Co-evolution of Morphology and Controller for Biped Humanoid Robot

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Abstract. In this paper, we present a method for co-evolving structures and control circuits of bi-ped humanoid robots. Currently, bi-ped 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 does not constrain design space of humanoid robot morphology or detailed control. Thus, engineers has to design control program for apriori designed morphology, neither of them shown to be optimal within a large design space. We propose evolutionary approaches that enables: (1) automated design of control program for a given humanoid morphology, and (2) co-evolution of morphology and control. An evolved controller has been applied to a humanoid PINO, and attained more stable walking than human designed controller. Co-evolution was achieved in a precision dynamics simulator, and discovered unexpected optimal solutions. 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 design in speedy manner. This is a major importance to the emerging robotics industries.

1 Introduction

Traditionally, robotics systems has 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 same degree of freedom to fit into the operational space. Numbers of humanoid robots have been developed aiming at possible deployment of humanoid for office and

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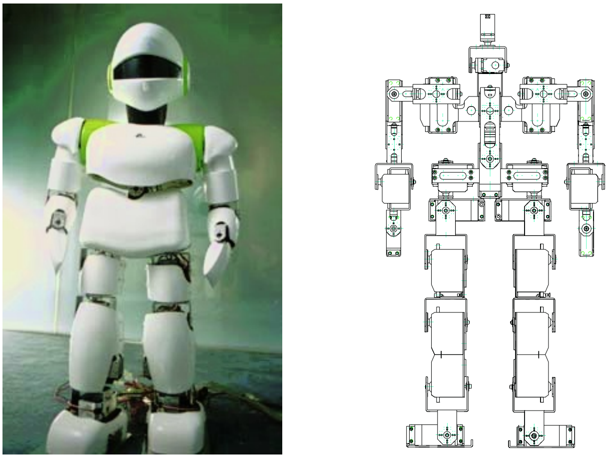


Fig. 1. Humanoid Robot PINO

home [1],[2]. However, all of them requires 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 Fig. 1, and 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 facilitates open evolution.

There are several interesting issues that have emerged. 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 cheap servomotor 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 method needs to be discovered to control it 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 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 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 designers of the robots should only set up an environmental constraint condition for the robots.

Artificial life is one of the approaches. 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 the 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][13]. 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 thought can be applied to development of the humanoid robot. In this paper, we propose two evolutionary approaches. At first, an evolved controller has been applied to a humanoid PINO, and attained more stable walking than human designed controller. Secondly, co-evolution were achieved in a precision dynamics simulator.

2 Humanoid Robot PINO

Humanoid robot PINO has been developed to be a platform of humanoid robot research used in many fields of studies such as interaction, artificial intelligence and so on. PINO is composed of such cheap of-the-shelf components as servomotors used in radio control car and so on. Fig. 2 shows the whole system of PINO.

Here, only the control program is generated with Genetic Algorithm. PINO has 6 DOFs for each leg, 5 for each arm, 2 for the trunk, and 2 for the head. 10 DOFs of legs are used for walking and the others are kept staying. Each joint is control to follow the desired trajectory which is given with

$$\dot{\theta}_i = \alpha_i \sin(\omega t + \theta_{1i}) + \beta_i \cos(\omega t + \theta_{2i}) \tag{1}$$

Where α_i and β_i denote the gain, and θ_{1i} and θ_{2i} denote the phase difference of sinusoidal and cosine waveform respectively. Also, ω represents the angular velocity. These parameters are generated with GA. we use the evaluate function as follow:

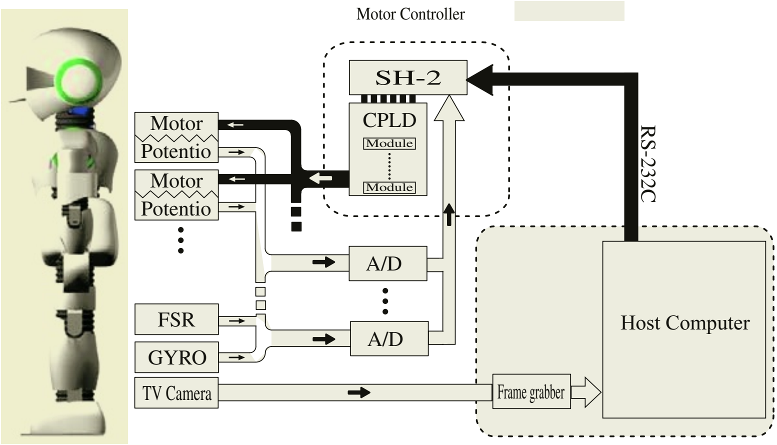


Fig. 2. system of PINO

$$
\begin{aligned}
fitness = 800 - 1000 \times height_{foot} \\
-5.0 \times energy_{max} \\
-0.1 \times energy_{sum} \\
-0.8 \times neckangle_{max} \\
+5.0 \times time
\end{aligned} \tag{2}
$$

where $height_{foot}$ is the max height of lifted leg, $energy_{max}$ is the max energy of robot, $energy_{sum}$ is the sum of energy of robot, $neckangle$ is the max angle of neck toward absolute axis and $time$ is the time for which PINO can walk in the dynamic simulation. After 10 second dynamic simulation, all robots are evaluated with this function. The parameters of GA is shown in Table 1.

Table 1. GA parameters

population size	100
generation	300
crossover ratio	0.9
mutation ratio	0.02

As the result, the walking pattern shown in Fig. 3 is generated. However the structure of robot is given before the simulation and control method is a simple oscillatory circuits. We cannot say that this is the optimal robot which has optimal structure and control program. In order to generate the optimal robot, the structure have also to be considered as well as control program. From the next section, we propose the method for co-evolution of morphology and controller of bi-ped humanoid robot.

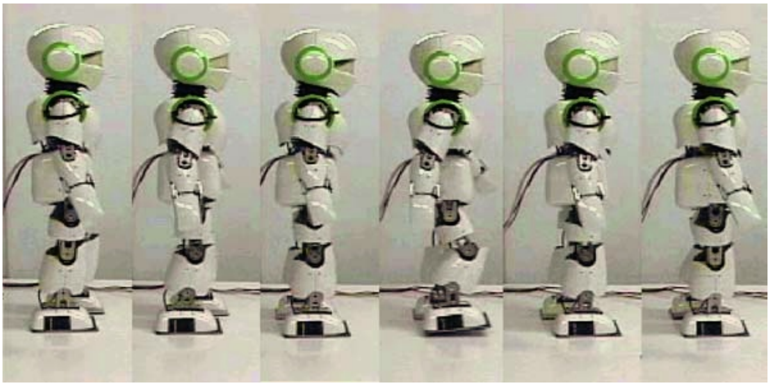


Fig. 3. walking pattern of PINO

3 Model of Robot

3.1 Morphology

Humanoid robots are composed of large numbers of components such as sensors, actuators and so on that it is difficult to consider optimal choice for all of them simultaneously. In order to develop the basic method for generating the both of morphology and locomotion, at first, the models which are easy to simulate in computers for short time are needed. Therefore The multi-link model of robot as shown in Fig. 4 is used here. This three-dimensional robot is composed of 10 links for body and legs and two plates for each foot. The length of five links for upper body, upper limbs 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. 4. Driving torque of each joint can be change from -30kgfcm to 30kgfcm reflecting the real robots that may be constructed in the future study. The joints 3 and 8 have the range of motions between 0 and $\pi/2$ and other joints have 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 study. These parameters are constant though the lengths of upper body, upper and lower limbs of the robot change in the process of GA.

3.2 Controller

A lot of researches about generating the locomotion of artificial life or robots with neural network and evolutionary computation have been conducted[14][15]. However the size of chromosomes becomes too large to effeciently generate the valid solution when the both morphology and locomotion are evolved simultaneously. Moreover we have to take the velocity of all joints and external force from the ground in account in order to control the robots. In the biomechanics,

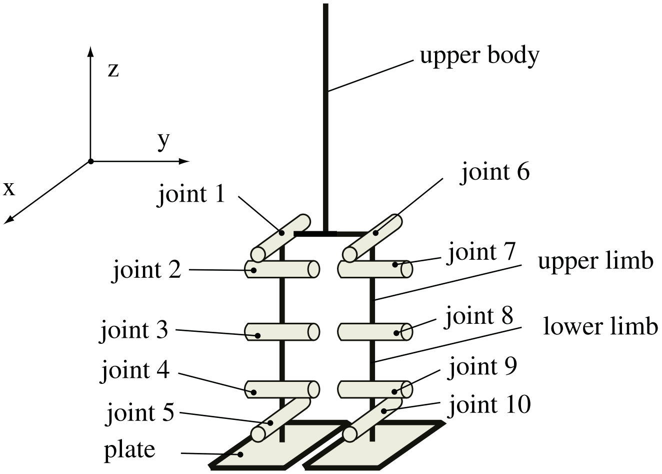


Fig. 4. model of robot

pattern generators are often used for generating the walking pattern of human because the bi-ped walking the periodical and symmetrical motion, that is to say, 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 designing method that can generate detail structure and locomotion of bi-ped humanoid robot. Therefore we can make the difference between the real world and computer simulation minimal with our method.

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.

$$\begin{aligned} T_i\dot{u}_i &= -ui - \sum_{ij} w_{ij} y(u_j) - \beta y(v_i) + U_0 \\ &\quad + \sum_k FB_k \end{aligned} \tag{3}$$

$$T'_i\dot{v} = -v_i - y_i \tag{4}$$

$$y(x_i) = \frac{1}{1+e^{-\tau(x_i)}} \tag{5}$$

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

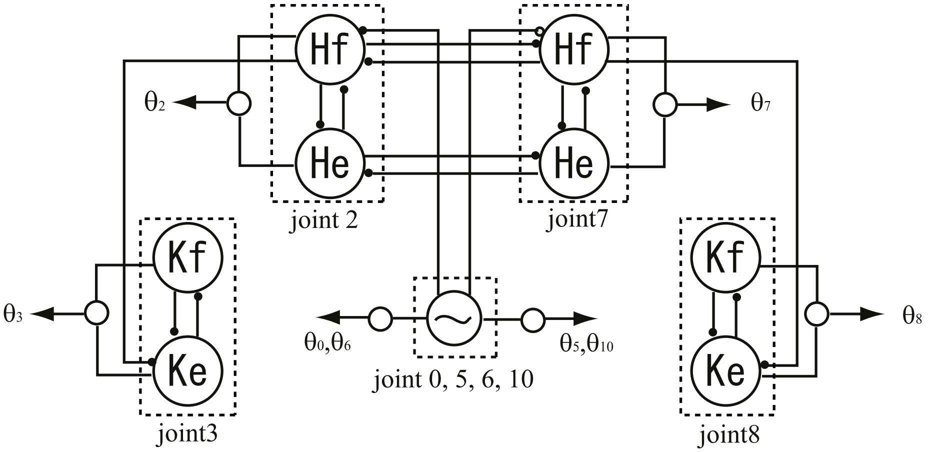


Fig. 5. structure of control system

effect, respectively. The neuron which is in top of Fig. 5 is for joint 0, 5, 6, and 10 that generates only sine signal. In the white circle in Fig. 5, the desired trajectory of each joint is given with following,

$$\theta_k = p_k(y(u_{k1}) - y(u_{k2})) \tag{6}$$

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 ±30kgfcm and each gain for PD control are decided in advance. This value is decided based on the PINO. 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.

4 Method

4.1 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 begin, the control system starts to work and driving torque is generated at the each joint, that is, the robots begin to walk. The only robots with neural systems that can generate the rhythm for walking get periodical and stable bi-ped walking. On the contrary, the robot with bad control system falls down immediately. If the knee, hip and other parts of body of robots gets contact with the ground or the motion of robot continue staying the same place for 0.5sec, simulation is over and next one begin in order to avoid wasting the time.

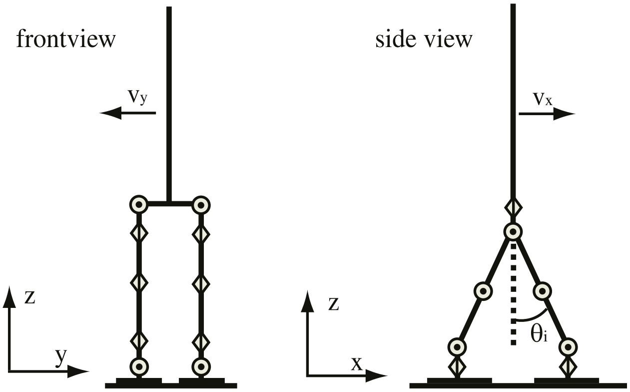


Fig. 6. initial state

Dynamic simulation is conducted to calculate for 5 sec per a robot. the movement of robots resulting from their interaction with the environment. Motions of the robot are calculated by the fourth order Runge-Kutta method. One time step is 0.2 msec. Contact response with ground of the links is accomplished by a hybrid model using both spring and damper under the influence of friction and gravity. The friction is so large that robots never slip during walking.

4.2 Evolutionary Computation

GA is the method for optimization based on the evolution of creature. GA has been used for many 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 control systems are generated from generation to generation. 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:

$$c_{1i,2i} = u(min(p_{1i}, p_{2i}) - \alpha I_i, \\ max(p_{1i}, p_{2i}) + \alpha I_i) \tag{7}$$

$$I_i = |p_{1i} - p_{2i}| \tag{8}$$

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 deviates2 from x to

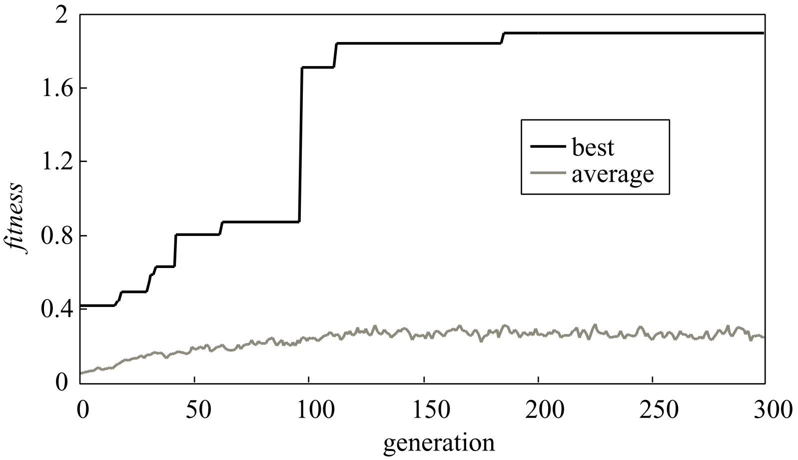


Fig. 7. change of fitness

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:

$$c_n = c_i + \frac{rand_g}{10} \tag{9}$$

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

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

$$fitness = l_g \tag{10}$$

is used, where l_g is distance of the center of gravity of robots from the initial point. That is to say, robots are evaluated just the moving distance. This condition emerges just bi-ped walking locomotion that robots lift one leg up, at first, brings it forward, and lifts another leg up when the swing leg get contact with the ground.

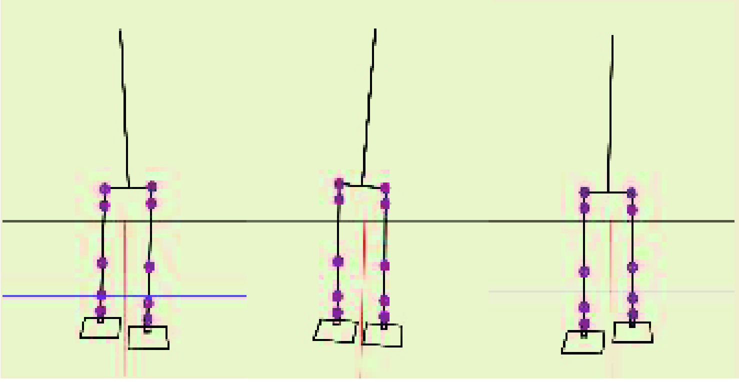
The parameters of GA is as shown in Table 2. Moreover we use the elite preservation strategy at the same time.

5 Results and Discussions

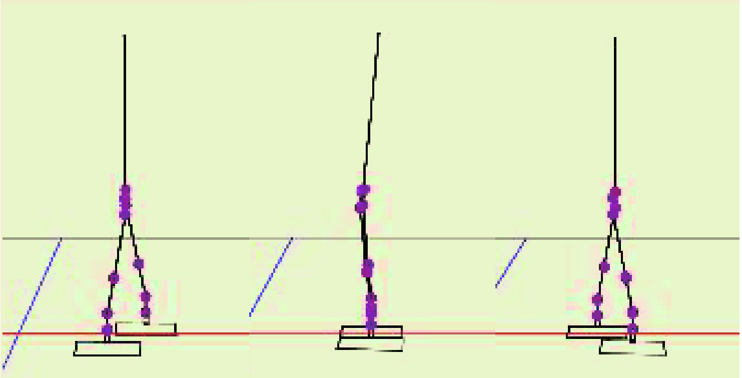
Calculation using GA is conducted for the model mentioned above. The best fitness and average of all is shown in Fig. 7. At first, all robots can move only

Table 2. GA parameters

population size	100
generation	300
crossover ratio	0.8
mutation ratio	0.05



(a)front view



(b)side view

Fig. 8. walking pattern of the best robot

a little bit and the fitnesses are low. Gradually, the robots that can walk are emerged and their moving 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. 8, and angle of each joint during walking is shown if Fig. 9. 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 more useful than intuition.

After the calculation, the basic walking pattern is emerged that robot lifts one leg up, bring forward and lifts another leg up when the swing leg gets contact

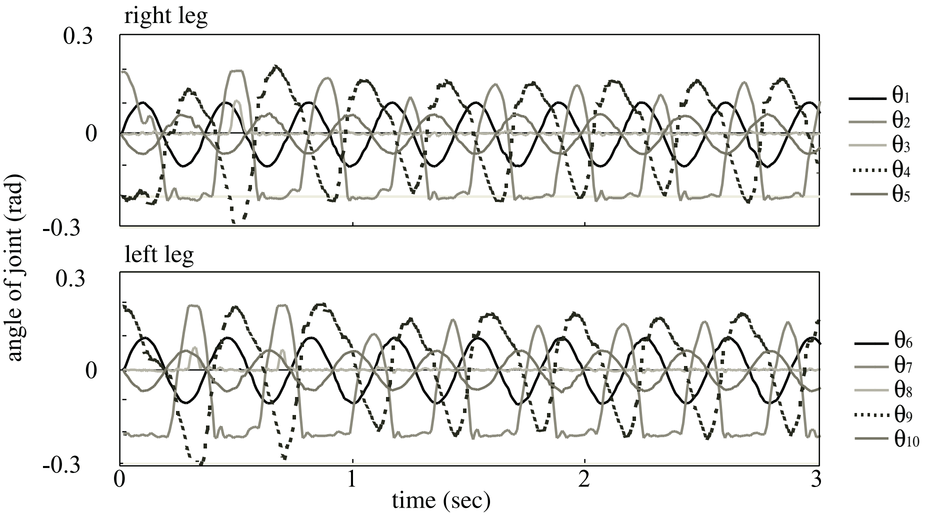


Fig. 9. angle of joint during walking

with the ground. Note that this robot walk with both of joint of knees $\theta_{3,8}$ kept straight. There are three possible reasons. 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 in the evolution. In order to walk on the ground which has some slope, or of which shape is not regular, robot cannot walk with this walking pattern. This is the problem about the evaluation and environment robot walk on in the dynamic simulation. Finally, the other evaluations such as efficiency of walking and so on are not considered during the evolution. Here, we pay attention to the establishment of basic method for co-evolution of morphology and controller. In the next section, the design of bi-ped humanoid robot is taken as multi optimal problem and the both the walking distance, efficiency of walking and stability are evaluated.

6 Multi Optimal Problem

In the former calculation, the only one evaluation function is used which is the distance between the center of mass of the robot and initial point. In this section, the design of the robot is taken as the multi optimal problem, MOP, in which two evaluate functions are considered. Moreover two calculations are conducted in order to discuss the influence for the walking pattern of each evaluation.

A distance of walking is often used for emergence of the ability of walking robot because it is easy to be handled and understood. Therefore we define one of the fitness as,

$$fitness_{movability} = l_g \tag{11}$$

like former simulation. The efficiency of walking is taken as a second evaluate function. The larger the sum of driving torque of all joints of the robot is, the lower the efficiency of walking is. So as the second fitness,

$$fitness_{efficiency} = \frac{1}{1 + \int_t \Sigma_i |\tau_i| dt} \tag{12}$$

is defined, where, τ_i is driving torque of joint i per a unit time step. The third evaluation function is

$$fitness_{stability} = \frac{1}{\int |\dot{\theta}_{upper}|} \tag{13}$$

where $\dot{\theta}_{upper}$ donates the angle velocity of upper body. This fitness means the stability of upper body. With these functions, two calculations are conducted, which one is with $fitness_{movability}$ and $fitness_{efficiency}$ (calculation 1), and the other is with $fitness_{movability}$ and $fitness_{stability}$ (calculation 2). Moreover, we use the method that is combined with pareto preserving strategy and vector evaluated GA. The parameters of GA is the same as the former calculation as shown in Table 2.

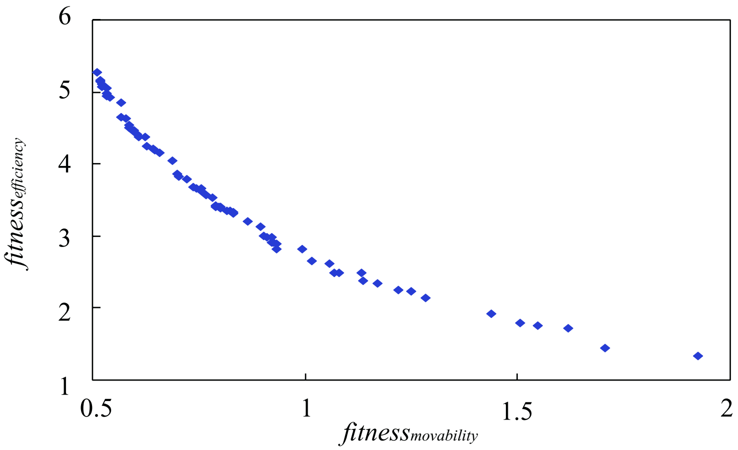
7 Results and Disccusions

After the calculation, pareto optimal solution, 73 for calculation 1 and 19 for calculation 2, are emerged at the final generaion as shown in Fig. 10. However all of them walk with the leg kept straight like the robot in Fig. 8. The value of $fitness_{movability}$ means just the point which the robot falls down in the calculation 1. In fact, the robot which falls down as soon as the dynamic simulation begins can get high $fitness_{efficiency}$. This robot can survive if other efficient walking pattern dose not exist. This means that the efficiency of walking has no relationship with the way to walk like this. In the calculation 2, the robot which just stand without walking can get high $fitness_{stability}$ if other stable walking pattern dose not exist because upper body does not move. Therefore we can say that this gait is the best solution under the condition which robot with this controller walk on the flat ground.

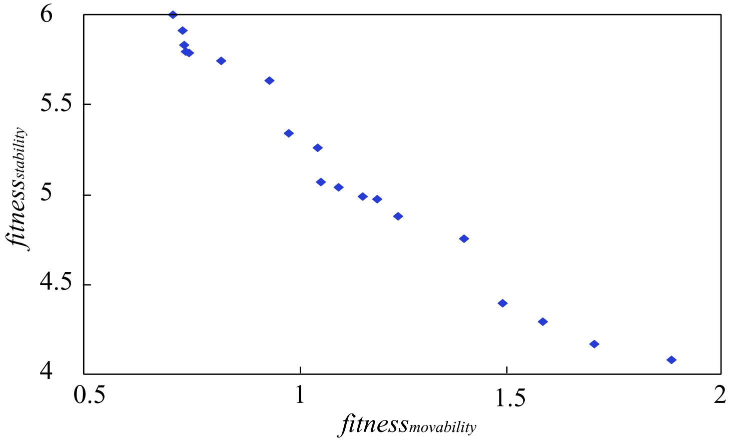
8 Future Works

In this paper, the walking distance, efficiency of walking and stability of upper body are evaluated for just walking. However we can use many other evaluation functions for other tasks. Secondly, we use the simple multi-link model. More detail structure have to be used in order to improve PINO or make the other real robot. Finally, the movement of upper body such as arm can be considered for walking or the other tasks. The size of chromosomes of our method is so small that all of them are possible to be conducted.

The resulting walking patterns are nowhere near human walking pattern. It it an interesting future subject of study that what constraints give emergence to human like walking patterns.



(a) the result of calculation with calculation 1



(b) the result of calculation with calculation 2

Fig. 10. pareto optimal solutions of final generation

9 Conclusions

In this paper, we present a method for co-evolving structures and control circuits of bi-ped humanoid robots. We propose evolutionary approaches that enables: (1) automated design of control program for a given humanoid morphology, and (2) co-evolution of morphology and control. An evolved controller has been applied to a humanoid PINO, and attained more stable walking than human designed controller. Moreover, Co-evolution were achieved in a precision dynamics simulator, and discovered unexpected optimal solutions which walk with knees kept straight with the small size of chromosome.

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