Acquisition of Humanoid Walking Motion Using Genetic Algorithm
– Considering Characteristics of Servo Modules –

Fuminori Yamasaki†‡, Ken Endo†*, Hiroaki Kitano†§ and Minoru Asada‡

†Kitano Symbiotic Systems Project, ERATO, Japan Science and Technology Corp.
‡Graduate School of Engineering, Osaka University,
* Graduate School of Science and Technology, Keio University,
§Sony Computer Science Laboratories, Inc.

Suite 6A, 6-31-15 Jingumae, Shibuya-ku, Tokyo 150-0001, Japan
Tel: +81-3-5468-1661, Fax: +81-3-5468-1664

E-mail : yamasaki,endo,kitano@symbio.jst.go.jp, asada@ams.eng.osaka-u.ac.jp

Abstract— **This paper presents a method for humanoid walking acquisition with less energy consumption based on a two-stage genetic algorithm. In the first phase of genetic algorithm, in order to acquire the continuous walking motion, the fitness function consists of a walking distance (longer is better). In the second phase, the fitness function consists of a walking distance (longer) and energy consumption(less) for acquisition of highly energy-efficient walking. Further, we restrain the relationship among some joints and keep knee joint straight on supporting leg in order to ensure the less energy consumption. We apply the method to our platform PINO which has low-torque actuators owing to the servo modules. In order to realize a genetic process, we encode the scaling parameter of the joint movements and the phase difference between the joints into the computational simulation which considers the characteristics of the servo module used in our platform, PINO. The evolved results are applied to a real PINO and its smooth and stable walking with less energy consumption is verified.**

Keywords— **Humanoid walking, Genetic algorithm, Less energy consumption**

I. INTRODUCTION

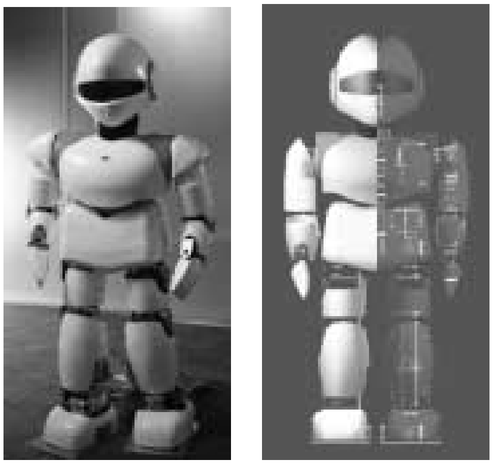
Stable biped walking generally requires highly precise control and powerful actuator systems [1]. It forces the use of expensive actuators and gear systems, therefore, the total cost of the robot tends to be very high. They are very different from normal human walking. It should be noted that most of the existing control methods for humanoid walking are designed independent of the structural properties of the robot hardware.

On the other hand, McGeer has studied Passive Dynamic Walk (PDW), in which the simplest leg-like structure can walk down a gentle slope without any actuators to control it [2]. In such methods, walking motions are determined by the relationship between a gravity potential effect and the parameters of the robot mechanical structure. Therefore, no control of walking behaviors such as speed or dynamic change in step size is possible as its name stands for.

Motors that are affordable for many researchers have only limited torque and accuracy. Development of a method that allows biped walking using low-cost components would have a major impact on the research community as well as industry [3]. Therefore, we have developed the humanoid PINO [4] which is a low-cost humanoid platform for various kinds of research issues. It is intentionally designed to have low-torque motors and low-precision mechanical structures because such motors and mechanical structures significantly reduce production cost. Figure 1 shows the whole view and the mechanical architecture of PINO. PINO has 26 degrees of freedom (DOF) and these components consist of low cost and off-the-shelf components. Especially, actuators of PINO are for radio control models of which maximum torque is 2.45 [N·m].

It is considered that the use of genetic algorithm enables humanoids with high DOFs to acquire highly energy-efficient and natural walking motion in a real environment [5],[6]. In these bi-ped walking algorithms, however, knees are always bended, therefore, knee joint motors are highly loaded continuously. It is known that the keeping a knee joint straight and the periodical matching between the motion of lateral plane and sagittal plane enable a humanoid to reduce the energy consumption. If a robot, however, evolve its walking locomotion performed by a walking distance and energy consumption simultaneously, a individual which does not move is selected.

In this paper, therefore, we apply a two-stage genetic algorithm for acquisition of stable and smooth walking trajectories with less energy consumption. In the first phase of genetic algorithm, the fitness func-



(a) A whole view

(b) A half skelton view

Fig. 1. Picture and mechanism of Our Platform, PINO

tion consists of a walking distance (longer is better) to acquire the continuous walking motion. In the second phase, the fitness function consists of a walking distance (longer) and energy consumption(less) for acquisition of highly energy-efficient walking, and the best results of first phase are used as initial individuals. Further, we restrain the relationship among some joints and keep knee joint straight on supporting leg in order to ensure the less energy consumption. Also, the specification of the each servo module is identified by the system identification, by which we expect the reliability of the computational simulation against the real robot.

Finally, we apply the computational results acquired by the genetic algorithm to our platform PINO, and its smooth and stable walking with less energy consumption is verified.

II. Genetic Algorithm for Humanoid Walking

In order to simplify the problem, we assume that the locomotion of right and left legs are symmetry and periodical. Further, the phase difference is π [rad]. Here, we adopt combination of sinusoidal and cosine function to represent such locomotion as follows:

$$\dot{\theta}_{(i)} = \alpha_i \sin\left(\omega t + \theta_{1(i)}\right) + \beta_i \cos\left(\omega t + \theta_{2(i)}\right), \qquad (1)$$

where α_i and β_i denote the gains, and $\theta_{1(i)}$ and $\theta_{2(i)}$ denote the phase difference of sinusoidal and cosine waveforms, respectively. Also, ω represents the angular velocity. ω, α_i, β_i, $\theta_{1(i)}$ and $\theta_{2(i)}$ are parameters for each individual, and each parameter is represented by 70bits.

In the first phase of the evolution, the total walking distance during one trial should be evaluated for acquisition of the continuous walking motion without falling down.

A fitness function of this phase is given by,

$$f = l_{walk}, \qquad (2)$$

where l_{walk} is a distance from the start point [m].

In the next phase, the energy consumption and the walking distance from the start point should be evaluated using results of first phase, because the natural and smooth walking motion needs less energy.

Therefore, a fitness function is given by,

$$f = \frac{l_{walk}}{E_{consumption}}, \qquad (3)$$

where $E_{consumption}$ are energy consumption during total walking [J], and this fitness function denotes the moving efficience of a robot.

An energy consumption is calculated as,

$$E_{consumption} = \sum \int_0^{t_{walk}} \tau_i \dot{\theta}_i \, dt, \qquad (4)$$

where t_{walk}, τ_i, $\dot{\theta}_i$ denote the total walking [sec], a torque and angular velocity of the i_{th} joint, respectively.

Table 1 shows the condition of genetic algorithm. The crossover module creates new individuals by combining segments of the string of parents. The mutation module replaces the segments of the string of another one. Also, the best individual is stored to the next generation, and the elitest scheme is always selected. The crossover module and mutation module function are shown in Figure 2.

TABLE I

Condition of genetic algorithm

Population	50
Generation	50
Crossover ratio	0.9
Mutation ratio	0.02

III. Conditions and Simulations

A. System Identification for Servo Module System

A computational simulation should have high accuracy against the real world. Especially, a characteristic of an actuator is one of the most important parameters. It is clear that the servo module for radio control model has a PD control system inside. Therefore we

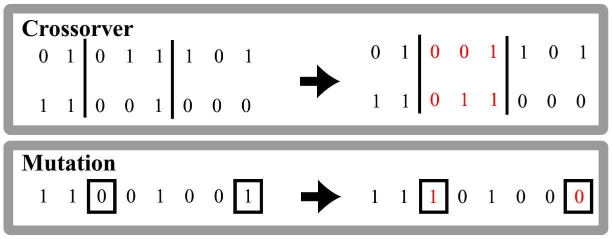


Fig. 2. The crossover and mutation module function

assume that a servo module has the system as equation (5),

$$K(\theta_{dt} - \theta_t) - C\dot{\theta}_t = I\ddot{\theta}_t, \tag{5}$$

where I, C and K denotes a moment of inertia, viscosity coefficient and damper coefficient, respectively.

In order to obtain these parameters, we had the system identification. From preliminary experiments, we obtain the time series of angular acceleration, angular velocity and angle at the output axis when we input the desired angle. From equation (5), parameter matrix $[C, K]^T$ is obtained by,

$$\begin{aligned} \left[\dot{\theta}_t, \theta_t\right] [C, K]^T &= I\ddot{\theta}_t \\ [C, K]^T &= \left[\dot{\theta}_t, \theta_t\right]^{+1} I\ddot{\theta}_t, \end{aligned} \tag{6}$$

where $\left[\dot{\theta}_t, \theta_t\right]^{+1}$ denotes the pseudo inverse matrix of a matrix $\left[\dot{\theta}_t, \theta_t\right]$.

To verify the validity of these parameters, stability of this system are discriminated. As a result, it is verified that these parameters of servo module are valid, because a real part of these eigenvalues is be left side in the complex plane, that is, this system is stable model.

B. Condition of Dynamical Simulation

Dynamical simulations are analyzed by the fourth Runge - Kutta method, and the time interval is 0.2 [ms]. The dynamic equation of this model can be represented as follow:

$$[M(\theta)]\left\{\ddot{\theta}\right\} + [C(\theta)]\left\{\dot{\theta}^2\right\} + [K(\theta)] = [\tau], \tag{7}$$

where $[M(\theta)]$, $[C(\theta)]$ and $[K(\theta)]$ denote the parameter matrices of the mechanism and angular positions of the links, and $[\tau]$ denotes feedback torque vector.

Desired angles of each joint are simultaneously updated at 13.5 [ms] interval which is same to servo module one. In computational simulations, the floor force is calculated based on spring - dumper contact model. Local feedback torque are given by,

$$\tau_i = k(\theta_{di} - \theta_i) - k_v\dot{\theta}_i, \tag{8}$$

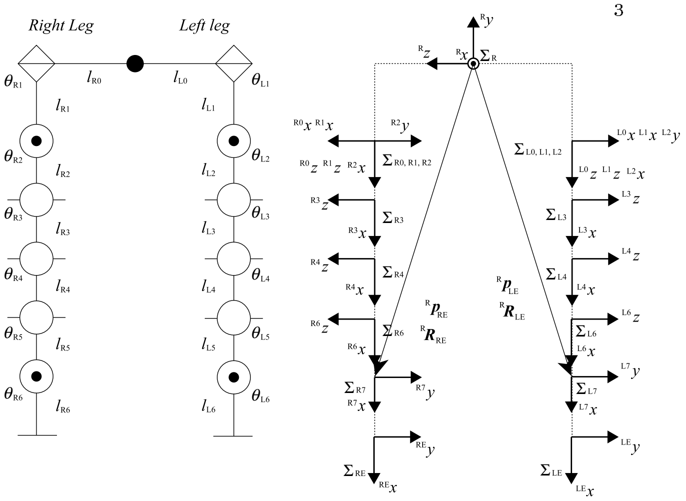


Fig. 3. Coordinate frames of legs of the robot

where k and k_v are the control gain of servo modules, and θ_{di} denotes the desired angle of θ_i. k and k_v are obtained by the system identification of servo module.

Also, a maximum torque of servo module is defined as ±2.45 [N·m]. The trial of each individual runs for 20 [sec]. If the robot walk for 20 [sec] or falls down halfway, the trial is finished and the individual is evaluated by fitness function.

In order to keep the foot plate parallel against the ground and avoid collision between the swing leg and the ground, following equations are defined,

$$\begin{aligned} &\theta_{R1} = \theta_{L1} = 0[rad] \\ &\theta_{R2} = \theta_{R6} = \theta_{L2} = \theta_{L6} \\ &\theta_{R3} + \theta_{R5} = \theta_{R4} \\ &\theta_{L3} + \theta_{L5} = \theta_{L4} \\ &\theta_{R4} = \pi[rad]\ (at\ supporting\ phase) \\ &\theta_{L4} = \pi[rad]\ (at\ supporting\ phase) \\ &\theta_{R3}(\omega t) = \theta_{L3}(\omega t + \pi)\ (delay\ half\ period) \\ &\theta_{R4}(\omega t) = \theta_{L4}(\omega t + \pi)\ (delay\ half\ period) \\ &\theta_{R5}(\omega t) = \theta_{L5}(\omega t + \pi)\ (delay\ half\ period), \end{aligned} \tag{9}$$

where each θ_i denotes the desired angle of each joint and correspond with the Figure 3 number.

IV. EXPERIMENTS

A. Results of Computational Simulation

In the result of the first phase of genetic algorithm, the best and average of fitness value changes shown in Figure 4, ,which indicates transitions of best fitness value and average fitness value of each generation.

The second phase of genetic algorithm is evolved using the results of first phase.

Figure 5 indicates transitions of best fitness value

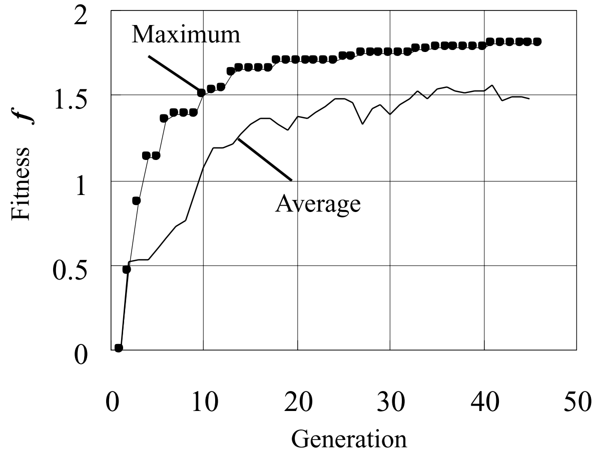


Fig. 4. Maximum and average fitness value in the first phase

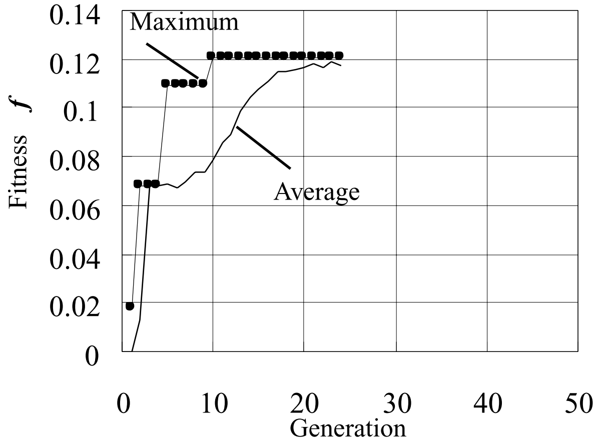


Fig. 5. Maximum and average fitness value in the second phase

and average fitness value of each generation of the second phase.

Also, a walking step period and a size of one step on the initial and evolutional motion are shown in table. 2.

B. Results at Real Robot

The results of computational simulations are performed by the real robot. The time series of desired joint angle of each joints are given, which is 13.5 [ms] interval. From the experimental results, PINO realize the walking motion smoothly. Besides, we had the experiments to make PINO walk in the real environment using conventional control method, whose locomotion are obtained by inverse kinematics, and zero moment point are controlled by moving into support surface [4],[7]. In this time, PINO achieve only the unstable walking motion because motors are highly loaded continuously, and sometimes PINO fells down. Figure 6 shows the time series of walking motion of real PINO using conventional control method and results of genetic algorithm.

From these figures, the walking pattern obtained by genetic algorithm realizes fewer distortion of upper body than that of conventional control method, that is, this walking motion needs less energy consumption and achieve the smooth locomotion.

TABLE II

Walking period and step size

	Initial motion	Evolutional motion
Period [sec]	1.01	1.49
Step size [m]	0.062	0.098

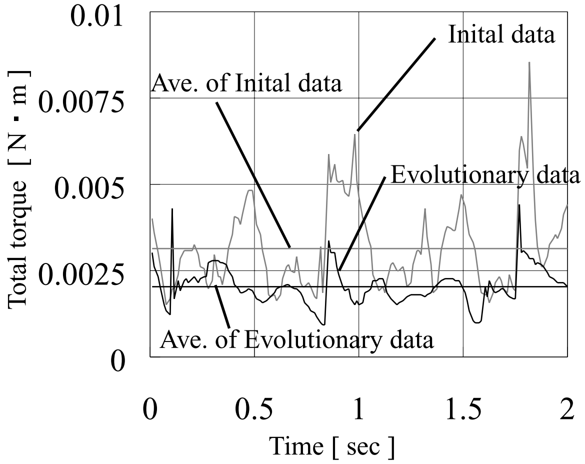


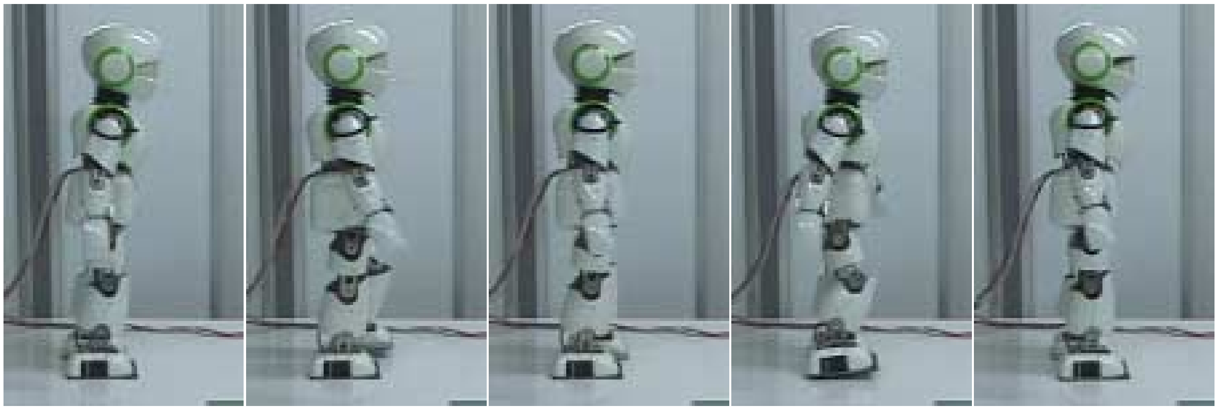
Fig. 7. Time series of total torque

V. Discussion

Time series of the total torque for two seconds of initial human designed walking motion and evolved walking motion are shown in Figure 7. Also, average of these data are shown in it. Further, the differencial total torque of them are shown in Figure 8.

Evolved locomotion needs less energy consumption against the initial locomotion and conventional control method one. At the point of spike torque in Figure 7, the swing leg touches down with the ground and the knee of supporting leg is locked straight. This spike torque of evolved locomotion extremely reduces against initial one. In Figure8, it is verified that the deviation of torque of evolved locomotion is smaler than that of initial one, that is, this locomotion achive the smooth and stable walking.

(a) Walking motion of a real robot (Conventional control method)



(b) Walking motion of a real robot (Genetic algorithm)

Fig. 6. Experimental result

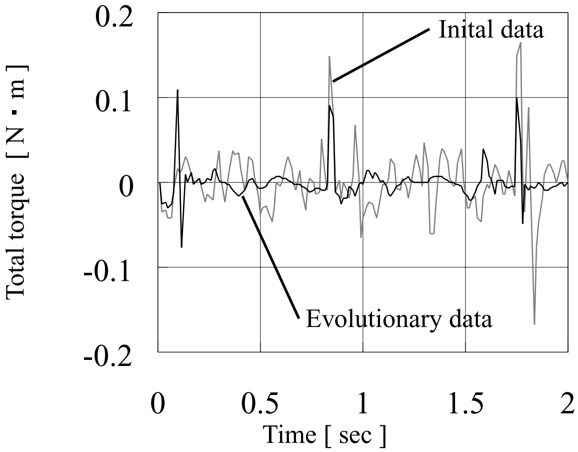


Fig. 8. Time series of differencial total torque

TABLE III

Torque consumption in each condition [N·m]

	Initial motion	Evolutional motion
each 1 [m]	127.1	76.9
each 1 [sec]	15.5	10.2
each 1 [step]	15.7	15.1

It is shown in table 3 a torque consumptions in each 1 [m], each 1 [sec] and each 1 [step], walk period and step size from Figure 7. From these results, it is verified that evolved walking motion achieves the highly energy-efficience. Also, humanoids with limited torque like PINO can realize a walking motion which is acquired from genetic algorithm.

VI. Conclusion

This paper present the method for humanoid walking acquisition with less energy consumption with genetic algorithm. In order to realize smooth and stable walking with less energy consumption, in the first phase of genetic algorithm, the fitness function consists of a walking distance (longer is better) to acquire the continuous walking motion. In the second phase, the fitness function consists of a walking distance (longer) and energy consumption(less) for acquisition of highly energy-efficient walking. Further, we restrain the relationship among some joints and keep knee joint straight on supporting leg in order to ensure the less energy consumption.

We apply the method to our platform PINO which has low-torque actuators owing to the servo modules. As a result, the evolved results are applied to a real PINO and its smooth and stable walking with less energy consumption is verified. As future work, we plan to generate various kinds of behaviors using this method.

VII. Acknowledgements

The dynamic simulator is developed by Mr. Masaki Ogino of Osaka University. The authors acknowledge him and members of Asada Laboratory of graduate school of engineering, Osaka university, and members of symbiotic intelligence group of Kitano Symbiotic Systems Project, ERATO, Japan Science and Technology Corporation.

References

[1] 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*, CD-ROM, 2000.

[2] T. McGeer, “Passive dynamic walking”, *The International Journal of Robotics Research*, Vol.18, No.6, pp.62–82, CD-ROM, 1990.

[3] 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.

[4] 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*, CD-ROM, 2000.

[5] Arakawa, T., Fukuda, T., “Natural Motion Generation of Biped Locomotion Using Hierarchical Trajectory Generation Method Consisting of GA,EP Layers”, *Proc. of IEEE International Conference on Robotics & Automation*, pp. 211-216, 1997.

[6] Fukuda, T., Komata, Y., Arakawa, T., “Stabilization Control of Biped Locomotion Robot Based Learning with Gas having Self-adaptive Mutation and Recurrent Neural Netwrok” *Proc. of IEEE International Conference on Robotics & Automation*, pp.217-222, 1997.

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