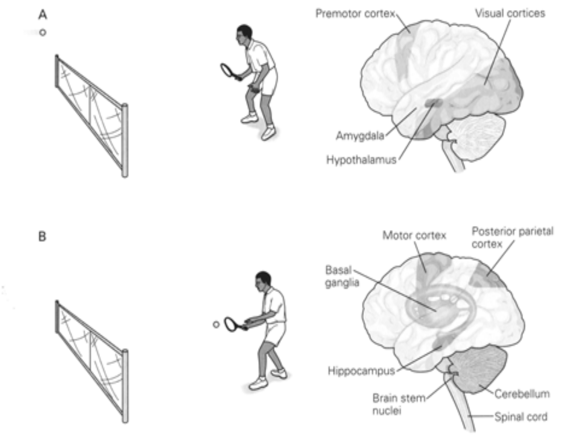
Review Comments of

Prof. Sten Grillner
(Karolinska Institute, Sweden)

Mobiligence

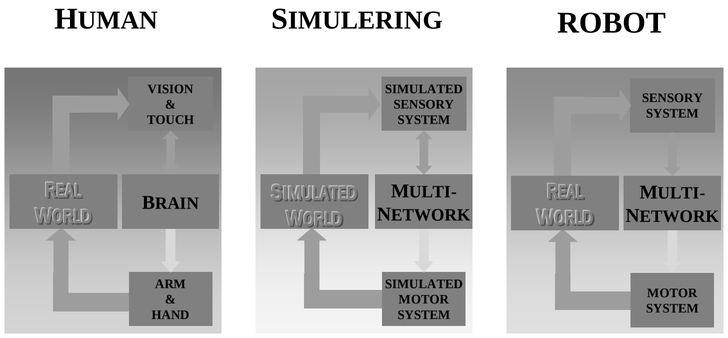
- *adapt to the surrounding world*
- *interpret percepts – match against information stored in memory*
- *priorities - selection of behaviour*
- *motor infrastructure*

  -reaching, grasping, posture, locomotion
- *motor learning*



Similar conceptual problems for action in

animals, man and advanced robots



HUMAN

VISION & TOUCH

REAL WORLD

BRAIN

ARM & HAND

SIMULERING

SIMULATED SENSORY SYSTEM

SIMULATED WORLD

MULTI-NETWORK

SIMULATED MOTOR SYSTEM

ROBOT

SENSORY SYSTEM

REAL WORLD

MULTI-NETWORK

MOTOR SYSTEM

Courtesy of Roland Johanson

Multidisciplinary expertise required

- *From applied mathematics to cognitive neuroscience*
- *From neurobiology to robotics and brain-like computing*

- **need for *close interaction* between researchers with different training, but with a *focus* on the same scientific problem**
- **need to *bridge the gap* between mathematics – physics and biology**

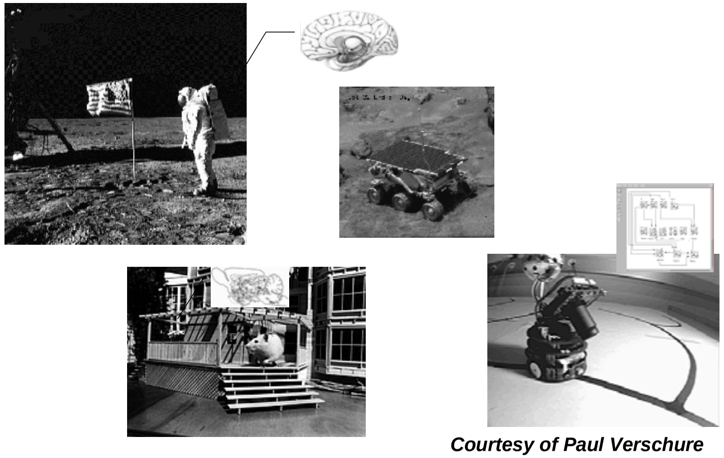
Difficulties?

- ***career difficulties* at the border between parent disciplines/faculties**
- ***lack of understanding* between researchers with different basic training (eg physics/engineering versus neurobiology)**

Programs

- *A. Adaptation to environment*
  - *Koji Ito and Masafumi Yano*
- *B. Control Mechanisms of adaptive locomotion*
  - *Kazuo Tsuchiya, Kaoru Takakusaki, Naomich Okihara, Koh Hosoda*
- *C. Mechanisms by which animals adapt to society*
  - *Hitoshi Aonuma, Jun Ota and Daisuke Kurabayashi*
- *D. Common principles of Mobiligence*
  - *Koichi Osuka, Akio Ishiguro*

Conceptual problem: The living brain in the world



Courtesy of Paul Verschure

Control of Action

the only thing mankind can do is to move things
……whether whispering or felling a forest

(Sherrington)

Review Comments of

Prof. Shinzo Kitamura
(Kobe University, Japan)

December 5, 2005

Comment by S. Kitamura (Kobe University)

The plan of the research initiative of “Mobiligence” is well organized. Herewith I appreciate the efforts done by Professor H. Asama and his colleagues for starting this initiative and also for realizing the meeting in Sapporo.

Although I have scarcely anything to say at this moment, I wish to add a comment:

> Attending this meeting, I have reconfirmed the importance of interdisciplinary studies such as the topics here. However, to promote this research initiative actively for next four years, it will be very important to have substantial discussions between young researchers from different fields; in our case, engineering, biology and medicine.
>
> I would like to ask the Steering Committee to prepare such opportunities, especially at the starting stage of the initiative.

Review Comments of

Prof. Ryoji Suzuki

(Kanazawa Institute of Technology, Japan)

Comments on Mobiligence ’05 at Sapporo

by Ryoji Suzuki (Kanazawa Institute of Technology)

Can the brain work without the body,
If it can receive all of information from
Environment ?

Brain (Mind) and Body Issue has been discussed from the view point of Philosophy and Religion, but not enough from Science and Engineering

Isolated brain complex is expected as a final result of the evolution of human being (by J.D.Banard, History of Science)

Criticism to the idea of isolated brain
M.Miura (philosophy) in his book “Thinking Body” (1999)
Not only behaviors, but language and mind activities are also supported by body.

Body (Physicality), Sociality and Ecological viewpoint must be taken in designing artificial environments such as man-machine Interface, virtual reality system and robots.

Transdiciplinary Approach by Brain Science, Biology, Psychology, Social Science, Physics and Engineering is important.

I am expecting for this Mobiligence Project to get a productive answer to the above mentioned problem.

Tight collaboration of biological researches and engineering researches is very important, but is not so easily realized.
The proposed process seems promising, if all of the member keep the significance of this process in his mind.
At stage 3, simulation study may be also utilized.

At present, this project is focusing to the emergence of adaptive behavior, but I am expecting to get some breakthrough to Intelligence as suggested by Prof.Pfeifer.

Research on Adaptation Process to Environment is important for behavior control and the approach by Group A seems promising, that is to find the constraints adaptively in real time.
My question is what is the essential difference between A01 and A02, if any. Is A01 focused on discrete movement such as reaching and is A02 on rhythmical movement such as locomotion? If so, I am expecting for this group to find a way to connect each other, because the transit process from rhythmic to discrete movement is very important issue to understand the mechanisms of voluntary movements.

How about the tight cooperation between biology and engineering ?
And how do you cooperate with Group B?

Group B
What is differ from Group A?
How to cooperate with Group A?

Group C

Insects show typical example of animal adaptation to society and today' talk by Dr.Aonuma was very beautiful. I would like to know how to generalize these results on insect to other animals.
Also, topics C03 and "Adaptive function for organizing society" are very interesting and I would like to know in detail. Especially, the process where the hierarchy of society emerges is very important and interesting from the view point of social science. Results from this study may be a good present to our tax payer.

Group D
Well-Balanced Concept is interesting as a candidate of common principle of mobiligence.
Is this concept acceptable by other groups?
Or not, how do you cooperate with them to find the final answer.

Each group itself is organized very well and is being expected to achieve remarkable results.
However the total strategy of cooperating each other is not so clear.
I found some overlapping on the targets. Making different approach to the same target may be a good strategy. Have you talked each other?

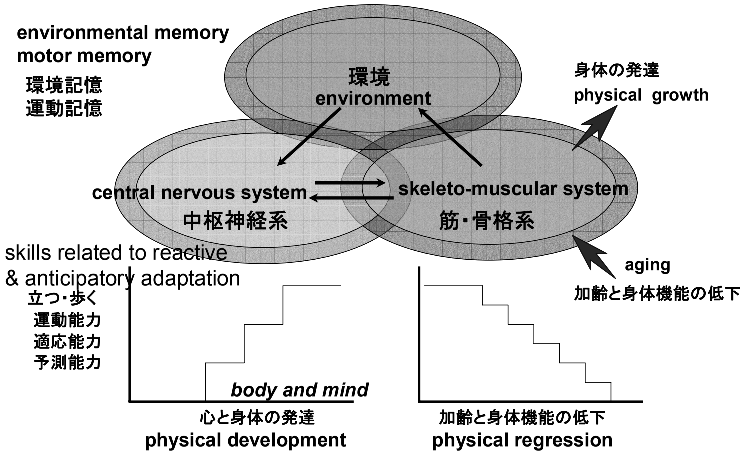
This project is on priority area and has the mission. So, how to invite proposed topics is also important. However, the spirit of "Kakenhi" (curiosity-driven research) should be preserved.

Review Comments of

Prof. Shigemi Mori

(National Institute for Physiological Sciences, Japan)

[redacted]



environmental memory
motor memory
環境記憶
運動記憶

環境
environment

central nervous system
中枢神経系

skeleto-muscular system
筋・骨格系

身体の発達
physical growth

aging
加齢と身体機能の低下

skills related to reactive
& anticipatory adaptation
立つ・歩く
運動能力
適応能力
予測能力

body and mind
心と身体の発達
physical development

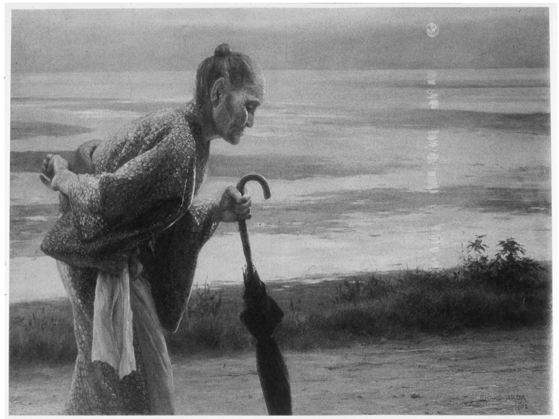
加齢と身体機能の低下
physical regression

[redacted]

adaptation of a little girl to the new environment allows her to acquire a new playing skill.

新しい環境に適応したスキルの獲得は脳を発達させ作りあげる

[redacted]



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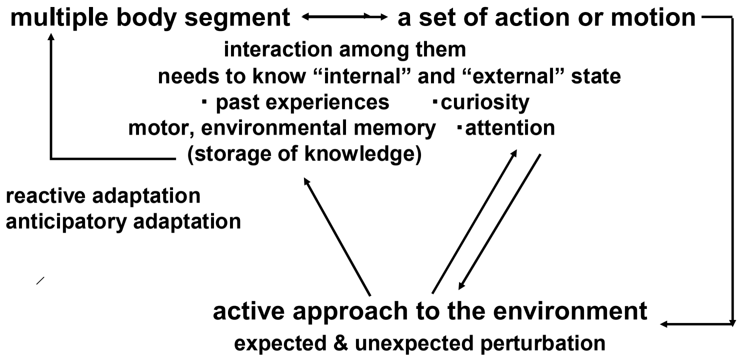
Understanding the principles of adaptive behavior



multiple body segment ⟷ a set of action or motion

interaction among them
needs to know “internal” and “external” state
・past experiences ・curiosity
motor, environmental memory ・attention
(storage of knowledge)

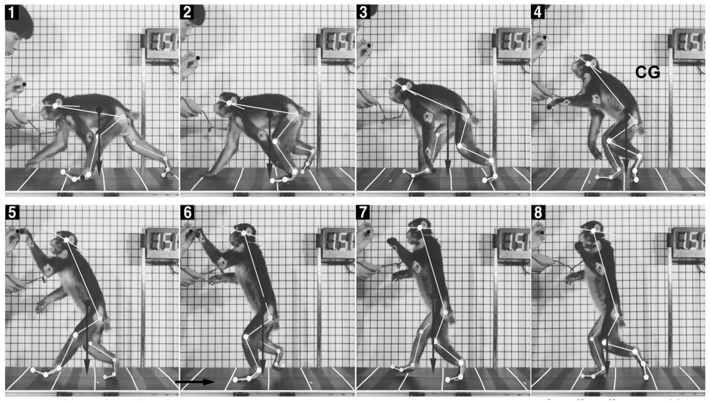
reactive adaptation
anticipatory adaptation

active approach to the environment

expected & unexpected perturbation

emergent property for task solution can be self- generated based on the past experiences (motor learning).

Once freed from weight bearing constraints, the monkey is able to use the freed forelimb for a skilled hand-finger motion (acquisition of a new motor skill).



Treadmill belt speed: 1.5 m/s