Biomimetic Design of Actuators, Sensors and Robots

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Abstract— **Biological life has greatly influenced a vast variety of products including actuators, sensors and robots. What should we be learning from biological life? BioRobotics focuses on learning from the underlying design strategy of biological systems as well as learning from the exquisite geometry and movement themselves because both are important in making artificial systems that function like living creatures. An overview on the various ongoing researches in the Keio BioRobotics lab will be discussed. First, actuators and sensors imitating the geometry and movement of actual living creatures will be introduced, such as the design of Ring-type ultrasonic motors imitating the locomotion of soft-bodied creatures that utilize a traveling wave within its body. For the research on sensors, a method will be shown in which we were able to find out that ridges and papillae of human fingers enlarge sensitivity of mechanoreceptors by analyzing contact problems between a finger pad and an object using the finite element method. Designs of artificial tactile sensors imitating the human finger will also be introduced. Second, an introduction on examples of robots imitating the design strategy of living creatures will follow. One is a research focusing on an evolutionary bottom-up design of geometry and movement. Locomotion of earthworms, caterpillars and inchworms was generated using genetic algorithms showing that stiffness and the environment are important in generating specific locomotion patterns through evolution. The optimum motion and morphology of moving robots and manipulators are designed using evolutionary computation including genetic algorithms and genetic programming. Another interesting research is a hierarchical control design strategy of grasping and manipulation. Manipulation was successfully conducted using the layered control scheme imitating the upper and lower layers of feedback loops of humans.**

Keywords- bio-mimetics; actuators; sensors; robots; design

I. INTRODUCTION

Biological systems are designed in a bottom-up fashion, in which the subsystems of the creatures themselves and the effect of environmental conditions are simultaneously designed. For example, actuators, sensors, structure and neural systems of creatures are all designed simultaneously. On the other hand, artificial products are designed in a top-down fashion. When we design actuators, the purpose and needs of the actuators are first decided as a boundary condition of the design problem, then the actuators displaying adequate performance for the supposed system is designed. Sensors, controllers and mechatronic devices that would constitute the system are designed separately by different researchers. Then the system designer gathers the achievement of each element. Conventional methods have proven difficult to design an optimal system since it is difficult to consider the mutual effects of the composing elements. To make artificial systems more human friendly, it is important to learn from the design of living creatures. In this paper, ways to design actuators, sensors and robots learning from biological system design achieved in Keio BioRobotics laboratory are introduced.

II. ULTRASONIC MOTORS LEARN FROM LOCOMOTION OF SOFT-BODIED CREATURES

A. *Driving principles of ultrasonic motors*

Fig. 1 and Fig. 2 show a schematic view of a ring-type ultrasonic motor with a diameter of 70 mm [1]. The stator has a PZT (Piezoelectric ceramic) sheet bonded to the bottom side of its metal vibrator. The stator has teeth on the upper surface of the vibrator. Two natural vibrations with frequencies of about 30 kHz with a phase difference of 90 degrees and amplitude of about 1 μm are excited by AC voltage input to the PZT. This generates a traveling wave that creates an elliptic locus at the surface of the stator. The teeth help increase the vibrating amplitude of the stator. As shown in Fig. 2, point P on the teeth surface moves counter-clockwise along its locus when the traveling wave moves to the right. The rotor has a ring and a flange-shaped spring to generate certain contact duration to the surface of the traveling wave.

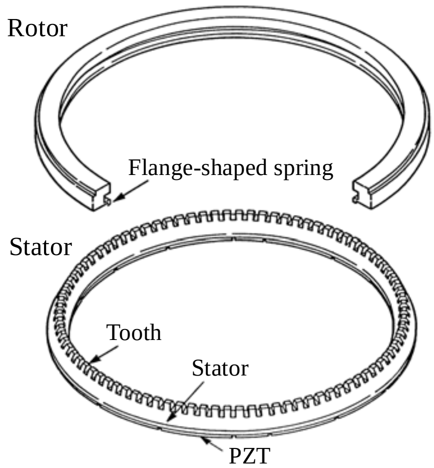


Fig. 1 Ring-type ultrasonic motor

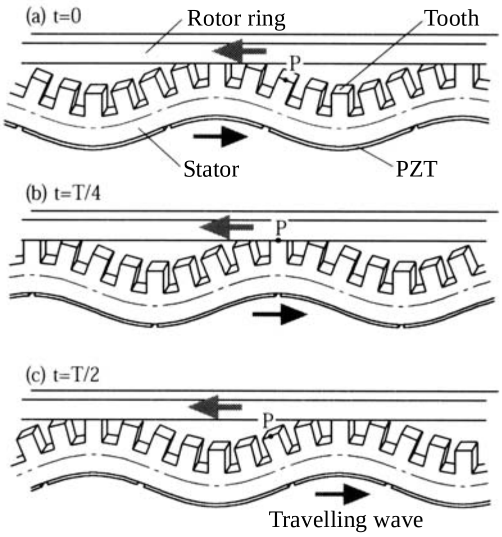


Fig. 2 Driving principle of ring-type ultrasonic motor

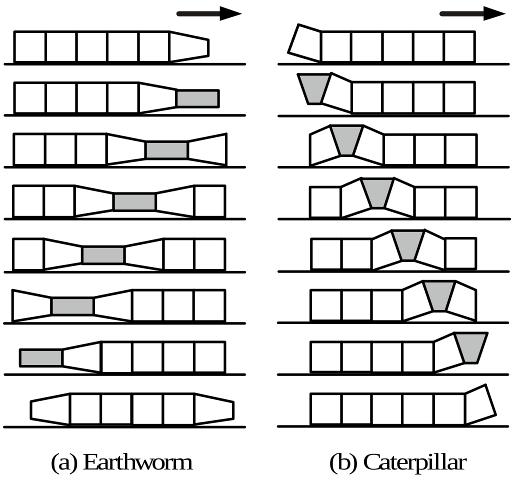


Fig. 3 Locomotion pattern of soft-bodied creatures

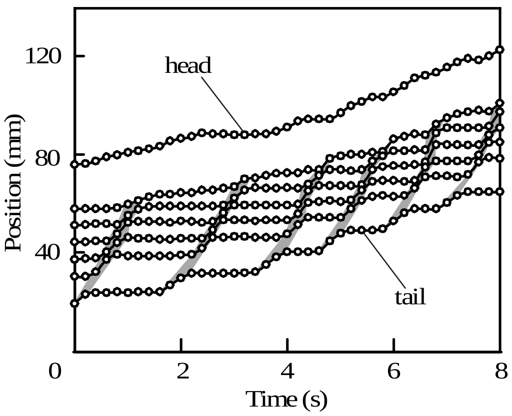


Fig. 4 Measured locomotion pattern of caterpillar

B. *Locomotion patterns of soft-bodied creatures*

Soft-bodied creatures including earthworms, caterpillars and inchworms utilize wave-like motion of their body to move. As shown in Fig. 3, earthworms and caterpillars use traveling waves similar to ultrasonic motors, whereas, inchworms utilize standing waves. As shown in Fig. 3, earthworms create a longitudinal mode. They move in the opposite direction from the traveling wave. Caterpillars move using bending vibration just like ultrasonic motors. They move in the same way as the traveling wave (See Fig. 4). If you imagine a caterpillar on the ground upside down, you will see the body of the caterpillar is like the stator and the ground is like the rotor of an ultrasonic motor. We can say that the movement pattern of the caterpillar and the ultrasonic motor are fundamentally the same. What is important is that the geometry and vibration mode of the body (stator) are designed simultaneously in both cases.

III. TACTILE SENSORS LEARN FROM HUMAN FINGERS

In the robotics field, although researchers have tried to place tactile sensors on robot fingers, most of them did not focus on making tactile sensors imitating tactile sensation in human fingers. However, it is worthwhile to mimic tactile sensors in humans. To make reliable master-slave robot systems, understanding human perception and its application to tactile displaying devices is important. To make autonomous robot hands having tactile sensors to detect quality of the touched surface and for feedback control of grasping force, mechanisms of tactile sensors can be learned from those of humans.

Hence, we first analyzed the contact problem between the finger cross section and objects having an even and uneven surface using finite element analysis (See Fig. 6) [2]. We found that epidermal ridges and papillae are to enlarge sensitivity of mechanoreceptors. We also found that four types of mechanoreceptors are located where strain is concentrated.

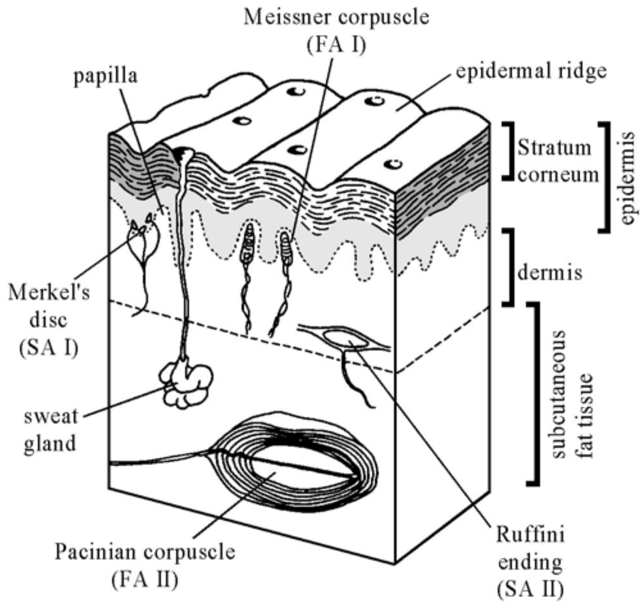


Fig. 5 Tissue and tactile receptors of glabrous skin

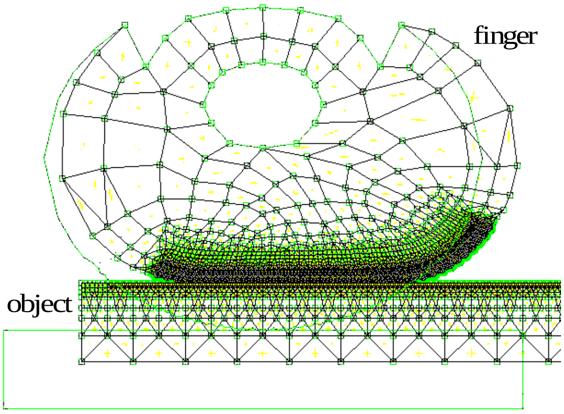


Fig. 6 Finite element model of finger cross section and object

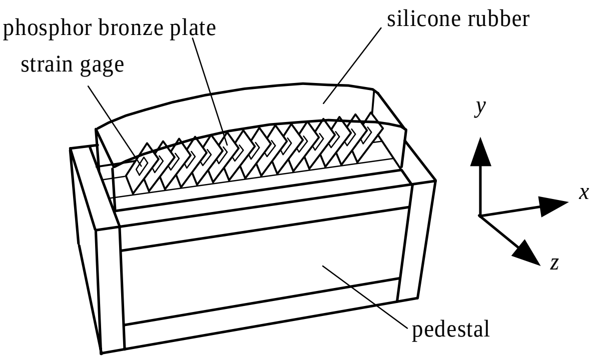


Fig. 7 Top view of finger-shaped sensor

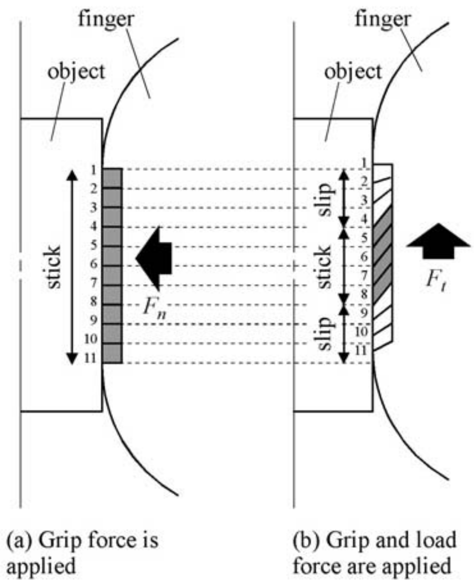


Fig. 8 Schematic view of stick/slip distribution at the surface of finger and strain distribution inside an artificial elastic finger

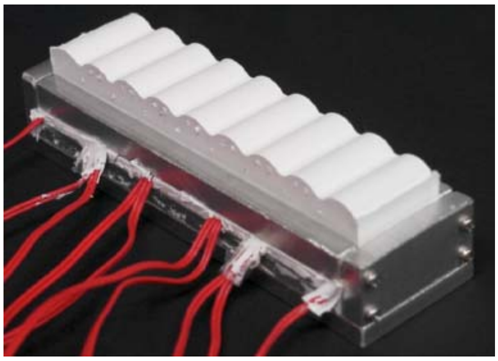


Fig. 9 Artificial elastic-finger-shaped sensor having ridges

Then we made tactile sensors imitating the human finger for grasp force control [3]. Sensors are distributed in an elastic silicone rubber with a curved surface. We focused not on detection of the intensity of signals but on detection of the pattern of multiple sensors. Fig. 8 shows the fundamental principles of the sensor. When only grip force is applied on the object as shown in Fig. 8 (a), deformation of the finger is symmetric. Normal contact force is distributed in a circle, i.e. it is large at the center of contact. If tangential force is added as shown in Fig. 8 (b), both edges of contact area easily slip because the normal force is small at the edge of the contact.

This means that strain inside the elastic rubber near the slip area is smaller than those near the stick area. Hence, we can detect the stick/slip distribution inside the contact area using sensors within the elastic finger. If we keep the partial slip area at both edges of the contact small enough, we can control grasping force at an adequate value without allowing the whole object to slip or without crushing the object by applying extreme force.

Fig. 9 shows another sensor imitating epidermal ridges of humans [4]. As a result of finite element analysis, we found that epidermal ridges are effective in making partial slip signals larger because one ridge slips at the same time.

As described above, we have been focusing on designing artificial sensors by utilizing knowledge obtained through analyzing the design of fingers and sensors of humans.

IV. ROBOTS LEARN FROM LIVING CREATURES

A. *Evolutionary computation of soft-bodied creatures*

As shown in Fig. 3, soft-bodied creatures with long bodies have different locomotion patterns. Earthworms use longitudinal backward traveling waves. Caterpillars use bending forward traveling waves. Inchworms use bending standing waves. In order to analyze the difference in motion, we made a model of soft-bodied creatures as shown in Fig. 10 [5]. Liquid filling in the body is modeled as solid links. Longitudinal and circular muscles are modeled in a two-dimensional plane as shown in the Fig. 10.

Patterns of movement are generated by a pattern generator using a series of sine functions with amplitudes and phases that are set to be variables. The variables are obtained by genetic algorithms so that the distance during a certain time period is maximized.

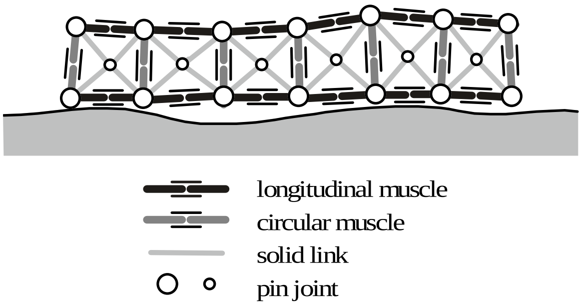


Fig. 10 Multi-link model of soft-bodied creatures

Fig. 11 shows the results. When the stiffness of the body is small, soft-bodied creatures move using longitudinal backward traveling waves as shown in Fig. 11 (a) like the earthworm. When stiffness becomes larger, the movement pattern changes as shown in Fig. 11 (b), which uses bending forward traveling waves similar to caterpillars. When the stiffness is even larger, the creature raises its body as shown in Fig. 11 (c) just like inchworms. Through measurements of earthworms, caterpillars and inchworms, we found that the order of the stiffness of their body is the same as the simulated results. Hence, we can say that soft-bodied creatures obtained their optimum movement patterns during evolution according to their stiffness. Fig. 11 (d) shows a result of calculation when the middle stiffness model is placed inside a narrow pipe. Placed in a pipe, it is difficult to use a bending forward wave as shown in Fig. 11 (b). Hence, the movement pattern changes to those an earthworm uses, i.e., backward longitudinal traveling wave. We can conclude that the movement pattern of soft-bodied creatures are also decided through evolution in accordance to their environment.

B. Evolutionary computation of robotss

When we design artificial products including robots, the hardware is usually designed first and the movement controlled later. On the other hand, geometry of the body and controlled locomotion patterns of living creatures are designed simultaneously during evolution as shown in the previous section. It is adequate to obtain a statically and dynamically optimum structure. Author insists that robots should be designed like living creatures in a bottom up fashion. Similar ideas have been introduced in the field of Artificial Life. However, researchers have yet to create hardware devices. Author is interested in designing real robots using evolutionary methods to make robots which does not look

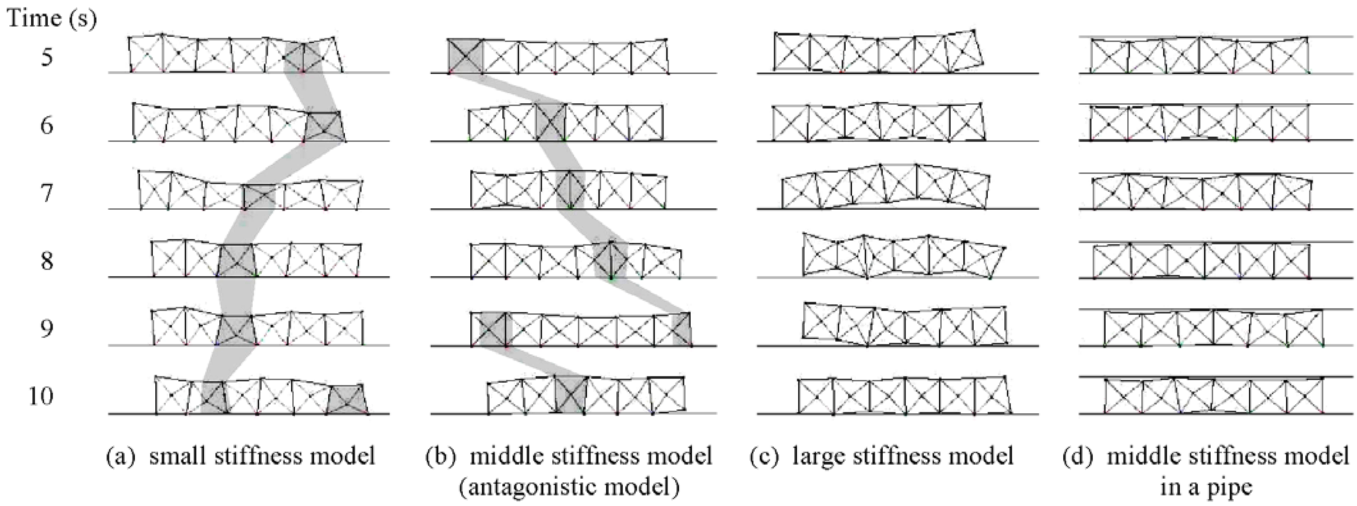


Fig. 11 Movement patterns of soft-bodied creatures generated using genetic algorithms

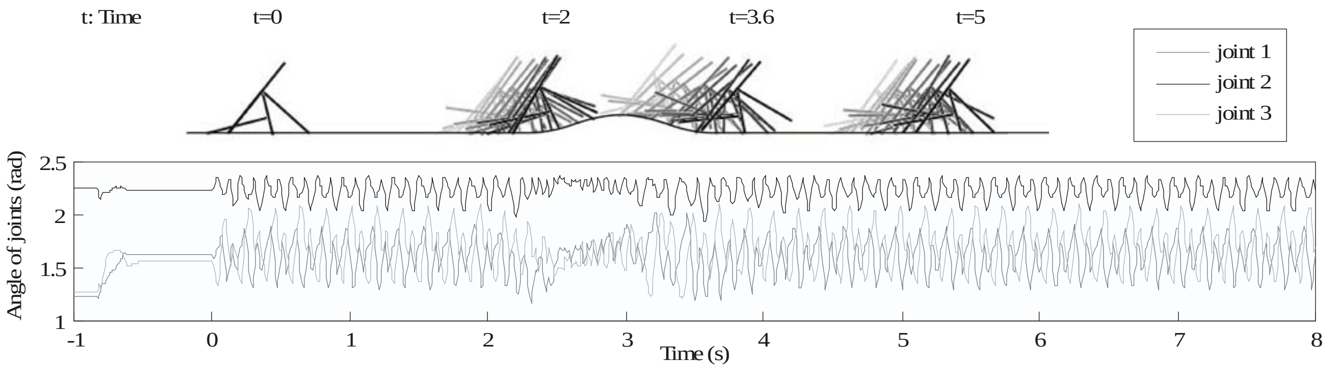


Fig. 12 Geometry and locomotion pattern of two dimensional link-type robot designed using genetic programing

similar to living creatures but look like robots because they have their optimum geometry and movement patterns according to their elements and environments.

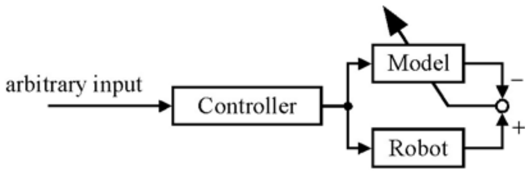
Author tried to design the geometry and locomotion pattern of two-dimensional link-type robots by use of genetic programming [6]. The body and control system of the robots are represented by a tree-like structure like a programming language lisp. It is set so that robots that can move faster by use of a smaller number of link elements survived. What is interesting is that unexpected geometry and locomotion pattern are obtained. Fig.12 shows one of the results of calculation. It is shown that geometry and locomotion pattern of the robot obtained could overcome a bump in the center of the diagram.

Author is also trying to generate the geometry and locomotion pattern of biped robot [7].

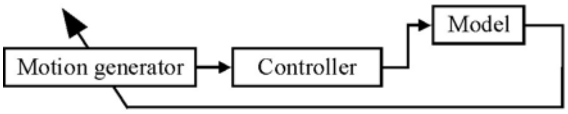
C. *Learning imitating motor imergery*

Another interesting feature of living creatures is that they can produce motion pattern through "motor imagery". Especially, primates can simulate their motion in their brain without real movement. We can imagine that it is because they have forward models that can be used to simulate the real motion.

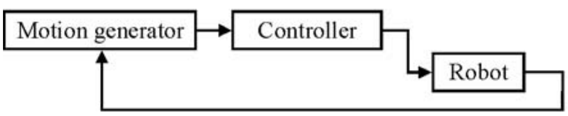
One of the reasons to make robots difficult to learn motion and behavior is that their life time is far shorter than those of living creatures. One of the advantages of robots is that they can repeat boring calculation accurately.



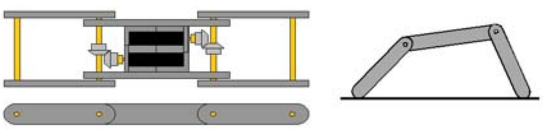
(a) Acquisition of model of body and environment



(b) Motor imagery (Acquisition of motion)



(c) Control of motion in real environment



(d) Model of robot

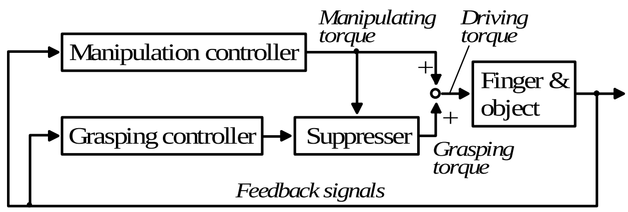
Fig. 13 Method of learning for robot that acquires environment model and motion pattern using motor imagery

From this, authors suggested a learning method for robots using motor imagery [8]. The outline is shown in Fig. 13. First, the robot acquires a model (forward model) of its own body and environment by real motion as shown in Fig. 13 (a). Then, the robot acquires the pattern of motion generator by "motor imagery" using forward model through evolution using genetic algorithms as shown in Fig. 13 (b). Then it can generate adequate motion for the given environment and body dynamics as shown in Fig. 13 (c). The robot used in this study is shown in Fig. 13 (d).

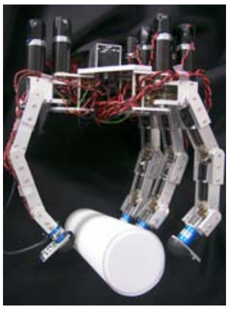
D. *Hierarchical control of grasping and manipulation*

One of the features of living creatures is that they have hierarchical control systems. As an example of bio-mimetic control, authors have suggested a control method focusing on the hierarchical relationship between grasping and manipulating [9]. Grasping is to control grasping force stably so that robot fingers do not drop an object in its grasp. Manipulating is to change touching fingers to move the object. Hence, hierarchical control method is proposed as shown in Fig. 14. The grasping controller is assumed to be in the lower layer to grasp an object stably. Manipulation controller is to plan the manipulation pattern. It is also used to suppress the grasping controller by giving a signal to the suppresser when the touching finger is changed. If the grasping controller is active when the manipulation controller plans to change the finger grasping the object, it is difficult to reduce the grasping force. Hence, the effect of the grasping controller is restrained when the manipulating torque is large enough.

This method is applied to a real robot hand as shown in Fig. 13 (b) and cooperative control between grasping and manipulating is successfully achieved. Authors are planning to apply this method for more complex tasks.



(a) Block diagram of manipulation/grasping control



(b) Model of robot hand

Fig. 14 Hierarchical control method of grasping and manipulation

V. CONCLUSIONS

First, actuators and sensors imitating the geometry and movement of living creatures are shown. The design of a ring-type ultrasonic motor imitating the locomotion of soft-bodied creatures utilizing traveling waves in the body is shown. Then, it is shown that the response of mechanoreceptors of human fingers can be understood by analyzing contact problems between a fingerpad and an object using the finite element method. Designed artificial tactile sensors imitating the human finger are shown as well. Second, examples of robots imitating the design strategy of living creatures are shown. Evolutionary bottom-up design of geometry and movement are focused on. Earthworm, caterpillar and inchworm locomotion is generated using genetic algorithms showing that stiffness and environment are important for generating their specific locomotion patterns through evolution. Then the optimum motion and morphology of moving robots is designed using evolutionary computation including genetic algorithms and genetic programming. Layered control design strategy of grasp and manipulation are also shown. Manipulation is successfully conducted by the layered control scheme imitating higher and lower feedback loops of creatures.

ACKNOWLEDGMENT

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