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Co-evolution of Morphology and Walking Pattern of Biped Humanoid Robot using Evolutionary Computation
-Consideration of characteristic of the servomotors-

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Abstract

In this paper, we present a method for co-evolving morphology and controller of bi-ped humanoid robots. Currently, bi-ped walking humanoid robots are designed manually on trial-and-error basis. Thus, engineers have to design control program for apriori designed morphology, neither of them shown to be optimal within a large design space. We propose evolutionary approach that co-evolves the morphology and controller. Two steps of co-evolutions were achieved in a precision dynamics simulator. One is for obtaining the optimal lengths of links using simple multi-link model and the other is for obtaining the optimal geometry of servomotor which is often used for radio control car. Finally, unexpected optimal solutions were discovered. This indicate that a complex design task of bi-ped humanoid can be performed automatically using evolution-based approach, thus varieties of humanoid robots can be designed in speedy manner.

1 Introduction

Until now, many types of robots have been developed, and utilized mainly in factories for high-precision routine operations. Recently, robots for non-traditional use attract many interests as represented by Sony's AIBO, rescue robots, and so on. Especially, humanoid robots are of particular interests because they can walk in the same environment as human, do complex tasks and less need to modify environment since robots have same degree of freedoms to fit into the operational space. Numbers of humanoid robots have been developed aiming at possible deployment of humanoid for office and home [1],[2]. However, all of them requires expensive components and extensive time to design and construct elaborate hum1 anoids because development of robots need many times of designs, produces and controls with trial-and error method. Morph is the humanoid robot which is composed of low-costed components[3]. It has high-range of motion, and can perform acrobatic motions. However, research of long years was needed to develop this robot.

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 by needed for industrial exploration. To promote this avenue of research a humanoid robot PINO [4] was developed with well designed exterior only by 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.

However, assuming the current structural designed of PINO, the traditional ZMP-compensation method [5] or inversed pendulum model [6] cannot be applied. Moreover, a current structual designed is not proven to be optimal, and it will never be proven, 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 for the given hardware. This is important for open evolution of robotics system, such as OpenPINO.

Our position is that we can 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 only when the suitable components and locomotions for the robots are selected appropriately through evolution. Design of the robots, by the robots, for the robots, should be achieved using evolutionary method, whereas design-

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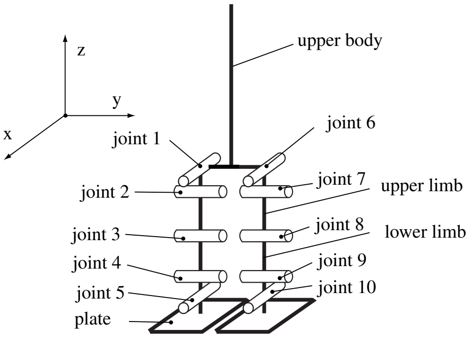


Figure 1: *model of robot*

ers of the robots should only set up an environmental constraint condition for the robots.

An artificial life is one of the answers. Sims [7] generated robots that can walk, jump and swim in computer simulation. He also generated virtual creatures which compete each other to obtain one resource [8]. Ventrella [9] presented evolutionary emergence of morphology and locomotion behavior of animated characters. Kikuchi and Hara [10] 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 [11] used Genetic Programming, GP [12], to emerge the simple linked-locomotive robot in virtual space. Lipson [13] 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 controller of biped walking robot [14]. In this paper, two steps of co-evolutions were achieved in a precision dynamics simulator using three dimensional model. At the first step, simple multi-link model is used and the optimal length of each link and walking pattern are obtained. At the second step, we assume the servomotors for radio control cars are used like PINO and their optimal geometries and walking pattern are obtained.

2 Materials and Methods

Biped walking is highly difficult locomotion. Therefore, two steps of calculations are conducted. In the first step, the basic walking pattern is emerged using the simple link-type model. After the first steps, much detailed model is used in the second step. In this section, materials and method of GA are introduced.

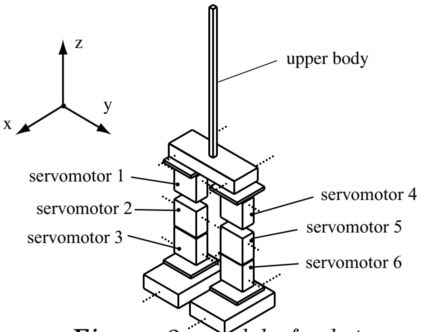
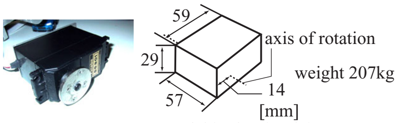


Figure 2: *model of robot*



servomotor model in the simulaiton

Figure 3: *servomotor*

2.1 Morphology of The First Step

Humanoid robots are composed of large numbers of components such as sensors, actuators and so on. It is difficult to consider optimal choice for all of them simultaneously. In order to develop the basic method for generating both of morphology and controller, at first, the simple models are needed for the dynamic simulation. Therefore, the multi-link model of robot as shown in Fig. 1 is used. This three-dimensional robot is composed of 11 links for body and legs, and two plates for each foot. The length of five links for upper body, upper and lower limbs change during the evolution though the total length of all links is constant. Joints are numbered as joint 1 to 10 as shown in Fig. 1. Driving torque of each joint can be change from -2.45 Nm to 2.45 Nm reflecting the real robots. The joint 3 and 8 have the range of motions between 0 and $\pi/2$ and other joints have the value between $-\pi/2$ and $\pi/2$, respectively. Densities of the links of leg and upper body are 0.314kg/m and 4.557kg/m, respectively, 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 body, upper and lower limbs of the robot change in the process of GA.

2.2 Morphology of The Second Step

At the second step, we used the model as shown in Fig. 2 because PINO's structure is considered. This model is composed of eight parts and six servomotors. The geometries of servomotor 1 to 6 are emerged through the evolution. In fact, we have redesigned these parts many times in order to control the robot easily. That is to say, these parts are

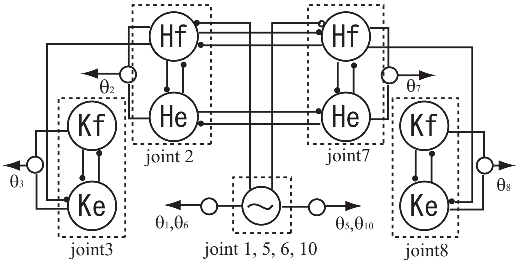


Figure 4: *structure of control system*

important for walking motion. Servomotor has the characteristic as shown in Fig. 3. This motor has the PD control system inside. The system identification was conducted in advance[15] and these parameters are used in the dynamic simulation. In this time, the interferences of motors are ignored to simplify the problem.

2.3 Controller

Many researches for generating the locomotion of artificial lives or robots with neural network and evolutionary computation have been conducted[16][17]. However the size of chromosomes becomes too large to generate the valid solution considering both the morphology and locomotion simultaneously. Moreover we have to take the velocity of all joints and external force from the ground in account to control the robots for stable walking. In the biomechanical field, pattern generators are often assumed to be exist for generating the walking pattern of human because the bi-ped walking is the periodical and symmetrical motion, and the structure of the control system can be decided in advance. Until now, many studies of neural oscillators have been conducted. The control system composed of neural oscillators can generate the rhythm for the bi-ped walking. Unlike the recurrent neural network, not so large size of chromosome is needed. However any application for the real robots has not been accomplished. Our goal is to propose the designing method that can generate the detail structure and controller of bi-ped humanoid robot. Therefore we can make minimal the difference between the real world and computer simulation with our method.

The structure of control system is decided according to the basic locomotion of bi-ped walking as shown in Fig. 4. Hf and He are neurons for the hip joints. Kf and Ke are neuron for knees. The action of each neuron is expressed as follow,

$$\begin{aligned} T_i \dot{u}_i &= -u_i - \sum_{ij} w_{ij} y(u_j) - \beta y(v_i) \\ &\quad + U_0 + \sum_k FB_k \end{aligned} \tag{1}$$

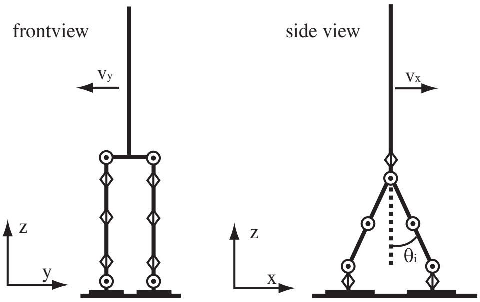


Figure 5: *initial state*

$$\begin{aligned} T'_i \dot{v} &= -v_i - y_i \quad (2) \\ y(x_i) &= \frac{1}{1+e^{-\tau(x_i)}} \quad (3) \end{aligned}$$

where FB_k is a feedback signal from the body of robot such as the angle of each joint or external force of the feet, u_i is the inner state 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. The neuron at the bottom of Fig. 4 is for joint 0, 5, 6, and 10 that generates only sinusoidal signal. In the white circle in Fig. 4, the desired trajectory of each joint is given as follows;

$$\theta_k = p_k(y(u_{k1}) - y(u_{k2})) \tag{4}$$

where, θ_k is the desired trajectory and p_k is the gain for the joint k. The desired trajectory of joint is given from the output of neurons. Thus the driving torque of each joint is given with controlling the angle of joints to desired trajectory with PD control. However the maximum driving torque is ±2.45 Nm and each gain for PD control are decided in advance. The plates of feet are kept parallel to the ground. This method is often used for bi-ped humanoid robot in order to make the problem simple.

This model is used in the first and second step.

2.4 Simulation

The environment which robots walk on is a flat ground. When the dynamic simulation starts, the posture of the robot is set to be the initial position as show in Fig. 5. Initial angle of θ_i and velocity v_x,v_y are decoded from chromosomes. When the dynamic simulation begins, the controller starts to work and generate driving torque at the each joint. The only robots with controller that generates the rhythm for walking can keep walking. If the knee, hip and other parts of body of robots start to be contact in with the ground or the motion of robot continue staying at the same place for 0.5 s, simulation is over and next one begin in order to avoid wasting the time.

Dynamic simulation is conducted for 5 s per a robot. The motion of robots is calculated from their interaction with the environment by the forth order Runge-Kutta method. One time step is 0.2 ms. Contact response with ground of the links is accomplished by a hybrid model using spring and damper under the influence of friction and gravity. The friction is large enough for robots not to slip while they are walking. This conditions is utilized for both the first and second step.

2.5 Evolutionary Computation

GA is a method for optimization based on the evolution of creature. GA has been used for many complex problems[18]. In this paper, a fixed length genetic algorithm 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 control systems. Here, we use the GA which deal with real number from 0 to 1. Robots with low-fitness are eliminated by selection. New robots are produced using crossover and mutation. Then their morphologies and controller are generated from generation to generation, and ,finally, converge to a reasonably optimal solution.

Crossover is the operation to create new children in the next generation from parents selected due to their fitness. Here, BLX-α [19] is used as the crossover for real number GA. BLX-α is useful for generating the walking pattern because this crossover can explore the best solution more certainly in the middle or latter part of calculation, that is to say, this method can adjust the walking pattern in detail. Each factor in the chromosomes is decided as follow:

$$\begin{aligned} c_{1i,2i} &= u(min(p_{1i}, p_{2i}) - \alpha I_i \\ &\quad , max(p_{1i}, p_{2i}) + \alpha I_i) \qquad (5) \\ I_i &= |p_{1i} - p_{2i}| \qquad (6) \end{aligned}$$

where $p_1 = (p_{11} \cdots p_{1n})$, $p_2 = (p_{21} \cdots p_{2n})$ are parents, $c_1 = (c_{11} \cdots c_{1n})$, $c_2 = (c_{21} \cdots c_{2n})$ are children, and $u(x, y)$ is the uniform deviates from x to y. Here α is set to 0.05. 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 is selected. Mutation is the operation to change the part of some chromosomes of robots selected randomly. When mutation occurred to c_i, the new factor c_n is given as follow:

$$c_n = c_i + \frac{rand_g}{10} \qquad (7)$$

where $rand_g$ donates the gaussian deviates. This operation also works without changing the total length of chromosomes. With these operations, the only robots with large fitness can survive.

Through the evolution, walking distance of all robots are evaluated. As the evaluate function,

$$fitness = l_g \qquad (8)$$

is used, where l_g is distance of the center of mass of robots from the initial point. With this function, robots are evaluated just by the walking distance.

The parameters of GA is as shown in Table 1. Moreover we use the elite preservation strategy at the same time. Both the first and second steps are conducted under this condition.

Table 1: *GA parameters*

population size	100
generation	300
crossover ratio	0.8
mutation ratio	0.05

3 Results and Discussions

3.1 The First Step

Calculation using GA is conducted for the models mentioned above. The best fitness and average of all the generation is shown in Fig. 6. At first, all robots can walk only a little distance and fitnesses are low. Gradually, the robots that can walk are emerged and their walking distance increase. Finally, some robots keep walking till the end of dynamic simulation.

The walking pattern of the best robot at the final generation is shown in Fig. 7. Angle of each joint during walking is shown in Fig. 8. This robot has 0.667m of upper body, 0.1309m of upper limbs and 0.0726m of lower limbs. When the real robot is constructed, these parameters can be useful.

After the calculation, the basic walking pattern is emerged in which the robot lifts one leg up, brings it forward and lifts another leg up when the swing leg touches the ground. Note that this robot walk with both of joint of knees $\theta_{3,8}$ kept straight. There are three possible reasons. This is because, At first, robot has low compliance at all joints because of PD controller. Human has the compliant joints and make use of this compliance to walk passively. Therefore, human walks efficiently with swing leg bended. Secondly, this robot walks only on the flat ground through the evolution. If the ground has some slope, or the shape is not regular, robots cannot walk with this walking pattern. This is the problem on the environment that robots walk on in the dynamic simulation. Finally, the other evaluations such as efficiency of walking and so on, are not considered

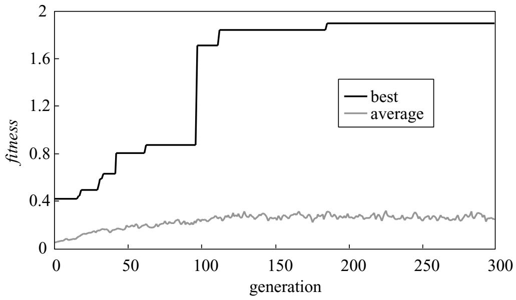
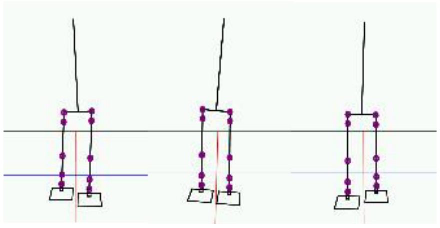
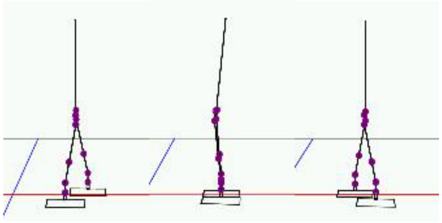


Figure 6: *change of fitness*



(a)front view



(b)side view

Figure 7: *walking pattern of the best robot*

through the evolution. Here, we pay attention to the development of basic method for co-evolution of morphology and controller. In the next section, the characteristic of servomotor is considered in the dynamic simulation and optimal geometries of each motors are searched.

3.2 The Second Step

Calculation using GA of the second step is conducted for the models mentioned above. The walking pattern of the best robot at the final generation is shown in Fig. 9. Unlike the best robot in the first step, legs are bent when the supprting leg is released from the ground. This walking pattern is emerged when the characteristics of servomoter such as the gain of PD controller, max-torque, inertia and so on are considered. Moreover, the footplates is defferent from one of the first step, for example the size, position to connect with ancles. These structure and materials causes the robot to walk in this way. In other words, this walking pattern is valid when the robot is developed with these servomotors.

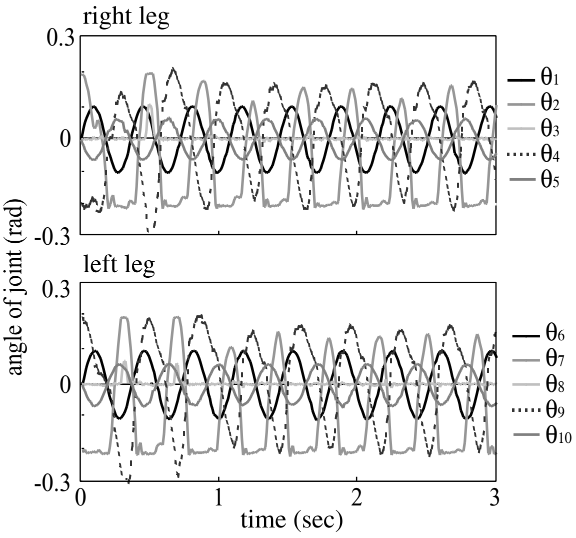
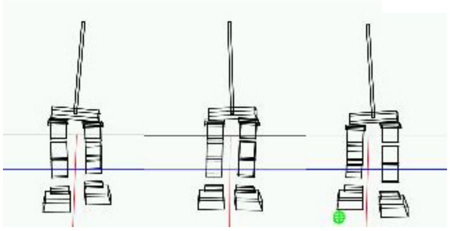
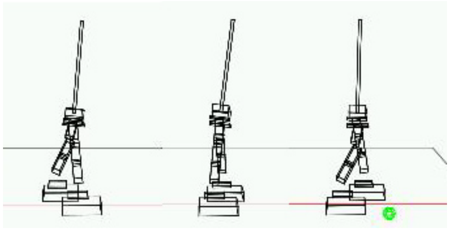


Figure 8: *angle of joint during walking*



(a)front view



(b)side view

Figure 9: *walking pattern of the best robot*

In this step, the detailed model of robot was emerged as mentioned above. The structure of the best robot of the second step is shown in Fig. 10. Usually, dynamic simulation is conducted under the condition that that the structure is given. It is because the it is hard to consider both the structure design and locomotion control. However, this traditional procedure is not suitable because the morphlogy and locomotion has the close relationship. This model as shown in Fig. 10 has the morphology which is emerged with the method in which the morphology and locomotion is generated simultaneously. This model is composed of the six servomotors and other parts. Therefore, this can be one clue for designing the humanoid robot which is composed of servomotors. Moreover, control of the robot developed according this model is easier than traditional developed robot.

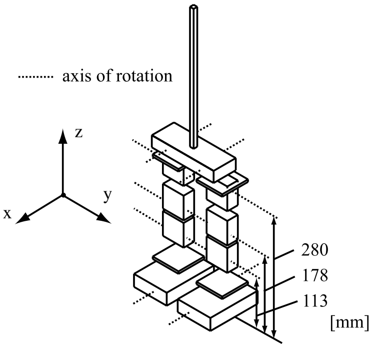


Figure 10: *model of the best robot*

4 Conclusions

In this paper, we present a method for co-evolving morphology and controller of bi-ped humanoid robots. We propose evolutionary approaches that enables that co-evolution of morphology and control. Two step of co-evolution were achieved and discovered unexpected optimal solutions. It was that robot walk with both swing and supporting legs kept straight. Moreover, the detail structure and walking pattern are obtained using the model considering the characteristics of the servomotor.

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