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

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Abstract— **Human, animals, or even insects have function to behave adaptively even in indefinite environment. Such an adaptive function is considered to emerge from the interaction of the body, brain, and environment, which is caused by motion of a subject. We call the intelligence for generating adaptive motor function *mobiligence*. The *mobiligence* program started from 2005 in Japan, as a five-year program to understand the mechanism on how the adaptive behaviors of the biological systems are generated by constructive approach with close collaborative research of biology and engineering In this presentation, the outline of the program is introduced.**

I. Introduction

THE *Mobiligence* program is a five-year program started from 2005[1], which was accepted as a program of Scientific Research on Priority Areas of Grant-in-Aid Scientific Research sponsored by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). Currently, 40 subjects are being carried out (11 subjects for planned research group, 20 subjects for applied research group, and one subject for operation). The first and second international symposium on *mobiligence* was held in December of 2005[2] and July of 2007[3] respectively, in which we discussed mainly the research results obtained in the *mobiligence* program and the research plans.

In this presentation, the outline of the program including the objective and the organization is presented. The concept of *mobiligence*, which can be defined as intelligence for generating adaptive motor function which emerges by mobility, and the approach to understand the mechanisms that generate the adaptive behaviors are explained, and a part of the current research outcome is introduced.

II. Objective of the *Mobiligence* Program

All the life forms such as humans, animals, and insects, can behave adaptively even in diverse and complex environment in various types of behaviors, such as locomotive behaviors in the form of swimming, flying, and walking, manipulation behaviors such as reaching, capturing, and grasping by using hands and arms, social behaviors to the other subjects, etc. The intelligent sensory-motor functions to generate adaptive behaviors are considered most essential and indispensable for them to survive.

It is known that such function for adaptive behaviors is disturbed in patients with neurological disorders. Parkinson disease is a typical example of such 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 has become urgent to cope with this problem. However, the mechanisms of generating such adaptive behaviors are not thoroughly known yet. With this background, the objective of the program is set to understand the mechanism that generates the adaptive behaviors.

III. Concept of *Mobiligence*

Such an adaptive function is considered to emerge by the active mobility of the cognitive subject. In the subject is in the stationary state, there is not so much interaction among body, brain, and environment. However, once the subject starts to move, the signals to move the body are transmitted from the brain to the body. As the result of the motion of the body, the physical interaction between the body and environment are made, and due to the interaction, the information from environment is input to the brain directly or fed back to the brain via the body as somatosensory signals. Namely, the motion of the subject accelerates the interaction among body, brain, and environment, which is considered essential for the subject to behave adaptively. Based on the consideration, we built up a working hypothesis that the adaptive function emerge from the interaction among the body, brain and environment, which requires actions or motions of the subject, and defined *mobiligence* as intelligence for generating adaptive motor function which emerges by mobility.

The information which can be acquired by mobility can be listed as follows:

1. Diverse information by changing location of the subject
2. Dynamical information by motion
3. Experience accumulated in the subject

There is difference in the concept of the conventional

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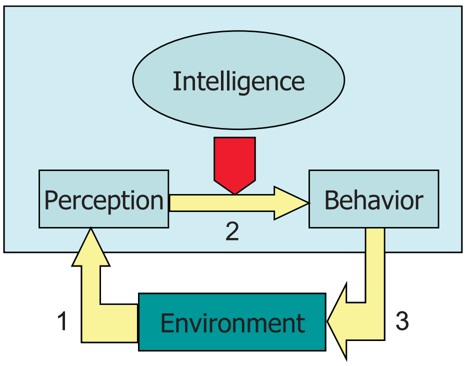
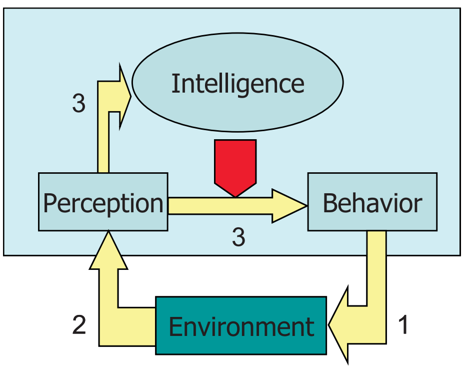
robotics and *mobiligence*, which are compared in fig. 1.

In the conventional robotics, which discusses intelligence for mobility, the first step is perception and cognition. The subject recognizes the environment based on the information perceived by sensors, then plans the motions by applying knowledge which should be implemented in advance, and behaves by controlling the actuators, namely, moves the body, which causes the interaction to the environment, as shown in fig. 1-(a). On the other hand, in the concept of *mobiligence* which investigates intelligence emerged by mobility, the first step is behavior as shown in fig. 1-(b). The perception is initiated by the behavior. As a result of the behavior, rich information can be acquired by the interaction between the body and the environment, and input to the brain. The information can be accumulated in the brain, and utilized concurrently to generate adaptive behaviors in real time. The combination of the two concepts derives the tight and continuous loop between cognition and behavior or among body, brain, and environment, which is considered quite important to understand the intelligence of living systems that behave adaptively or to design the intelligence of the autonomous artificial robots.



(a) Concept of conventional robotics



(b) Concept of Mobiligence

Fig. 1. Comparison of the concepts of conventional robotics and *mobiligence*

IV. Collaborative Research of Biology and Engineering

It is typical to use animal experiments in the conventional biological research. By this analytical approach, large amount of knowledge and findings have been obtained so far, such as the structure and function of various neural networks, neural transmitters/modulators, etc. However, there is also limitation in this conventional analytical approach based on animal experiments. The animal experiments are usually made with animals in the fixed conditions, and they can reveal only the simple brain function in a stationary state. For the *mobiligence* research, where it is required to investigate the complex function which emerges through interaction among brain, body, and environment in a dynamic state, the mechanisms that generate adaptive behaviors are hardly able to be elucidated only by the conventional analytical approach.

To overcome the problem, a new approach was introduced to tackle this problem in the *mobiligence* program. Based on the knowledge of biological research, such as neurophysiology, neuroethology, clinical medicine, cognitive science, microbiology, physiological models are to be derived. To these biological models, dynamic system modeling technology is applied to derive biological system models, which can be implemented on simulators or actual robot systems. By constructing the adaptive function on the simulators or actual robots based on the models, we can verify the models, evaluate the effects of the various parameters, and introduce new hypotheses to the biological scientists. In the *mobiligence* program, this approach is called a constructive approach by collaborative research of biology and engineering.

In the *mobiligence* program, three methodologies for collaborative research of biology and engineering have been proposed and in practice so far:

A. System Biomechanics

By neurophysiological research, we can derive models for nervous systems. On the other hand, by engineering and anthropological research, musculoskeletal models can be derived. By integrating the nervous system models and musculoskeletal models, dynamic system models can be introduced, and can be implemented on simulators or actual robots. As the results of experiments using the simulators or actual robots, we can verify the models or hypotheses, produce new possible hypotheses on the mechanisms which generates the adaptive behaviors, and feed them back to the biological scientists, or provide robotic scientists with design principle to realize adaptive artificial systems. This methodology for collaborative research is shown in figure 2-(a).

B. Synthetic Neuroethology

From neurophysiological research, enormous independent pieces of physiological knowledge are acquired in diverse levels from chemical reaction to cellular and behavioral (individual or social) level. Multiple pieces of the knowledge in multi-levels can be synthesized by technologies in robotics or engineering to derive dynamic system models, which represent the hypotheses of the mechanisms that generate adaptive behaviors. The behavior or performance of the models which should be implemented on simulators or actual robots can be compared with the behavior or performance of the actual living systems, and the models or hypotheses can be verified in ethological manner. This methodology for collaborative research is shown in figure 2-(b).

C. *Brain-Machine Integrated System*

Biology can provide us with biological body components, such as brains, limbs, organs etc. Engineering or robotics can provide us with mechanical body parts, such as sensor devices, actuators, processors, etc. By integrate these body parts, we can construct brain-machine integrated systems, which can also be called *cyborg*. By analyzing the behavior and function of the integrated system, we can investigate the function of the biological components or systems, and can provide robotics scientists with the methodologies to realize artificial systems that can behave adaptively. This methodology for collaborative research is shown in figure 2-(c).

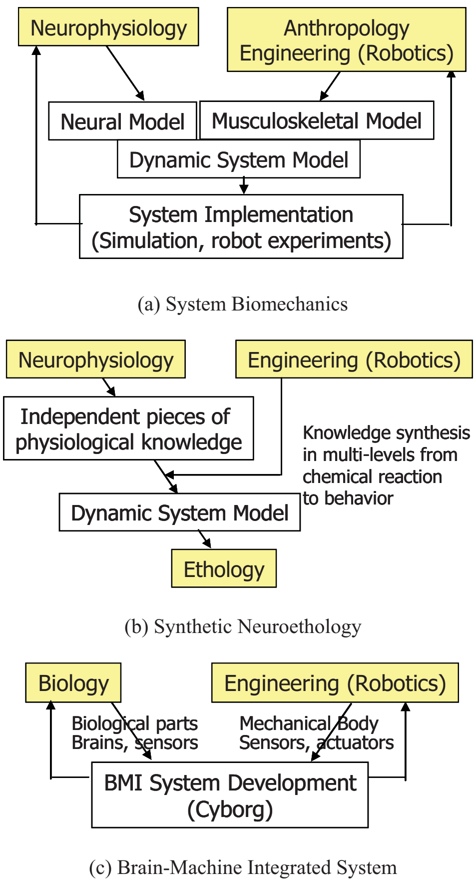


Fig. 2. Methodologies for collaborative research of biology and engineering

V. Research Subjects and Groups

In the *mobiligence* program, we focused on the following three aspects to investigate the mechanisms that generate adaptive behaviors, and organized three research groups for each aspect:

Group A (Adaptation to the environmental change)

Investigation of mechanism to generate the information adaptively based on cognition of the environmental change

Group B (Physical Adaptation)

Investigation of mechanism to control the motion of the body adaptively according to the environment

Group C (Social Adaptation)

Investigation of mechanism to select the behaviors adaptively to the other subjects and the society

The researchers in these three groups conduct their respective research on specific subjects, such as cognition, learning, motion generation, and body control, focusing on specific life forms, such as humans, animals, and insects in individual level and social level. However, another important target of this program is to clarify the universal and common principle underlying the mechanism of *mobiligence*, and establish the design principle for adaptive systems. We organized the fourth group to understand the common principle:

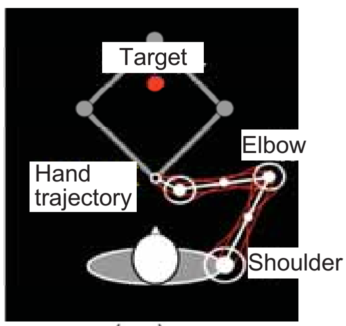
Group D (Common Principle)

Investigation of common principle on dynamics in generating adaptive behaviors

VI. Recent Research Outcome

In the *mobiligence* program, many collaborative research subjects have been initiated, and various valuable research outcome have been obtained so far by the intensive specific research in the group A, B, and C. In parallel to the specific research, some common structures and features have been extracted as the common principle on the structural dynamics or information creation of the mechanisms for adaptation. Followings are a part of the recent research outcome:

In the research of group A, which focuses on cognition to the environmental change, adaptation to dynamic



$$M(\theta)\ddot{\theta} + h(\theta, \dot{\theta}) = \tau - J(\theta)^T F_h$$

Fig. 3. Reaching behavior

environments in reaching movements as shown in Fig. 3 has been investigated by Ito, et. al[4]. Two types of force fields, namely velocity-dependent force field for internal model adaptation and divergent force field for impedance adaptation, have tested, in which the subject should learn to reach the targets. It was proved that the subjects can learn to generate the optimal hand force patterns in both cases, and can adapt even when that force field was changed in the middle of the motion. As a result of the experiments, it can be assumed that the impedance and internal-model controls can be programmed in a feedforward manner in adaptation to the contexts of dynamic environments. This function is called anticipatory adaptation. Yano, et. al. investigated real time adaptation mechanisms on a feedforward structure, especially mechanisms on generating real time constraints as *Minashi* (abductive) information, taking an example of olfactory computation in slug brain[5]. As a result of experiments, it was found that the initial signals to move the body, which is considered to correspond to emotional behavior, precedes about 40-60[msec] to the memory accessing signal flow, which is considered to correspond to interpretation of the perceived information.

In the research of group B, which focuses on physical adaptation, namely adaptation in the individual level, emergence and control in adaptive locomotion under changing environment has been investigated by system biomechanics approach, namely systematic approach based on neural and musculoskeletal models. Takakusaki, et. al. investigated function of basal ganglia, cerebral cortex, brainstem, spinal cord, thalamus, limbic system, and cerebellum on locomotion, and discovered a detail structure on the signal flow in the neural networks[6]. Especially, Nakajima, et. al. investigated how cortical motor areas (M1, SMA, PMd) in primates contribute to the gait control by using Japanese (Macaque) monkey[7]. As a result of experiments on recording the firing pattern of cortical neurons during locomotion of macaque monkeys on moving treadmill, it was found that the discharge frequency drastically increased when the monkey converted its locomotor pattern from quadrupedal to bipedal. A block diagram on the locomotion was derived as a physiological model for locomotion, where it was also indicated that the postural control system is activated earlier than the movement control system, and sends feedforward signals to movement control system. On the other hand, Tsuchiya, Ogihara, et. al. developed a musculoskeletal model of Japanese monkey based on anatomical data and CT data by anthropological and engineering approaches[8], which is shown in fig. 4. It is expected to integrate the physiological model and the musculoskeletal model to enable simulation on dynamic locomotion of Japanese monkey by constructive approach for further investigation in near future.

In the research of group C, which focuses on social adaptation, namely adaptation in the social (multi-agent) level, cognition of other agents and selection of adaptive behaviors to other agents or society have been investigated by synthetic neuroethology approach. Aonuma, et. al. focused on fighting behaviors between male crickets as shown in fig. 5. As a result of experimental investigation, new physiological knowledge were obtained such that aggressiveness increases by inhibition of NO/cGMP cascade, OA level in the brain decreases by NO and fighting behavior, and the decrease level depends on the results of fights (win or lose)[9]. Fujiki, Asama, et. al. implemented a mathematical model of the neural mechanism by reaction diffusion equations[10], and Ashikaga and Ota, et. al. implemented a mathematical model of interaction between male crickets by

Fig. 5. Fighting behavior of male crickets

Fig. 4. Musculoskeletal model of Japanese monkey

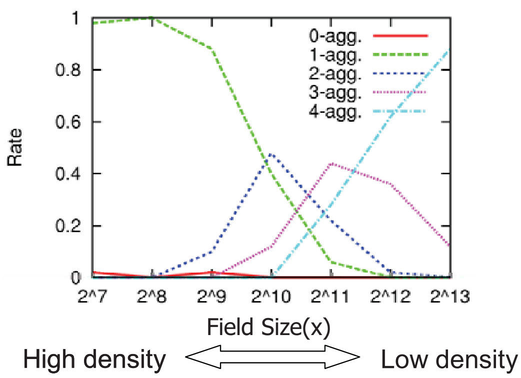


Fig. 6. Simulation results on aggressiveness depending on density

finite automaton[11]. By integrating both models, the behavior selection of male cricket can be simulated from chemical reaction level in the brain to the social interaction level. As a result of simulation results, it was suggested that the different types of the society emerge depending on the density, namely the number of individuals per unit area. Figure 6 is the simulation results on aggressiveness of male crickets depending on the density. The graph shows that all the individuals become aggressive in low density (large field size) condition, while only small number of individuals become aggressive in high density (small field size) condition. It is pointed out in the ethological research that this simulation results fits the behaviors of actual make crickets very well, and from these consideration, the models we derived are proved to be reasonable.

In the research of group C, Kanzaki, et. al. have investigated the adaptive brain function of silk moth by brain-machine integrated system approach[12]. A mobile robot integrated with insect brain, which is shown in fig. 7 has been developed, where the robot can be controlled by the embedded insect brain signals. As a result of pheromone source localization experiments with this robot, it was found that the silk moth brain can successfully control the robot body and localize the pheromone source even if the control gain of the right wheel and the left wheel were differentiated. This result verified the plasticity of the silk moth brain. By changing body dynamics, control gain or other parameters of the body, it is expected to investigate the adaptive function of the silk moth brain and neural systems more in detail.

In the research of group D, which focuses on common principle, balance dynamics in mechanical properties and information processing in control has been investigated from the viewpoint of physical constraints, because it is considered that the balance between mechanical embodiment and neural control system is considered very important for realization of adaptive function. The main concern of this group is what kind of balance mechanisms exist in living systems, and how this should be designed in autonomous artificial systems. Osuka, et. al. have focused on adaptive function in passive dynamic walking, and discovered a stabilization mechanism by implicit feedback structure in body dynamics[13]. Ishiguro, et. al. have developed a modular robot system "Slimebot" based on collective behavioral approach as mimesis of slime mould (amoeba), which is shown in fig. 8[14]. The robot system employs a fully decentralized control by exploiting embodied coupled nonlinear oscillators, and passivity by s spontaneous inter-modular connectivity control mechanism. As a result of actual robot experiments, it was discovered that a certain passivity can significantly increases its adaptiveness.

From the research outcome obtained so far in the *mobiligence* program, there found a common characteristic in the mechanisms that generate adaptive behaviors as shown in fig. 9. The perceived sensory information is dimensionally compressed in environment cognition. However, the information which can be obtained is not always sufficient to generate motion. In such situation, *Minashi* (abductive) information is generated in real time, which is equivalent to constraints for control of redundant degrees of freedom in the physical body. The motion is not always generated or switched in a reactive manner (such as impedance adaptation). The internal models learned and formed in the brain through experience are quite essential to generate adaptive behaviors effectively according to the context. The motion generation complexity depends much on the embodiment. If the body is well organized, the active mechanism to control the body can

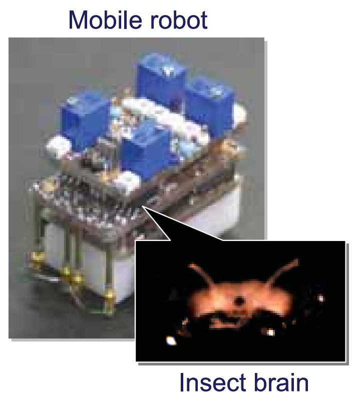


Fig. 7. Mobile robot integrated with silk moth brain

Fig. 8. Modular robot system "Slimebot"

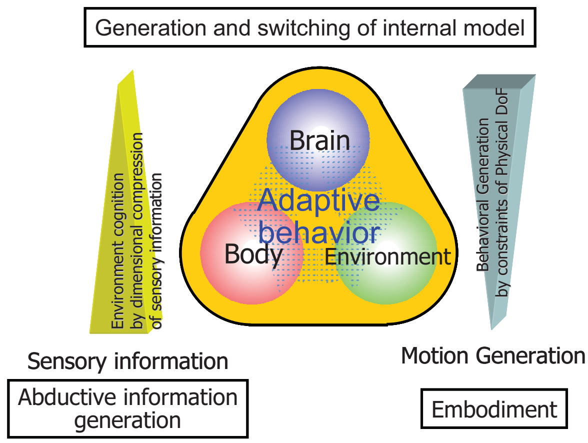


Fig. 9. Common characteristic in adaptive behavior generation mechanisms

be simplified.

VII. EXPECTED IMPACT OF THE *MOBILIGENCE* PROGRAM

By the *mobiligence* program, various types of mechanisms that generate adaptive behaviors in various living systems, such as humans, animals, and insects, are expected to be elucidated as well as common principle. Although the main contribution will be brought to biological field, huge impacts to other fields are expected as well. To the medical field, the results of our research will contribute to the discovery of a method to improve motor impairment and develop rehabilitation systems. To the engineering field, the results of our research will contribute to the derivation of the design principles of artificial intelligence systems. By the *mobiligence* program, the new research discipline is expected to be explored, and a new research organization that integrates biology and engineering is expected to be established, where new programs or curriculums are implemented to foster young engineering scientists and biologists to conduct collaborative and interdisciplinary research between biological and engineering research, respectively.

Junior Academy of the *mobiligence* program was established, and tutorials, workshops, and seminars have been carried out for the young researchers in *mobiligence* program. The academy is now working on editing the terminology related to the *mobiligence* research.

VIII. CONCLUSION

The *mobiligence* program was introduced, which started from 2005 in Japan as a five-year program of Scientific Research on Priority Areas of Grant-in-Aid Scientific Research sponsored by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). The concept of *mobiligence* was explained, which can be defined as intelligence for generating adaptive motor function which emerges by mobility. The objective of the program and the constructive approach by collaborative research of biology and engineering for the *mobiligence* research were mentioned as well as the subjects and organization of the program. Finally, a part of the current research outcome was introduced.

The outline of the program including the objective and the organization was presented. The concept of *mobiligence*, which can be defined as intelligence for generating adaptive motor function which emerges by mobility, and the approach to understand the mechanisms that generate the adaptive behaviors were explained. A part of the recent research outcome was introduced.

Detail and other research outcome was presented in AMAM ’08 (Fourth International Symposium on Adaptive Motion of Animals and Machines), and will be presented in this workshop of IROS ’08 (2008 IEEE/RSJ International Conference on Intelligent Robots and Systems), DARS ’08 (2008 International Symposium on Distributed Autonomous Robotic Systems), and Mobiligence ’09 (Third International Symposium on Mobiligence), which will be held in Awaji, Japan, in Nov., 2009.

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