Co-evolution of Morphology and Walking Pattern of Biped Humanoid Robot using Evolutionary Computation -Designing the Real Robot-

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Abstract—In this paper, a method for co-evolving morphology and controller of real biped walking robot is proposed using evolutionary computation. 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.

The detail model of morphology is used for morphology in which the characteristics of servo module are considered. As the controller, pattern generators are used. The biped walking robot which can walk the longest distance are designed with two step genetic algorithm.

As a result, the detail model of the robot which can walk the longest distance is generated from limited size of chromosomes. Moreover, emerged result of caululation is used for design of the real biped walking robot.

I. INTRODUCTION

Traditionally, robot systems have been utilized in factories for high-precision routine operations. In recent years, A lot of robots have been developed which are related to human lives directly such as Sony's AIBO and so on. Especially, 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 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 servo modules 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 controller 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 to learn from evolution of living systems on how they have developed morphology and control systems at the same time. 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. However, all of them do not consider how to construct practical robots.

On the other hand, evolutionary method has been tried to apply to the practical robots. Kitamura [8] used Genetic Programming(GP) [9] to emerge the simple linked-
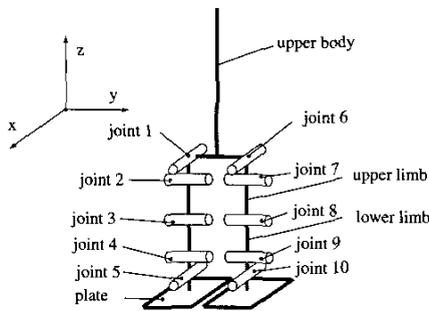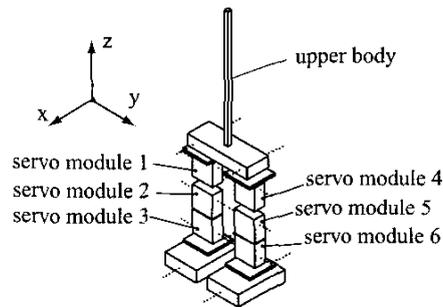
Fig. 1. model of robot of the first step

Fig. 2. model of robot of the second step

Fig. 3. geometries of servo modules

Fig. 4. characteristics of servo module

locomotive robot in virtual space. Lipson [10] 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 loco-motive robots [11] and applied it for the simple biped walking robot [12]. In this paper, we generate detail model of the biped walking robot and its controller in which pattern generators are used. the characteristics of servo module are considered in the dynamic simulation. Moreover, emerged solution is used for design of the real biped walking robot.

II. MATERIALS AND METHODS

A. Morphology

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. Moreover, it is also difficult to obtain biped walking because it is advanced locomotion. 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 at the first step. This three-dimensional robot is composed of 12 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 3.14kg/m and 4.557kg/m, respectively, and the length of one leg is 0.28m. These parameters are constant though the lengths of upper body, upper and lower limbs of the robot change in the process of GA. The basic locomotion of biped walking is emerged with this simple model.
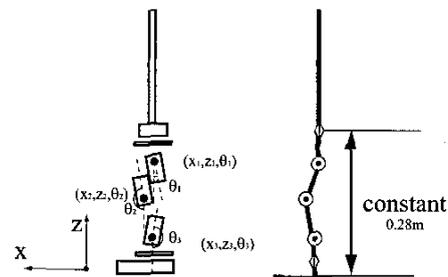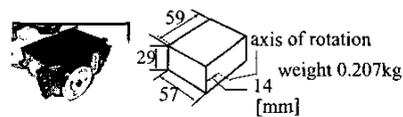
At the second step, we assume that the robot is composed of the servo modules S5301 with metal gears from Futaba which can be obtained easily. This three-dimensional robot is composed of 6 servo modules and some other parts as shown in Fig. 2. the geometry of each modules (x_i, z_i, θ_i) as shown in Fig. 3 is emerged during the evolution though the height of hip is constant for 0.28m. In fact, we have redesigned these parts many times in order to control the robot easily. That is to say, these parts are important for walking motion. There are some robot composed of similar servo modules such as morph[13]. morph is the humanoid robot which has high-range of motion, and can perform acrobatic behavior. Ar-rangement of servo modules of morph is well considered not to disturb any motion. However, research of long years was needed to develop this robot. With our method, the best arrangement of servo modules for walking is emerged without long time.

The characteristics of servo modules as shown in Fig. 4 are considered in the dynamic simulation so that the
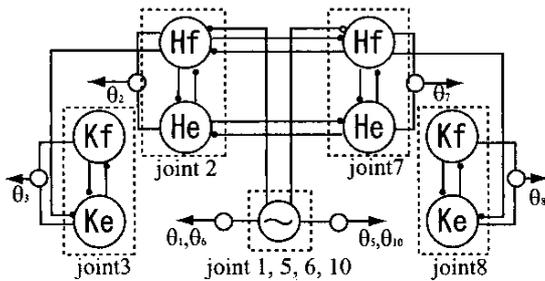
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Fig. 5. controller

Fig. 6. initial state

generated robot is nearly close to the real robot. Moreover, the system identification is conducted in advance and these parameters are used in the dynamic simulation because this module has the PD control system inside. Driving torque of each joint can be change from -2.45 Nm to 2.45 Nm reflecting the servo module.The detail model of morphology can be obtained with this model.

B. Controller

A lot of researches about generating the locomotion of artificial lives or robots with neural network and evolutionary computation have been conducted[14][15]. However the size of chromosomes becomes too large to generate the valid solution considering the both 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. In the bio-mechanics field, pattern generators are often used 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 length 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 detail structure and controller of bi-ped humanoid robot. Therefore, pattern generator is used as a conroller for real walking robot.

The structure of control system is decided according to the basic locomotion of bi-ped walking as shown in Fig. 5. Hf and He are neurons for the hip joints. Kf and Ke are neuron for knees. The action of each neuron is expressed
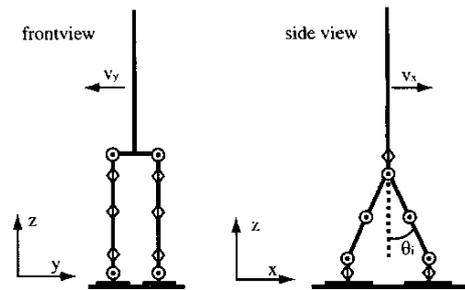
as follow,

$$T_i \dot{u}_i = -u_i - \sum_{ij} w_{ij} y(u_j) - \beta y(v_i)$$
$$+ U_0 + \sum_k FB_k \qquad (1)$$

$$T_i' \dot{v} = -v_i - y_i \qquad (2)$$

$$y(x_i) = \frac{1}{1 + e^{-\tau(x_i)}} \qquad (3)$$

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 which is in the center of Fig. 5 is for joint 1, 5, 6, and 10 that generates just sine wave for motion in the lateral plane. In the white circle in Fig. 5, the desired trajectory of each joint is given with following,

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

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. The gains of PD controller and maximum driving torque are given from the system identification of servo modules. 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.

C. Simulation

The environment which robots walk on is the flat ground. When the dynamic simulation starts, the posture of the robot is in the state of the initial position as show in Fig. 6. 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

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the knee, hip and other parts of body of robots gets in contact with the ground or the motion of robot continue staying at the same place for 0.5 s, simulation is over and next one begins in order to avoid wasting the time.

Dynamic simulation is conducted for 5s per a robot. the movement of robots resulting from their interaction with the environment. Motions of the robot are calculated by the forth order Runge-Kutta method. One time step is 0.1ms. 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.

D. Evolutionary Computation

GA is the method for optimization based on the evolution of creatures. GA has been used for a lot of complex problems[16]. 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, and 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 [17] is used as the crossover for real number GA. BLX-α is useful to generating the walking pattern because this crossover can explore the best solution more certainly in the middle or latter of calculation, that is to say, this method can adjust the walking pattern in detail. Each factor in the chromosomes is decided as follow:

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

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:

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

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.
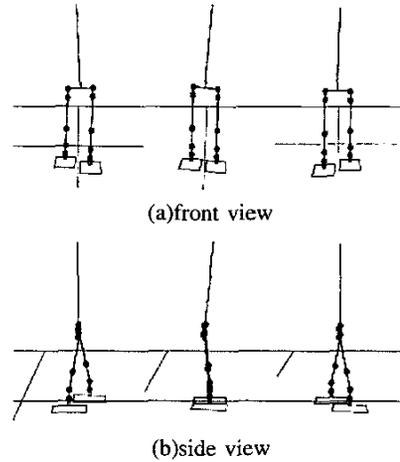

(a)front view

(b)side view

Fig. 7. walking pattern of the best robot

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

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

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 the walking distance.

The parameters of GA is as shown in Table 1. Moreover we use the elite preservation strategy at the same time. These method and condition is used at the first and second step.

TABLE I

GA PARAMETERS

population size	200
generation	300
crossover ratio	0.8
mutation ratio	0.05

III. RESULTS AND DISCUSSIONS

A. The First Step

Calculation using GA is conducted for the models mentioned above. 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 gets in contact with 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
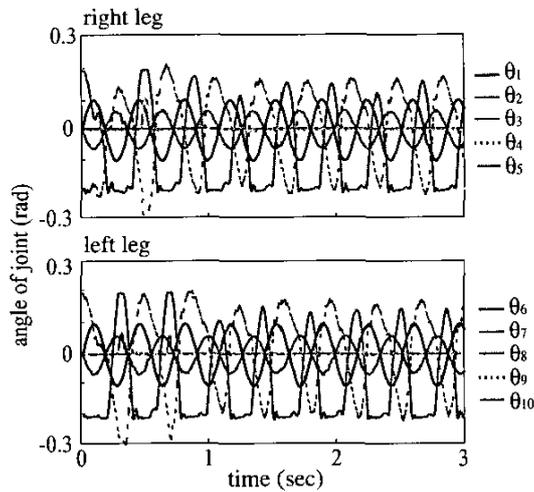
Fig. 8.   angle of joint during walking
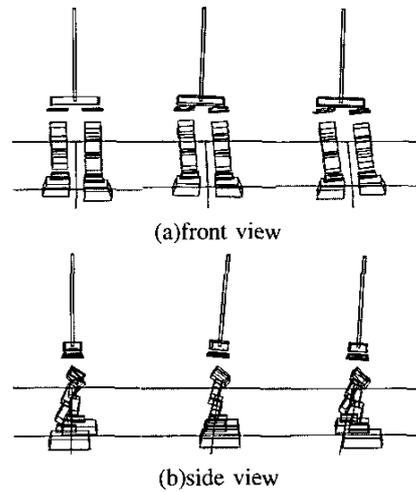

(a)front view

(b)side view

Fig. 9.   walking pattern of the best robot

compliance at all joints because of PD controller. Human has high 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 manner. 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 through the evolution. Here, we pay attention to the development of basic method for co-evolution of morphology and controller.

B. the Second Step

The walking pattern and morpholgoy as shown in Fig.9 are generated after the second step GA. At the first step, the basic biped walking pattern is generated. In this step, both the detail model of morphology and walkng pattern for it are generated simultaneously.Therefore, this results are valid model if we assume the robot is composed of the servo modules. The arrangement of servo modules of morph has been obtained with huge time and work because design of robot much depends on the experience of designer. With our method, the optimal arrangement for the fitness function can be obtained for short span.

C. Designing the Real Robot

At the second step, detail model of morphology is emerged. The real robot is designed with refering to the result of GA. Fig. 10 is the design of the real robot. Each servo module is located at the same geometry as the result of GA. Although the weight and inertia of materials of
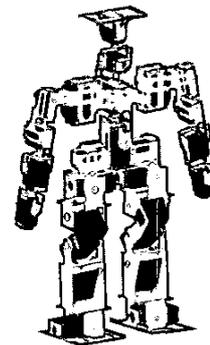

Fig. 10.   design for the real robot

sheet metal are ignored in the simulation, it is because servo module is much heavier than the other parts. Tt is much better for designers to refer to the result than to construct robot with their intuitions. Moreover, time for trial-and-errors for designing is not needed.

IV. CONCLUSIONS

In this paper, a method for co-evolving morphology and controller of bi-ped humanoid robots is suggested. 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 servo module.

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