Proceedings of the 2002 IEEE
International Conference on Robotics & Automation
Washington, DC • May 2002

A Method for Co-Evolving Morphology and Walking Pattern of Biped Humanoid Robot

Ken Endo, Fuminori Yamasaki, Takashi Maeno and Hiroaki Kitano

Abstract— **In this paper, we present a method for co-evolving structures and controller of biped walking robots. Currently, biped walking humanoid robots are designed manually on trial-and-error basis. Although certain control theory exists, such as zero moment point (ZMP) compensation, these theories assume humanoid robot morphology is given in advance. Thus, engineers have to design control program for apriori designed morphology. If morphology and locomotion are considered simultaneously, we do not have to spare time with trial-and-error. Therefore a method useful for designing the robot is proposed .**

At first, the simple models of both morphology and controller are used for the dynamic simulation, which are multi-link model as morphology and two kinds of controllers. One is a layered neural network and the other is neural oscillator. The robots with the optimal energy efficiency of walking are designed with Genetic Algorithm.

As a result, various combinations of morphologies and gaits are generated, and obtained relationship between length of each link and moving distance which gives the optimal energy efficiency. Moreover, the robots are encoded from limited size of chromosomes.

Keywords— **Biped Walking, Genetic Algorithm, Neural Network, Oscillator.**

I. INTRODUCTION

Traditionally, robot systems have been used dominantly in factories for high-precision routine operations. In recent years, there are increasing interest in robotics systems for non-traditional use, as represented by Sony's AIBO, several prototype attempts for home robotics, rescue robots, etc. Among various possible robot shapes, human-like robots, humanoids, are of particular interests because of its visual appeal and less need to modify environment since robots has the same degree of freedom as humans to fit into our living space. Numbers of humanoid robots have been developed aiming at possible deployment for office and home [1],[2]. However, all of them require expensive components and extensive time to design and construct elaborate humanoids.

For humanoid to share a serious proportion of robotics industry, however, low-cost and faster design cycle is required. Research for low-cost and easy-to-design humanoid is essential for industrial exploration. To promote this avenue of research a humanoid robot PINO [3] was developed with well designed exterior as shown in Fig. 1, and only using off-the-shelf components. In addition, all technical information for PINO was disclosed under GNU General Public License, as OpenPINO (http://www.openpino.org/), to facilitate open evolution.

There are several interesting issues. First, one of the challenges is to identify methods to control such robots to walk and behave in a stable manner by overcoming lack of torque and non-trivial backrush, because only cheap servomotors for radio-controlled toys are used to lower the cost. Assuming the current structural design of PINO, the use of traditional ZMP-compensation method did not fits well as it requires sufficient torque and precision to stably control the robot[4]. A new control methods need to be discovered to control the robots to walk in a stable manner.

Second, a current structural design is not proven to be optimal, and it will never be proven to be optimal because control methods are generally designed assuming specific hardware is given. What we wish to attain is to optimize both morphology and control at the same time, so that it is optimized for the walking behavior, instead of optimizing walking behavior

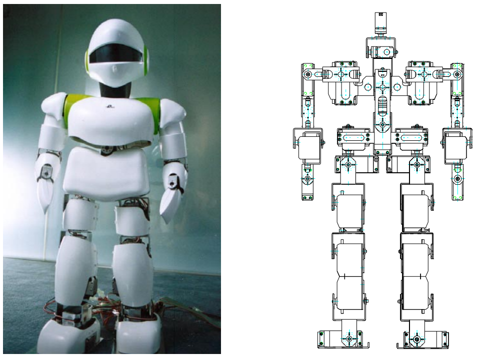


Fig. 1. Humanoid Robot PINO

K. Endo is with Kitano Symbiotic Systems Project, ERATO, JST, Tokyo, Japan and Keio University. E-mail : endo@symbio.jst.go.jp

F. Yamasaki is with Kitano Symbiotic Systems Project, ERATO, JST, Tokyo, Japan and Osaka University. E-mail : yamasaki@symbio.jst.go.jp

T. Maeno is with Mechanical Engineering in Keio University. E-mail : maeno@mech.keio.ac.jp

H. Kitano is with SONY Computer Science Labolatories and Kitano Symbiotic Systems Project, ERATO, JST, Tokyo, Japan . E-mail : kitano@symbio.jst.go.jp

0-7803-7272-7/02/$17.00 © 2002 IEEE

for the given hardware. This is important for open evolution of robotics system, such as OpenPINO.

Our position is to learn from evolution of living systems on how they have developed morphology and control systems at the same time. What we should learn from the living creatures is not the structures and components themselves but how they have been emerged during evolution. Optimum structures of robots can be designed when the suitable components and locomotions for the robots are selected appropriately through evolution.

An artificial life is one of the answers. Sims [5] generated robots that can walk, jump and swim in computer simulation. He also generated virtual creatures which compete each other to obtain one resource [6]. Ventrella [7] presented evolutionary emergence of morphology and locomotion behavior of animated characters. Kikuchi and Hara [8] studied a method of evolutionary design of robots having tree structure that change their morphology in order to adapt themselves to the environmental conditions. However, all of them do not consider how to make practical robots.

On the other hand, evolutionary method has been tried to apply to the practical robots. Kitamura [9] used Genetic Programming(GP) [10] to emerge the simple linked-locomotive robot in virtual space. Lipson [11] adopted the rapid prototyping to produce the creatures that were generated in three-dimensional virtual space. However, all of them are far from practical robots.

Until now, we have developed the method for designing the morphology and neural systems of multi-linked locomotive robots [12]. Both the morphology and neural systems are represented as a simple large tree structure and both of them are optimized simultaneously using evolutionary computation. This method can be applied to develop a humanoid robot. In this paper, we generate the link-type biped walking robot that can walk efficiently as the simple problem of the simultaneous optimization of morphology and locomotion of robot. The robots move on the flat ground in the two-dimensional lateral world under the effect of the gravity. As the control systems, two kinds of method are used. One is Neural Network and the other is neural oscillator. The problem for designing such robots was treated as a multi optimization problem (MOP). It was shown, as a result, that the generated robots have diverse morphology and control system and their biped walking are fast and efficient. Moreover, the robots with optimal walking pattern are emerged with a limited size of chromosomes.

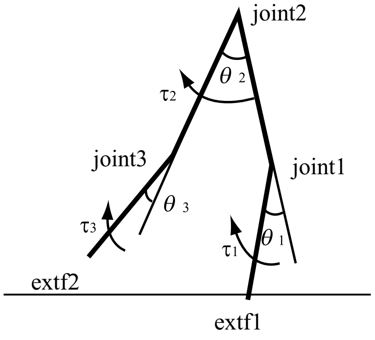


Fig. 2. model of robot

II. Materials and methods

A. Morphology

Humanoid robots are composed of large numbers of components including sensors and actuators. Thus it is difficult to consider optimal choice of all of them simultaneously. In order to develop the method that both the morphology and locomotion emerges, the simple models are used for the dynamic simulation at first. The model of robot as shown in Fig. 2 are used. This two-dimensional model is composed of four links and the length of each link changes through the evolution while the total length is constant. Joints are numbered as joint 1, 2 and 3 as shown in Fig. 2. Driving torque of each joint can be changed from -1.0 Nm to 1.0 Nm reflecting torque of the real robots. The joint 1 and 3 have the range of motions between 0 and $\pi/2$ and joint 2 has the range between $-\pi/2$ and $\pi/2$. Density of link is 0.314 kg/m and the length of one leg is 0.28 m. These parameters are based on PINO, so as to improve the structure of PINO in the future. These parameters are constant though the lengths of upper and lower limbs change in the process of GA.

B. Control System

Various kinds of control methods for biped walking robots have been applied[13][14]. However these approaches explore a narrow design space of walking pattern because the morphologies are given in advance. In this paper, the morphologies of robots change through the evolution. Therefore, the various kinds of walking patterns have to be generated from the controller.

First, a layered neural network is used to control the robot. The number of links and joints that compose the robot does not change. Therefore, there are three neurons for each angle of joint in the output layer. The velocity, acceleration of each joint, location of each links and zero moment point have not been considered for input to neural network because it makes the length of chromosomes larger.

In the structure of controller, a pair of hidden layers

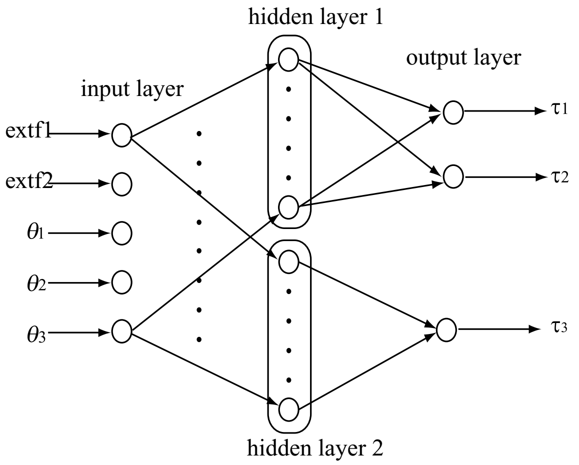


Fig. 3. structure of neural network

are located parallel to each other in control system as shown in Fig. 3. The neuron as shown in Fig. 4(a) is the one in hidden layer 1 and Fig. 4(b) is one in hidden layer 2. $\theta_{1,2,3}$ are the angle of each joint and ext1 and ext2 are the external force of feet from the ground, respectively. If the weights of the neuron of hidden layer 1 are distributed as Fig. 4(a), the weights of the opposite neuron in hidden layer 2 are changed like Fig. 4(b) because biped walking is accomplished with moving the both legs symmetrically. For example, if the robot has the controller which generate driving torque τ at the joint 1 when the posture of the robot is left one of Fig. 5, this controller also generate τ at joint 3 when the posture is right one in Fig. 5 to continue cyclic biped walking. It enables the robots to do the same action if the states of two legs are exchanged, and the length of chromosomes to decrease. The activation of each neuron is computed by

$$a = \sum_{i=i}^{n} w_{ij} O_i \tag{1}$$

where O_i is the output of neuron in previous layer, and w_{ij} is the weight of the synapse connecting them. The output of this neuron is then given by

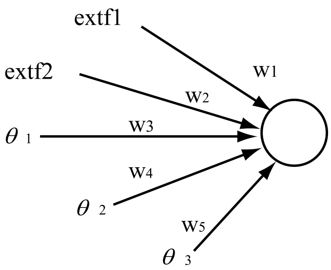
$$O = \frac{1}{1 + e^{-a}} \tag{2}$$

With this, the values of neurons in output layer vary from 0 to 1. Driving torque of each joint is defined by

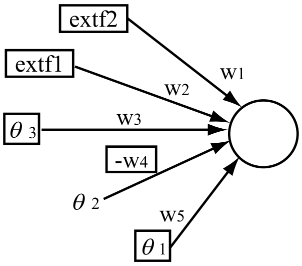
$$\tau_i = 2.0 \times (O_i - 0.5) \tag{3}$$

With this, the driving torque varies from -1.0 Nm to 1.0 Nm.

C. Genetic Algorithm



(a) neuron of hidden layer 1



(b) neuron of hidden layer 2

Fig. 4. difference of hidden layer 1 and 2

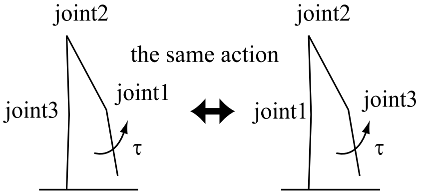


Fig. 5. the work of controllers

GA is a method for optimization based on the evolution of creatures. GA has been used for many complex problems [15]. In this paper, a fixed length genetic algorism is used to evolve the controllers and morphologies. Each chromosome includes the information of initial angle, velocity, length of each link and weights of each neuron in layered neural network. Robots with low-fitness are eliminated by selection, and new robots are produced using crossover and mutation. Then their morphologies and control systems are generated from generation to generation and, finally, converge to a reasonably optimal solution.

Crossover is the operation to exchange some parts of chromosomes due to their fitness. Crossover can exchange the same length of the parts of chromosomes. In this way, the length of total chromosomes does not change. Selection is operated due to finesses of the robots. The larger the fitness is, the easier the robot tends to be selected. Mutation is the operation to change the part of some chromosomes of robots selected randomly. This operation also works without changing the total length of chromosomes. With these operations, the only robots with large fitness can sur-

TABLE I
GA PARAMETERS

	first phase	second phase
population size	200	200
generation	600	300
crossover ratio	0.6	-
mutation ratio	0.01	0.01

vive.

However biped walking is highly difficult locomotion. In order to generate biped walking, two steps of GA are applied.

At the first phase, the evaluate function,

$$f_{distance} = l_g \tag{4}$$

is used, where l_g is a distance between the center of mass of robots and the initial point. That is to say, just the walking distance is evaluated. This first step of GA emerges just biped walking locomotion that the robot lifts one leg up, at first, brings it forward, and lifts another leg up when the swing leg get contact with the ground.

At the second phase, the design of robot is taken as the multi optimal problem, with which two evaluate functions are considered. Robots are evaluated both by the efficiency and stability of walking with two evaluate fitness as follow.

$$\begin{aligned} f_{efficiency} &= \frac{10}{1+\int_t(\sum_i|\tau_i|)dt} &\quad (5)\\ f_{movability} &= \sum_{k=1}(step_o - |step_k - step_0|) &\quad (6) \end{aligned}$$

τ_i is a driving torque of joint i, $step_0$ is the length of first step of the robot and $step_k$ is the length of 'k'th step. With equation (5), robots can obtain high $f_{efficiency}$ when they can walk efficiently. And with equation (6), they can get high $f_{movability}$ when robots can walk stablly. If both feet of robot are not in contact with ground, simulation is terminated. Moreover any part of the robot without the foot get contact with the ground, simulation is also terminated. These constraint prevent the simulation from wasting time. With these conditions, GA emerges biped waling robot that can walk stably and efficiently.

The parameters of each step of GA are as shown in Table 1.

III. RESULT OF NN

The best robot at the first step lifts one leg up, brings it forward and lifts another leg up when the swing leg gets contact with the ground, which is the basic locomotion of biped walking. Therefore, the purpose of the first step is accomplished.

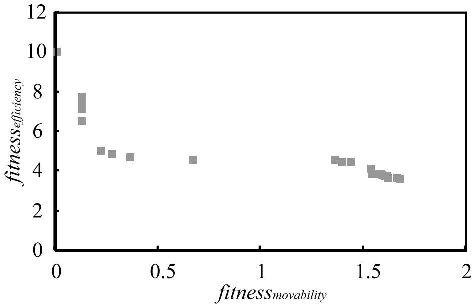


Fig. 6. pareto optimal solution of the second phase

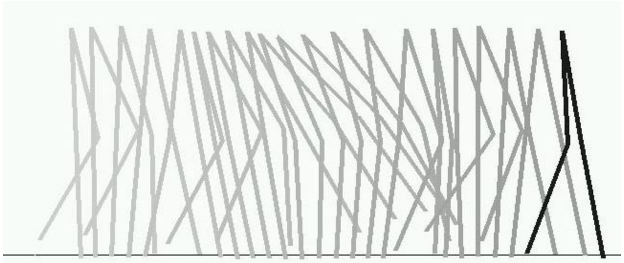


Fig. 7. the locomotion of preferred solution in the second phase

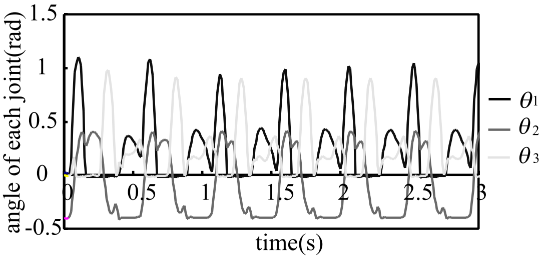


Fig. 8. angle of each joint of preferred solution

After the first step of GA, the second step is conducted. The best 20 robots of the first step are included in the initial population. This procedure causes the calculation to be completed easily. The result is shown in Fig. 6. It shows the pareto optimal solutions at 300 generation of the second step. The only robots which have less than about 5.0 in $f_{efficiency}$ can walk. It means that robots need a certain driving torque to be generated at each joint in order to keep walking. We selected the robot with the best $f_{movability}$ as the preferred solution.

Biped walking of preferred solution is shown in Fig. 7 and change of angle of each joint is shown in Fig. 8. This robot can walk with periodical locomotion. We can say this locomotion is stable and efficient because this robot is pareto optimal solution. Any pareto optimal solutions with less $f_{efficiency}$ are not emerged. It means that the robot cannot walk longer

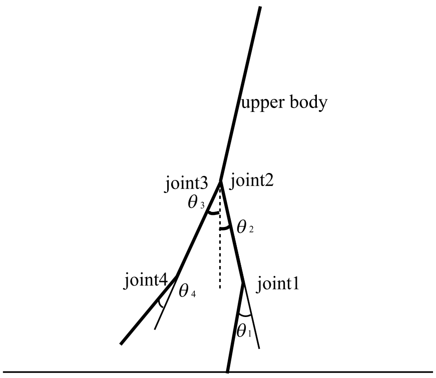


Fig. 9. model of robot

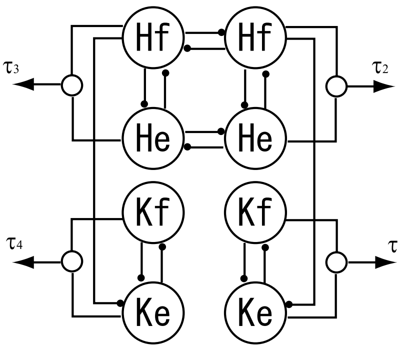


Fig. 10. model of control system of neural oscillators

than preferred solution even though it can generate more torque. Moreover, this morphology is suitable for this locomotion because both of them are considered through the evolution. That is to say, the preferred solution has appropriate locomotion and morphology. It also means that the optimal combination of two finesses exist in the hyper-space we defined and it is the preferred solution.

IV. Neural Oscillators

The robot which can walk efficiently is emerged with the model of neural network. However, the model of the body is too simple and its walking patter is not natural. That is because the length of chromosomes is too large for GA to model the robot, and the velocity, acceleration of each joint are not included in the input to the control system. In order to solve these problems, the neural oscillators are used because the biped walking is the periodical and symmetrical motion. Until now, many studies of neural oscillators have been conducted[16]. Neural oscillator can generate the rhythm for the biped walking. Unlike the neural network, not so large length of chromosome is needed. However any application for the real robots is not accomplished.

In this time, the model of body as show in Fig. 9 is used. Unlike the former model, this model has the upper body with length of 0.3 m and the mass of 1.0 kg. This causes the increase of the length of chromosomes. However, It doesn't matter for the neural oscillators because the needed length of chromosome for neural oscillators is not so large. Of course, the each length of the upper and lower limbs changes in the process of the evolution.

The structure of neural model is decided as shown in Fig. 10 according to the basic biped walking locomotion. The action of each neuron is expressed as follow.

$$T_i\dot{u}_i = -ui - \sum_{ij} w_{ij}y_j - \beta v_i + U_0 + \sum_k FB_k \quad (7)$$

$$T'_i\dot{v} = -v_i - y_i \quad (8)$$

$$y_i = max(0, u_i) \quad (9)$$

where FB_k is a feedback signal from the body of robot such as the angle of each joint or external force of the foots, u_i is the inner state of the ith neuron, y_i is the output of the ith neuron, v_i is a variable representing the degree of the adaptation or self-inhibition effect of the ith neuron, u_0 is an external input with a constant rate, w is a connecting weight, and T_i and T'_i are time constants of the inner state and the adaptation effect, respectively. Note that the velocity of each joint, acceleration of each joint are not included in the FB because the same condition is used as the neural network model except for the body. However the maximum driving torque is ±2.0 Nm.

The condition such as the parameters of GA, dynamic simulation, evaluate functions are the same as those of the model with neural network.

V. RESULT OF NEURAL OSCILLATOR

The result of the second step has the same tendency as that of the model with neural network, that is, a certain degree of output torque is needed for biped walking. The walking pattern of the robot which can walk the longest distance is shown in Fig. 11. Even if this model has the upper body, it can keep walking. Of cource, like the model of NN, this morphology is suitable for this locomotion because both of them are considered through the evolution. The change of each angle is shown in Fig. 12. In fact, the size of chromosome is smaller than the former model. However the similar pattern is emerged.

VI. DISCUSSION

The walking patterns of two robots with neural network and neural oscillators are similar, even though the sizes of chromosomes are much different. The controller with neural network is encoded from almost

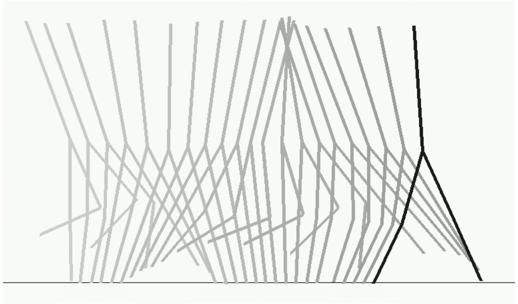


Fig. 11. walking pattern

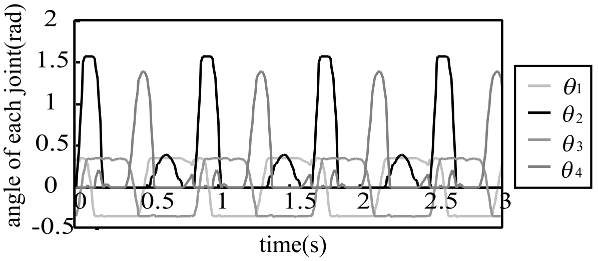


Fig. 12. the change of each angle

1000-bit-size chromosome and that with neural oscillator is encoded from only about 300-bit-size. It means that neural oscillator is enough to generate the rhythm for the biped walking even though its hyperspace is smaller than that of neural network. Therefore larger model such as three-dimensional model as well as the model with arms and foot-plates can be applied to the model with neural oscillators. Moreover, the preferred solution of the model with oscillators has the 0.13 m lower limbs, even if the preferred solution of the model with neural network has 0.15 m lower limbs. That means that there is the close relationship between the morphology and locomotion. If the condition of the robot changes, the optimal solution also changes. Therefore, it is useful to consider both morphology and locomotion. The co-evolution of the morphology and control system may be a potentially powerful method for the design of the real robot.

VII. CONCLUSION

In this paper, the basic method for co-evolving the morphology and control system is proposed. Although biped walking is highly difficult locomotion, the robots which can walk stably and efficiently are emerged in this method with two step GA. Furthermore walking locomotion is accomplish using limited size of chromosome.

As the next step, the walking pattern with extensive sensor information such as velocity of each joint, zero moment point, can be created and integrated into this system. The use of three dimensional model is an important next step. Moreover, reproduction of the PINO or construction of other type of robots based on this method is planned to confirm the effectiveness of this method.

ACKNOWLEDGMENTS

The dynamic simulation is supported by M Ogino in Osaka University and the exterior is designed by T Matsui. We appreciate the members of Maeno laboratory, Prof. Yamazaki in Keio University, and Symbiotic Intelligence Group in Kitano Symbiotic Systems Project for their support and discussions.

REFERENCES

[1] Inaba, M., Kanehiro, F., Kagami, S. and Inoue, H., "Two-armed Bipedal Robot that can Walk, Roll Over and Stand up", *Proc. of International Conference on Intelligent Robots and Systems*, 1995.

[2] Hashimoto, S. Narita, S., Kasahara, K., Shirai, K., Kobayashi, T., Takanishi, A., Sugano, S., et. al, "Humanoid Robots in Waseda University – Hadaly-2 and WABIAN", *Proc. of The First IEEE-RAS International Conference on Humanoid Robots*, vol. CDROM, 2000.

[3] Yamasaki, F., Matsui, T., Miyashita, T. and Kitano, H., "PINO The Humanoid that Walk", *Proc. of The First IEEE-RAS International Conference on Humanoid Robots*, vol. CDROM, 2000.

[4] M. Vukobratović, B. Borovac and D. Šurdilović, "Zero-Moment Point – Propoer Interpretation and New Apprications", *Proc. of The Second IEEE-RAS International Conference on Humanoid Robots*, vol. CD-ROM, 2001.

[5] Karl Sims, "Evolving Virtual Creatures", Computer Graphics Proceedings", *Computer Graphics Proceedings*, pp. pp.12–22, 1994.

[6] Karl Sims, "Evolving 3D Morphology and Behavior by Competition", *Artificial Life IV*, pp. pp.28–39, 1994.

[7] J. Ventrella, "Exploration in the Emergence of Morphology and Locomotion Behavior in Animated Characters", *Artificial Life IV*, pp. pp. 436–441, 1994.

[8] Kohki Kikuchi and Fumio Hara, "Evolutionary Design of Morphology and Intelligence in Robotic System", *Proceedings of the fifth international conference on SAB*, pp. pp. 540–545, 1998.

[9] Shinzo Kitamura, Yuzuru Kakuda, Hajime Murao, Jun Gotoh and Masaya Koyabu, "A Design Method as Inverse Problems and Application of Emergent Computations", *SICE*, vol. Vol.36, no. No.1, pp. pp. 90–97, 2000.

[10] J. Koza, *"Genetic Programming II"*, MIT Press, 1994.

[11] H. Lipson and J. B. Plollack, "Automatic design and manufacture of robotic lifeforms", *Nature*, vol. Vol.406, no. No.6799, pp. pp. 974–978, 2000.

[12] Ken Endo and Takashi Maeno, "Simultaneous Generation of Morphology of Body and Neural System of Multi-Linked Locomotive Robot using Evolutionary Computation", *Proceedings of the 32nd International Symposium on Robotics*, vol. CDROM, 2001.

[13] T. McGeer, "Passive dynamic walking", *The International Journal of Robotics Research*, vol. Vol.18, no. No.6, pp. pp.62–82, 1990.

[14] Ono, K., Takahashi, R., Imadu, A. and Shimada, T., "Self-Excitation Control for Biped Walking Mechanism", *Proc. of International Conference on Intelligent Robots and Systems*, vol. CDROM, 2000.

[15] Kitano, H., "Designing neural networks using genetic algorithms with graph generation system", *Complex System*, pp. pp.454–461, 1990.

[16] Taga, G., "A model of the neuro-musculo-skeltal system for human locomotion", *Biol. Cybern.*, pp. pp.97–111, 1995.