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# Adaptive Gait Pattern Generation of Biped Robot based on Human's Gait Pattern Analysis

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***Abstract*—**This paper proposes a method of adaptively generating a gait pattern of biped robot. The gait synthesis is based on human's gait pattern analysis. The proposed method can easily be applied to generate the natural and stable gait pattern of any biped robot. To analyze the human's gait pattern, sequential images of the human's gait on the sagittal plane are acquired from which the gait control values are extracted. The gait pattern of biped robot on the sagittal plane is adaptively generated by a genetic algorithm using the human's gait control values. However, gait trajectories of the biped robot on the sagittal plane are not enough to construct the complete gait pattern because the biped robot moves on 3-dimension space. Therefore, the gait pattern on the frontal plane, generated from Zero Moment Point (ZMP), is added to the gait one acquired on the sagittal plane. Consequently, the natural and stable walking pattern for the biped robot is obtained.

***Keywords*—**Biped robot, Gait pattern, Genetic Algorithm.

## I. Introduction

HUMANOID robots are expected to assist human activities in daily life. Therefore, humanoid robots are asked to walk natural to provide intimacy to human. The human gait is a complex dynamic activity. The complicated human model that has 3D deformable frame, high DOF, and complex mechanical structure cannot be applied directly to simplified biped robots. To overcome these problems, many researches have assumed that the human gait is optimized in the view of the gait energy, and they have defined the natural gait of the biped robot as the movement that minimizes its gait energy. Therefore, many researches about the gait pattern generation of the biped robot focus on minimizing the gait energy of them[1,2,3,4].

Since a lot of the parameter values cannot be obtained only from minimizing the gait energy of the biped robot, adaptive techniques such as Genetic Algorithm and Neural Network Algorithm have been studied. Capi[5] proposed a gait synthesis method of biped robots using GA. The gait synthesis during walking is analyzed from the minimum consume energy (MCE) and minimum torque change (MTC). The stability of the robot gait is verified by ZMP of the biped robot. Zhe Tang[6] analyzed dynamic elements of the sagittal, frontal and transverse plane and combined the dynamic elements on every planes using Pareto Optimal Solution and GA.

Although these works have achieved the minimum energy and stability of the gait pattern using MCE and adaptive technique, the gait pattern of the biped robot is still not natural like human because it was considered only in the viewpoint of robot's structure

In order to achieve the natural gait of biped robot like human, human's gait has to be modeled accurately. However, since the human's gait is composed of dynamic motions on the sagittal, frontal and transverse plane, the complete gait of the biped robot can be achieved only if the gait is analyzed on two more planes.

This paper proposes adaptive gait pattern generation method using GA. Since the simplified structure of biped robot is not enough to model human's complex body structure, to accurately analyze the human's gait pattern, sequential images of the human's gait on the sagittal plane are acquired, and then human's gait control values are extracted from the image sequences. The extracted gait control values are applied to the biped robot model, and the dynamic elements on two more planes have to be considered to obtain 3-Dimensional gait patterns. For this purpose, this paper analyzes dynamic elements on the sagittal and transverse planes, and then generates the adaptive gait pattern using GA.

The human's sagittal plane analysis drives the biped robot gait pattern similar to the human natural gait pattern. And then dynamics elements on the transverse plane generate the gait pattern of the biped robot on the frontal plane. That is, the gait pattern of the biped robot on the frontal plane is generated so that the calculated ZMP of the biped robot converges into the desired ZMP.

This paper is organized as follows. Section II explains the analysis method of human's gait pattern. Section III describes the walking dynamics. Section IV presents the gait planning method of the biped robot. Experiments of gait generations and simulations about the biped robot are executed in Section V. Conclusions are given finally.

## II. Human's Gait Pattern Analysis

It is difficult for the human's gait pattern to be applied to the biped robot model because it has the complicated mechanical structure. Therefore, the human model for the gait analysis

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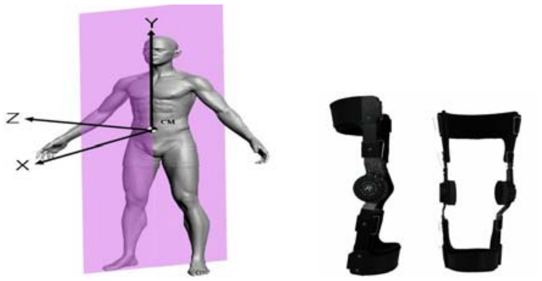
needs to be as possible as simple. From this point of view, physiologists make it show that the most walking dynamics take place on the sagittal plane [7], or the plane bisecting the human body as shown in Fig. 1(a). Hence, this paper uses a 5-link biped locomotion model to approximate the human's complex mechanical structure in the image sequences.

The helpful walking device as shown in Fig. 1(b) is used so that the human's walking movement is limited to sagittal plane. That is, the human's walking pattern is limited to X-Y plane.




(a) sagittal plane (b) the helpful walking device

Fig. 1 sagittal plane and the helpful walking device

The 5-link biped model is constructed as shown in Fig. 2. The biped robot model consists of five links: a torso and two legs. It also has two pelvises at the hip, two knees between the thighs and the shanks, and two ankles at the tips of the two limbs. All of the joints can only rotate on the sagittal plane and have no friction. Feet are not considered in this biped model. This five link biped model parameters are represented as follows.

$M_i$ : mass of link i

$L_i$ : length of link i

$d_i$ : distance from joint i to the COM of link i

$I_i$ : moment of inertia of link i

$\theta_i$ : angle of link i

$(x_e, y_e)$ : the coordinate of the supporting point

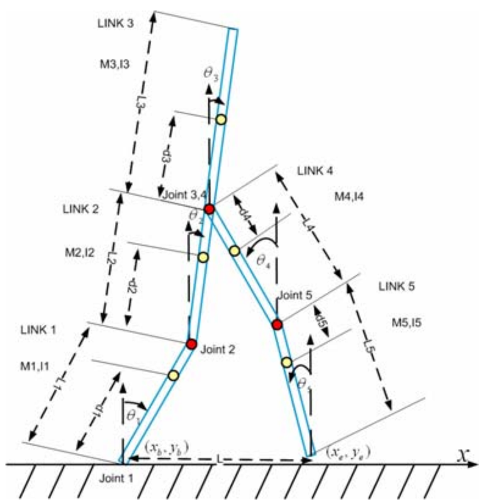



Fig. 2 5-link biped model

$(x_b, y_b)$ : the coordinate of the tip of the swing limb

$\tau_i$ : control torque of link i

## III. Walking Dynamics

This paper analyzes Single Support Phase(SSP) and Double Support Phase (DSP) using the dynamic model of Lagrangian equation of the 5-link biped robot [8].

### A. *Single Support Phase (SSP) dynamics*

The SSP is a state that one leg of the biped robot swings and the other leg is in contact with the ground. The dynamics of the 5-link biped on the SSP can be derived from Lagrangian equation as shown in Eq. (1)

$$\underline{D}(\underline{\theta})\underline{\ddot{\theta}} + \underline{H}(\underline{\theta}, \underline{\dot{\theta}})\underline{\dot{\theta}} + \underline{G}(\underline{\theta}) = \underline{T} \tag{1}$$

where $\underline{D}(\theta)$ is the $5 \times 5$ positive definite and symmetric inertia matrix, $\underline{H}(\theta, \dot{\theta})$ is the $5 \times 5$ Centrifugal and Coriolis matrix, $\underline{G}(\theta)$ is the $5 \times 1$ matrix of gravity terms, $\underline{\theta}, \underline{\dot{\theta}}, \underline{\ddot{\theta}}, \underline{T}$ are the $5 \times 1$ vectors of generalized coordinates , velocities, accelerations and torques, respectively.

### B. *Double Support Phase (DSP) Dynamics*

On the DSP, both of the feet are in contact with the ground. Since contact positions of tips of two limbs on the ground are known during DSP, a set of holonomic constraints is given as Eq. (2):

$$\Phi(\theta) = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} x_e - x_b - L \\ y_e - y_b \end{bmatrix} = 0 \tag{2}$$

where L is the distance between tips of two limbs. In order to be applied to the dynamic derivation, it is differentiated twice with respect to time as given in Eq. (3).

$$\dot{\Phi}(\theta) = \underline{J}(\underline{\theta})\underline{\dot{\theta}} = 0$$
$$\ddot{\Phi}(\theta) = \underline{\dot{J}}(\underline{\theta})\underline{\dot{\theta}} + \underline{J}(\underline{\theta})\underline{\ddot{\theta}} = 0 \tag{3}$$

where $\underline{J}(\underline{\theta})$ is the jacobian matrix in Eq. (4).

$$\underline{J}(\underline{\theta}) = \begin{bmatrix} l_1\cos\theta_1 & l_2\cos\theta_2 & 0 & l_4\cos\theta_4 & l_5\cos\theta_5 \\ -l_1\sin\theta_1 & -l_2\sin\theta_2 & 0 & -l_4\sin\theta_4 & -l_5\sin\theta_5 \end{bmatrix} \tag{4}$$

The vector equation of the dynamics on DSP is given in Eq. (5).

$$\underline{D}(\underline{\theta})\underline{\ddot{\theta}} + \underline{H}(\underline{\theta}, \underline{\dot{\theta}})\underline{\dot{\theta}} + \underline{G}(\underline{\theta}) = \underline{J}^T(\underline{\theta})\lambda + \underline{T} \tag{5}$$

where $\lambda$ is a $2 \times 1$ vector of Lagrange multipliers.

## IV. Gait Pattern Generation

Motion components of the complete gait for the biped robot are divided into three planes: sagittal, frontal, and transverse plane. Therefore biped robot must have gait patterns on two more planes. This paper considers two gait patterns on the sagittal and transverse plane to analyze the dynamics of the biped robot. The gait pattern on sagittal plane can be generated using human's gait control values. And the gait pattern on frontal plane is generated using the desired ZMP trajectory on transverse plane.

### A. Gait Phases

The gait of the human is a periodic motion which alternates between the DSP and the SSP. On the DSP, both of the humanoid robot feet are in contact with the ground. On the other hand, one leg swings and the other leg is in contact with the ground on the SSP. The constraint values of the biped robot can be extracted from the human gait.

The humanoid motion on the frontal plane aims to move the ZMP of the biped robot from one foot to the other. One leg of the robot has two DOFs, one at the hip joint and the other at the ankle joint, to control the robot gait on the frontal plane.

To simplify the gait planning, it is assumed that the biped robot always keep two legs parallel. So the angles of four DOFs have the same value $\theta_{frontal}$ as shown in Fig. 3. Moreover, it is assumed that the biped robot's feet are parallel with ground.

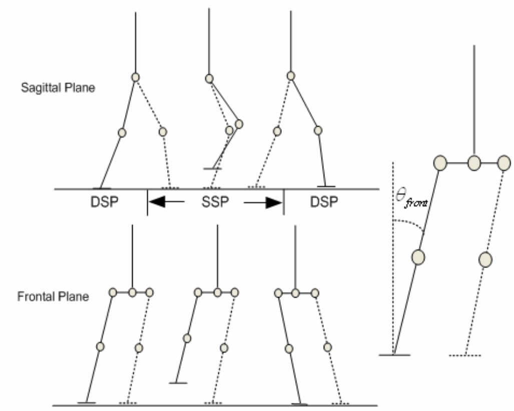



Fig. 3 Walking patterns on the sagittal and frontal plane

### B. Gait Control Values on the Sagittal Plane

In order to obtain features of the gait torques during gait, the skewness and kurtosis value of the gait torques are calculated.

The skewness and kurtosis, fundamental values in statistical analyses, characterize the variability of the distribution of a data set. The skewness is used as a symmetrical measure of the data distribution. If the skewness of a data set is zero, the distribution of a data set is symmetric. The kurtosis is a measure of whether the data distribution is sharp or flat relative to a normal distribution. That is, the distribution with high kurtosis tends to have a distinct peak at the mean, decline rather rapidly, and have heavy tails as shown in Fig. 4.

Therefore, the gait torque of the biped robot can be compared with the gait torque of human biped robot during walking. The gait pattern on the sagittal plane can be adaptively generated by the skewness and kurtosis value. For univariate data $Y_1, Y_2, \ldots, Y_N$ , formulas for skewness and kurtosis are given in Eq. (6) and Eq. (7) respectively.

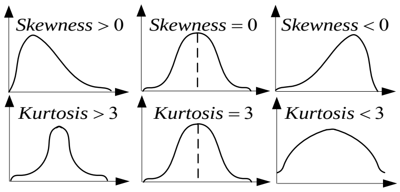



Fig. 4 Skewness and Kurtosis

$$Skewness = \frac{\sum_{i=1}^{N} (Y_i - \overline{Y})^3}{(N-1)s^3} \tag{6}$$

$$Kurtosis = \frac{\sum_{i=1}^{N} (Y_i - \overline{Y})^4}{(N-1)s^4} \tag{7}$$

where $\overline{Y}$ is the mean, s is the standard deviation, and N is the number of data points.

### C. Zero Moment Point (ZMP)

In this paper, the ZMP which determines the stable pose of the biped robot is used to generate the gait pattern of it. It follows that the motion of a biped robot would be always stable only if the ZMP is located inside the supported area where the feet of the biped robot are confined as the contacting boundary [9].

The ZMP is the point where the total inertia force of the biped robot equals zero. The ZMP can be given in Eq. (8).

$$x_{ZMP} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i \ddot{x}_i z_i - \sum_{i=1}^{n} I_{iy}\ddot{\Omega}_{iy}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \tag{8}$$

$$y_{ZMP} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)y_i - \sum_{i=1}^{n} m_i \ddot{y}_i z_i - \sum_{i=1}^{n} I_{ix}\ddot{\Omega}_{ix}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)}$$

where $m_i$ is the mass of link i, $I_{ix}$ and $I_{iy}$ are the inertial component, $\ddot{\Omega}_{ix}$ and $\ddot{\Omega}_{iy}$ are absolute angular acceleration components, g is the gravitational acceleration, $(x_i, y_i, z_i)$ is the coordinate of the mass center of link i in an absolute Cartesian coordinate system.

Using the Eq. (8), the ZMP of the biped robot can be designed on the transverse plane as shown in Fig. 5.

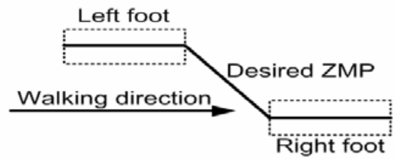


Fig. 5 Desired ZMP

### D. Adaptive Gait Pattern Generator

The schematic diagram of the proposed algorithm is summarized in Fig. 6.

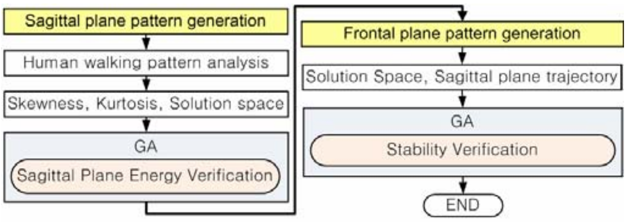


Fig. 6 Adaptive walking pattern generator

The algorithm begins to acquire the sequential images of the human's gait to find control values of the human's gait in the images. The control values generate the gait pattern of the biped robot on sagittal plane. In the second stage, Genetic Algorithm (GA) is executed as shown in Fig. 7.

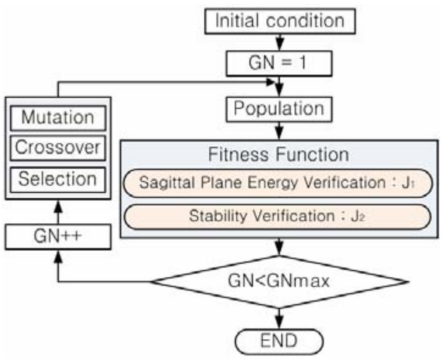


Fig. 7 Genetic Algorithm

The GA is used to find a true or approximated solution with respect to optimization problem. The GA is categorized as global search heuristics and inspired by evolutionary biology such as mutation, selection, and crossover. This paper defines fitness function of the GA for sagittal plane gait as following Eq. (9).

$$J_1 = \int_0^{T_c} (E_{skewness} + E_{kurtosis})dt \to \min \tag{9}$$

where $T_c$ is the walking cycle, $E_{skewness}$ is the absolute error value between the human skewness and robot skewness, and $E_{kurtosis}$ is the absolute error value between the human kurtosis and robot kurtosis.

After obtaining the gait pattern on the sagittal plane, the GA is executed to generate the gait pattern on the pattern frontal plane. The fitness function of the GA for the gait pattern on the frontal plane is defined as Eq. (10).

$$J_2 = \int_0^{T_c} E_{ZMP} dt \to \min \tag{10}$$

where $E_{ZMP}$ is the absolute error value between the desired robot ZMP and calculated ZMP given in Eq. (8).

## V. Experiments

### A. Human Gait Analysis

Four makers are attached to head, hip, leg, and ankle for analyzing the gait pattern of the human such as shown in Fig.8. Two gait helpful frameworks are also set at two legs so that the human's gait is limited to the sagittal plane. Then sequential images are acquired through CCD digital camera (IPX-VGA 120). The human's gait control parameters are obtained from Extract Human Walking Parameter (EHWP) program. And human's gait pattern is consisted of total 80 frames during one period.

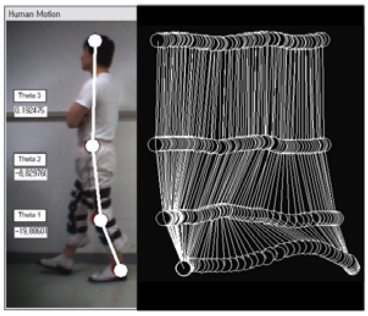
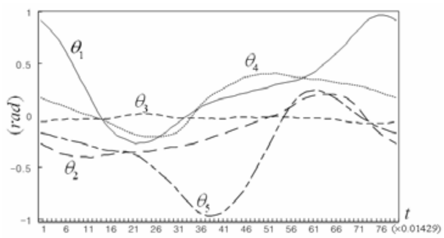
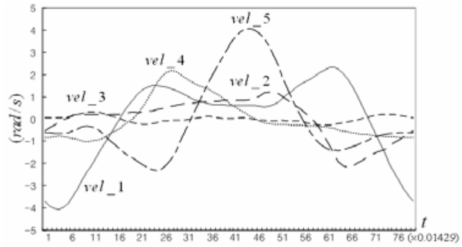


Fig. 8 Extraction Human Walking Parameter

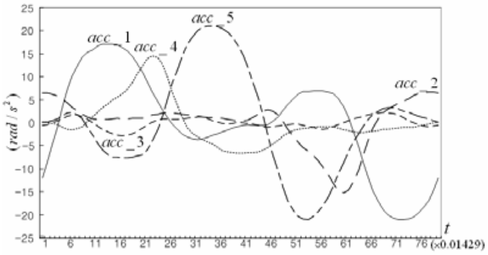
The angles, velocities, and accelerations of the joints of the human are shown in Fig. 9.



(a) Angle




(b) Velocity




(c) Acceleration

Fig. 9 Human gait control values

TABLE I
HUMAN SEGMENT PARAMETER

| Link | $M_i$ (kg) | $L_i$ (m) | $d_i$ (m) | $I_i\,(kg \cdot m^2)$ |
|---|---|---|---|---|
| 1 | 4.575 | 0.493 | 0.194 | 0.192 |
| 2 | 7.5 | 0.424 | 0.240 | 0.141 |
| 3 | 50.85 | 0.813 | 0.509 | 8.270 |
| 4 | 7.5 | 0.424 | 0.184 | 0.141 |
| 5 | 4.575 | 0.493 | 0.299 | 0.192 |

The human's segment parameters are given as Table I [10] and the human's segment torques are obtained from Lagrangian equations (Eq.(1) and Eq.(2)) as shown in Fig. 10.

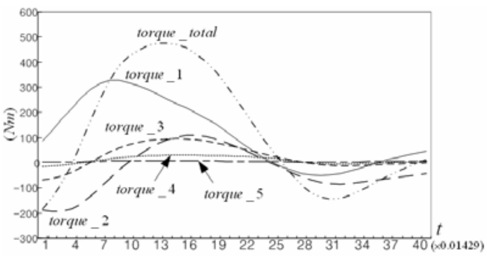



Fig. 10 Human Torque

### B. Gait Pattern Generation on the Sagittal Plane

Initial populations of GA and segment parameters of the biped robot must be previously determined to generate the gait pattern of the biped robot using the human's gait torques. Initial populations are given from a cubic spline interpolation method. The segment parameters of the biped robot are given in Table II, and the GA parameters are given in Table III.

TABLE II
ROBOT PARAMETER

| Link | $M_i$ (kg) | $L_1$ (m) | $d_i$ (m) | $I_i$ (m) |
|---|---|---|---|---|
| 1 | 2.23 | 0.332 | 0.189 | 0.033 |
| 2 | 5.28 | 0.302 | 0.236 | 0.033 |
| 3 | 14.79 | 0.486 | 0.282 | 0.033 |
| 4 | 5.28 | 0.302 | 0.066 | 0.033 |
| 5 | 2.23 | 0.332 | 0.143 | 0.033 |

TABLE III
GENETIC ALGORITHM PARAMETER

| GA parameter | |
|---|---|
| Maximum Generati | 300 |
| Population size | 11 |
| Crossover Probabil | 0.6 |
| Mutation Probabili | 0.05 |

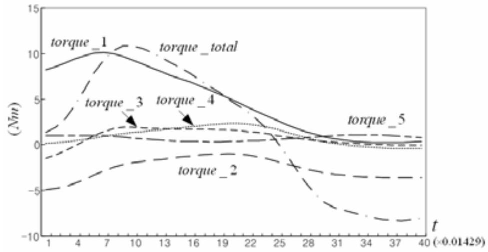
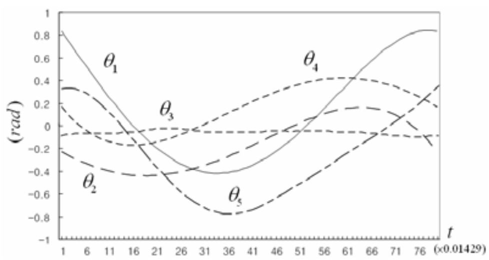
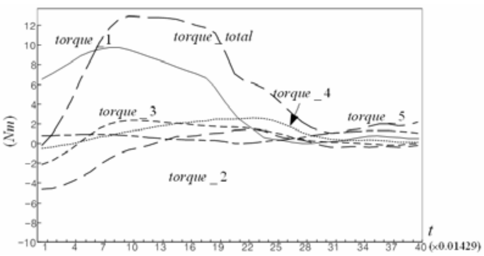



Fig. 11 Robot torque of initial population

Fig. 11 show joint torques of the biped robot before applying the adaptive gait pattern generator.




(a) Robot angle after optimization




(b) Robot torques after optimization

Fig. 12 Control parameter after optimization

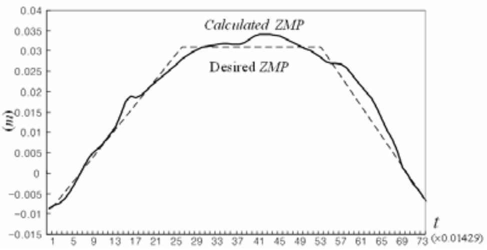
The natural gait pattern like human is obtained after applying the adaptive gait pattern generator. The Fig. 12 shows the joint torques of the biped robot after the optimization.

TABLE IV
SKEWNESS AND KURTOSIS

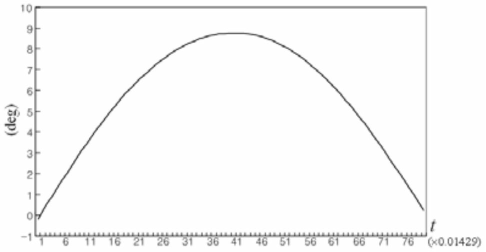
| | Human | Robot(before) | Robot(after) |
|---|---|---|---|
| Skewness | 0.291595 | -0.175355 | 0.279115 |
| Kurtosis | 1.494866 | 1.527261 | 1.489134 |

Table IV shows the human's skewness and kurtosis, and ones of the biped robot before and after optimization. It is showed that results of the biped robot after optimization become similar to the predefined ones of the human.

### *C. Gait Pattern Generation on the Frontal Plane*



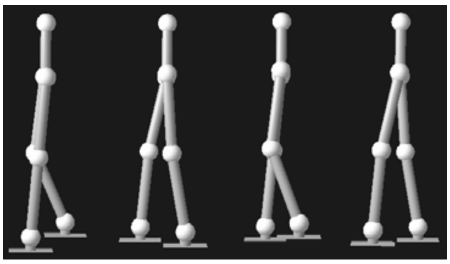

(a) ZMP trajectory



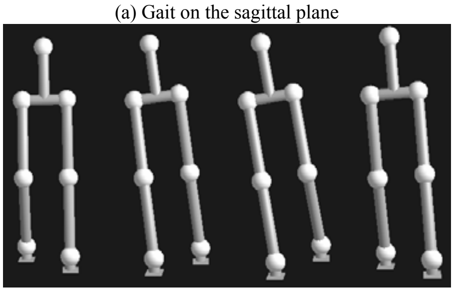

(b) Frontal plane gait pattern( $\theta_{frontal}$ )

Fig. 13 Frontal plane gait pattern

Fig. 13(a) shows that the optimized ZMP trajectory is much closer to the desired one. And Fig. 13(b) shows the $\theta_{frontal}$ generated from ZMP analysis.



(a) Gait on the sagittal plane



(b) Gait on the frontal plane

Fig. 14 Biped robot gait

In order to verify the effectiveness of the gait patterns after optimization, they were simulated using 3D biped robot model which was constructed by OpenGL. The simulated gait of the biped robot is shown in Fig. 14.

## VI. CONCLUSION

It is difficult to directly obtain the natural gait pattern of the simplified biped robot from the complicated human model. In order to solve these problems, this paper proposed the adaptive gait pattern generation of the biped robot using the genetic algorithm, which is based on the energy analysis of the human's gait and the desired ZMP of the biped robot. Experimental results have shown that the proposed algorithm has the gait pattern of the biped robot converging to the natural one of the human.

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