An Adaptive Biped Gait Generation Scheme Utilizing Characteristics of Various Gaits

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1. Introduction

The purpose of this study is to develop a biped locomotion movement generator, named the Sensor-Based Gait Generation system, for humanoid robots that puts biped locomotion to practical use in real environment. The proposed method, in short a gait generator, enables humanoids to use various gaits according to walking surface condition. Policies and structure of the Sensor-Based Gait Generation system are described. A gait generator that is based on the proposed method is designed and implemented onto an original humanoid to demonstrate effectiveness of the proposed method.
Human beings clearly differentiate their walking movements on the downward slope, on the slippery surface and on the flat ground. In other words, humans use a gait that is appropriate to the condition of the walking surface. At present, however, most humanoid robots use only a single gait with possibly adjustable parameters and therefore have clear disadvantage compared with humans. The proposed method imitates gait selection strategy of human and thus eliminates this deficiency.
Many gait generation methods have been proposed already. A gait generated by any one of those methods has good characteristics and shortcomings and therefore has advantages and disadvantages against a given walking surface condition. When humanoids adopt the proposed gait generator, they will be able not only to walk on every road conditions but also to take advantages of good characteristics of each gait.
Especially, we focus on policies of the Sensor-Based Gait Generation system in this paper. One of the two major topics is the explanation of its main components and the other is the configuration of criteria for gait evaluation. In addition, structure of the Sensor-Based Gait Generation system based on this methodology is discussed. After explaining the developed and implemented system that realizes the proposed method, details of environment for experiments are described. Experimental results clearly exhibit practical advantages of the proposed method. Capabilities of the implemental system shown by experimental results are summarized. Conclusions and items for further study are listed at the end.

2. Sensor Based Gait Generation System

The Sensor-Based Gait Generation system realizes continuous gait transition from the current gait to a suitable gait for the condition at the moment. The most important points,

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therefore, are the gait evaluation and the rule of gait changeover. "What can be the criterion for gait transition?" and "how we evaluate gaits?" are the main subjects of this section. They are described according to the proposed system outline and functions of its components. The policies on those points and the range of application of the proposed method are also described here.

A schematic diagram that shows the processing flow of the proposed system is given in Fig.1. The box with dotted line represents the proposed Sensor-Based Gait Generator and consists of a gait generator and a gait library. The gait generator contains a gait selector and an interpolator. The gait library stores gait modules and a transition module where each gait module is capable of generating a gait according to a conventional method.

When a walk command is given to the system, the gait selector chooses a suitable gait module according to the walking surface condition and robot's own state that are obtained from various sensors. Next, the interpolator generates reference angles for every joint using the selected gait module. The output of the gait generator is distributed to actuators through the gait stabilizer with possible compensations to gaits. Elements and functions of the gait generator and the gait library are explained in detail below.

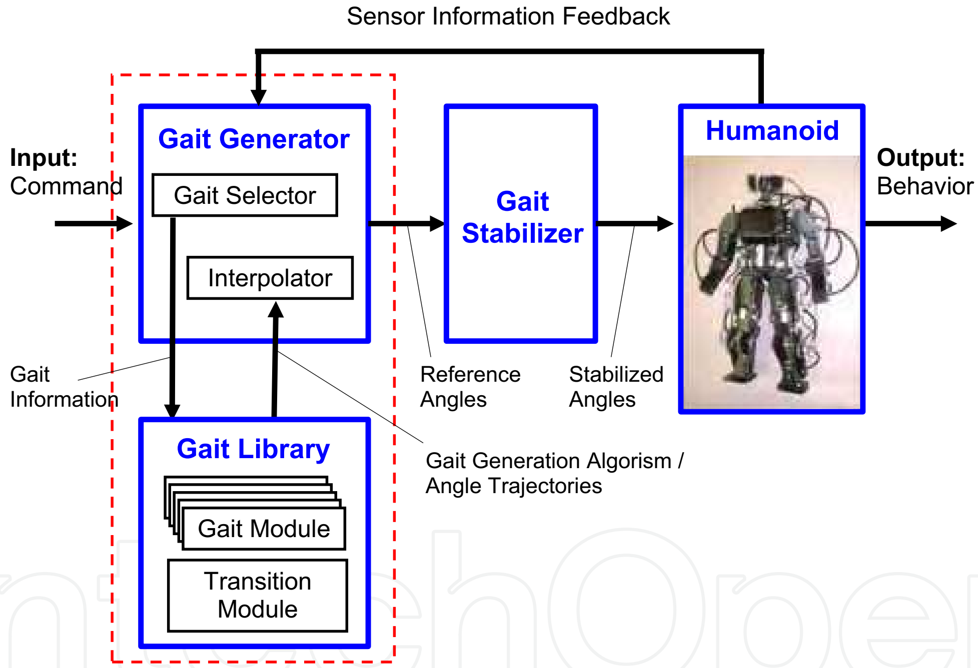

Figure 1. Schematic diagram of the Sensor-Based Gait Generation system

2.1 Gait Selector

Gait Selector is the central component of the proposed system and is responsible for choosing a gait from information on walk surface and on the state of the robot.

When designing the Gait Selector, we need to consider various factors. At least, the following factors must be considered.

Mobility

Mobility is the index of traversability of a given gait. The height that a target humanoid can go over is a good example of traversability. Applicable walking field condition of each gait module is also included. For instance, a gait module for generating constant stride is not applicable to steppingstone condition.

Stability Margin (Falling Risk Management)

To ensure sufficient stability margin is to keep avoiding tumbling. Not only the stability margin but also the risk management of tumbling should be included.

Motion State

Motion state is the index of performance against the desired motion. Gait Selector monitors the gait state to realize desired performance.

Although we have listed mobility, stability margin and motional state as the basic items to be considered, it is obvious that this set is not enough for an all-round gait switching rule for humanoid in real environment. When a humanoid walk on sludge, there are two choices of walking strategy. One way may be to walk faster and to pass the sludge as soon as possible without considering stability. The other way is to walk slowly with sufficient stability without considering the traversal time. The choice is dependent on the assigned task and the risk tolerance of falling. Expected energy efficiency can be important too when the given task requires long time duration. Dynamic priority arrangement of gait selection according to the given task for those situations is a quite interesting problem but is left for the future study. Sensory data are utilized, in this study, only for module switching according to the gait selection rule that is specified by the operator.

2.2 Interpolator

Interpolator is the gait generation engine of the system. It uses the gait module, which Gait Selector has chosen, in composing angle trajectories of joints. There are two procedures to generate gaits depending on the type of the chosen gait module.

Gait modules that can generate joint angles in real time

Gait setting parameters, such as walk period and stride, are given to the gait module chosen by the Gait Selector and reference angles of the links are generated real time basis.

Gait Modules not suited for real time generation

Two angle trajectories, chosen from a set of trajectories that are pre-generated and stored according to an algorithm, are compounded to form the reference angles.

2.3 Gait Modules

A gait module is a self-sustained package of a particular gait. It either contains a gait generating algorithm or a set of pre-generated gaits. Gait modules are identified by gait generation method. Gait modules that are generated by off-line algorithms contain numbers of pre-generated angle trajectories. These gait modules are compiled as a database and stored in Gait Library with required information for each gait module.

2.4 Transition Module

Each gait module simply generates gaits according to the chosen algorithm and therefore, a caution must be exercised when connecting the trajectories from different gait modules. The transition module contains one or more algorithms for generating transitional movements to maintain dynamical integrity of the walk when a change of gait is selected. In Section 4, the proposed algorithms are explained in detail.

2.5 Gait Evaluation

Numerical index of gait performance is required for evaluation of a gait module or a chain of gait modules. We utilize the following three indices, which can summarize the characteristics of a gait.

Achievement Rate

The rate of success of the desired traversal on conceivable surface environments

Moving Velocity

The traversal velocity on a given surface environment

Energy Efficiency of Locomotion

Traversal distance per unit energy (We use supplemented energy that is defined in the next subsection to calculate this index.)

Characteristics of gaits are converted into numerical values using these indices. In addition, weighted summation of these values is adopted as an integrated evaluation factor of a gait. It is mentioned that other criteria for evaluation can be added to this list when a need arises.

2.6 Supplemented Energy

Supplemented energy per step is defined to be the sum of consumed energy of actuators while a robot walks a step. It is obvious that smaller the supplemented energy less the lost energy. The supplemented energy is derived from the rates of changes of the positional energy and the kinetic energy. In case of a movement that has no lost energy, like a natural response of the inverted pendulum, the potential energy decreases as much as the kinetic energy increases because there is no actuation. Thus, it can be said that a movement is closer to ideal if the sum of the rate of potential energy variation, in short the power, and the rate of kinetic energy variation is closer to zero.

The supplemented energy is computed with the following procedures.

- The powers corresponding to the potential and the kinetic energy

$$P_P = \sum_{i=1}^{n} m_i g \dot{z}_i \tag{1}$$

where

P_P : Power by potential energy

n : Numbers of links

m_i : Mass of link i

g : Acceleration of gravity

z : Height position of CoG of link i

$$P_K = \sum_{i=1}^{n} \left\{ m_i \left(\ddot{x}_i \dot{x}_i + \ddot{y}_i \dot{y}_i + \ddot{z}_i \dot{z}_i \right) + I_X \ddot{\theta}_{Xi} \dot{\theta}_{Xi} + I_Y \ddot{\theta}_{Yi} \dot{\theta}_{Yi} + I_Z \ddot{\theta}_{Zi} \dot{\theta}_{Zi} \right\} \tag{2}$$

where

P_K : Power by kinetic energy

x_i, y_i : Position of CoG of link i

$\theta_{Xi}, \theta_{Yi}, \theta_{Zi}$: Angles of link i about the x , y and z axes

I_{Xi}, I_{Yi}, I_{Zi} : Height of CoG of link i

Next, the sum of the two powers is computed. Note that a positive sum implies that the total torque is applied towards the direction of walk. On the contrary, a negative sum implies that the total torque is acting on the reverse direction of walk. Here, it is assumed that the type of actuators of the robot have no capacity to keep energy. Then, the total 'effort' of actuators can be represented by the absolute value of the sum of powers. Hence, it is used here as the index of the consumed energy.

$$P = \left| \; P_p + P_K \; \right| \tag{3}$$

where

P : Total power

The total supplemented power per step is computed by integration of the total power over the time interval of a step.

$$E = \int_0^T P dt \tag{4}$$

where

E : Supplemented Energy

T : Time interval of a step

3. System Architecture Methodology

The architecture of the Sensor Based Gait Generation system is described in detail. The design procedure of the proposed system is described first. The selection criteria of gait modules are explained afterwards.

3.1 Procedure

The design flow of the Sensor-Based Gait Generation system is as follows:

1. Preparation of gait modules using available gait generation schemes
2. Evaluation of gait modules on each ground condition
3. Designing and development of Gait Selector
4. Installation and architecture optimization

We prepare self-sustained gait modules first. Then, gait modules are categorized according to their mobility and labeled with applicable ground conditions. We evaluate gait modules by rehearsal walking to verify the appropriateness of the relationship between the gait module and ground conditions. Next, Gait Selector is configured by criteria that are based on stability margin and motion state of walking. Finally, we fine-tune Gait Selector by installing the Sensor-Based Gait Generation system onto the target humanoid.

3.2 Selection Criteria of Gait Modules

Among three factors mentioned in Subsection 2.1, the mobility parameter of a gait module is included in the module because it is used only for the test of applicability of the module. Therefore, only gait selection based on stability margin and motion state is explained here. Basically, sensory information is classified roughly into prior information set and posterior one. For example, cameras and laser range finders give prior information of the ground condition. Environment maps that are given by the operator are also included in the prior information set. This information is typically utilized for prediction of ground conditions. Prior information is mostly used in determination of the applicable gait modules for the given ground condition. Preliminary motion for the expected change of ground condition (kajita2003) is a good application example of the prior information. On the other hand, posterior information is utilized to evaluate the stability margin and the motion state. The posterior information is obtained at real-time basis during actual walk. It is very important for the gait selection because disturbances on the balance of gaits can only be detected at real-time basis. Instability that is rooted in ground conditions undetectable by the prior information can, therefore, be absorbed by a gait switching according to the posterior information.

With the above observations, gait modules are selected according to the following policies based on the posterior information.

1. The stability margin must be kept at an appropriate level
2. The current motion state should be made closer to the ideal state

Here, we use the following physical quantities in evaluating the above policies:

- Criterion for stability margin: ZMP (Zero Moment Point)
- Criterion for motion state: Angular Momentum

This set of choices comes from the fact that the most gaits for humanoids are based on the ZMP stability criterion and all of the developed gait modules adopt ZMP criterion. Since ZMP and angular momentum are commonly used, discussions on those criteria are omitted here.

4. Gait Transition Algorithm

Two algorithms that connect joint angle trajectories at the time of gait module changes are described in this section. These algorithms are stored in the transition module.

4.1 Algorithm 1: Transition in Double-Leg Supporting Phase

This transition method is applicable when the switching of gait modules occur during the double-leg supporting phase. It generates motions in this phase for connecting gaits before and after this phase. Two 2-D dynamics models in the sagittal and lateral plane are used to simplify the actual 3-D movement of humanoid. Dynamics model in the sagittal plane is shown in Fig.2 together with the corresponding 3-D model. It is assumed that there is no interference between the sagittal and lateral planes. Trajectories of the waist joint in both sagittal and lateral planes are determined first from positions and speeds of the waist joint at the end of the prior gait and the start of the new gait. It is noted that all other joint angle trajectories of humanoids with geometrical configurations of the 3-D model in Fig. 2 are obtainable from this information.

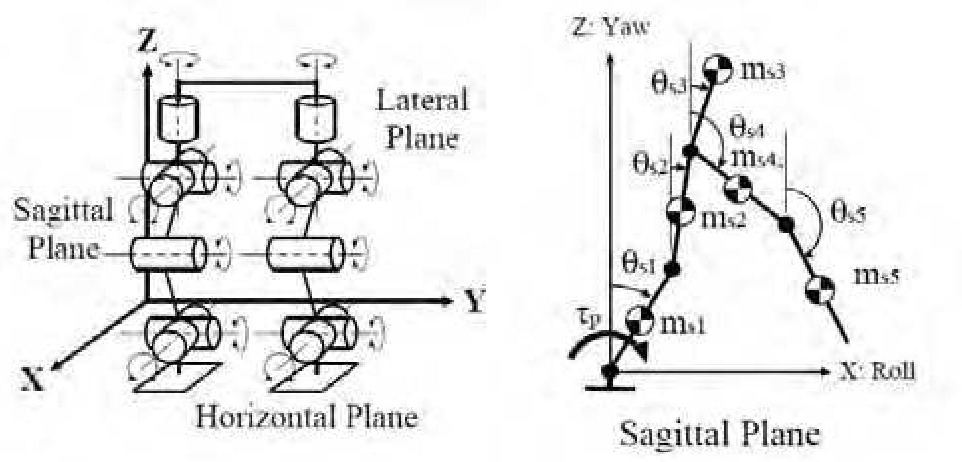

Figure 2. DOF distribution and dynamics model in the sagittal plane

The waist joint trajectory is designed using cubic polynomials as shown in Eq. (5), Eq. (6) and Eq. (7). Note that those functions have enough number of parameters to continuously connect the position and speed trajectories of the waist joint at the start and the end. Both the initial and final conditions of the waist joint trajectory are determined from the supporting leg, which is the hind leg for the initial condition and the fore leg for the final condition. It is also noted that the speed of the waist joint looking from the support-leg expresses the absolute speed of the robot trunk.

$$x_w(t) = \alpha_{x0} + \alpha_{x1}t + \alpha_{x2}t^2 + \alpha_{x3}t^3 \tag{5}$$

$$y_w(t) = \alpha_{y0} + \alpha_{y1}t + \alpha_{y2}t^2 + \alpha_{y3}t^3 \tag{6}$$

$$z_w(t) = \alpha_{z0} + \alpha_{z1}t + \alpha_{z2}t^2 + \alpha_{z3}t^3 \tag{7}$$

where

t : Time

$x_w(t), y_w(t), z_w(t)$: Position of waist at time t

$\alpha_{xn}, \alpha_{yn}, \alpha_{zn}$: Coefficients of cubic polynomial

The waist joint trajectories shown in Eq. (5) and Eq. (7) are used to compute angle trajectories of links in the sagittal plane. Here, the upper body is vertically fixed in order to prevent large movement of the center of gravity. The angle orbit of each link can be determined using Eq. (8) – Eq. (9) from geometrical constraints representing kinematics configuration of the robot. The same procedure is also applicable in the lateral plane.

$$\theta_{s1}(t) = \phi_{wf}(t) + \phi_1 \tag{8}$$

$$\theta_{s2}(t) = \theta_1(t) + \phi_2 - \pi \quad (9)$$

$$\theta_{s3}(t) = 0.00 \quad (10)$$

$$\theta_{s4}(t) = \phi_{wb}(t) - \phi_3 + \pi \quad (11)$$

$$\theta_{s5}(t) = \phi_{wb}(t) + \phi_4 + \pi \quad (12)$$

where

$\theta_{si}(t)$: Angle orbit of link i in sagittal plane

St : Stride

L_{wf} : Length parameter for computation of fore leg

L_{wb} : Length parameter for computation of hind leg

ϕ_{wf} : Angle parameter for computation of fore leg

ϕ_{wb} : Angle parameter for computation of hind leg

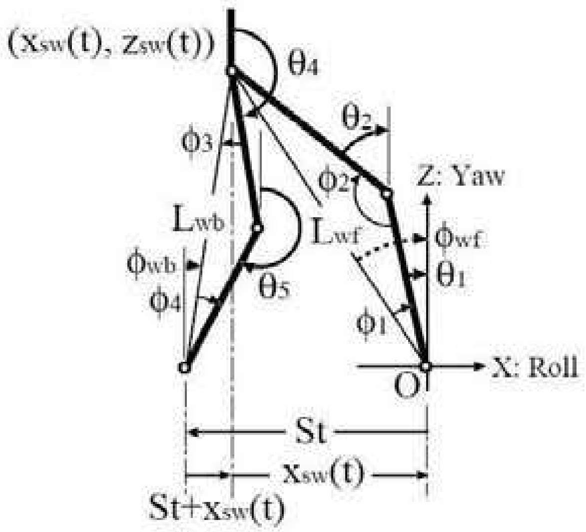

Figure 3. Movement while transition in double-supporting phase

The advantage of this algorithm is that it can easily connect gait modules by the simple geometrical computation with real-time calculation. But, the walk under this algorithm tends to become unstable at the transition of gait module because of discontinuities in acceleration. Nevertheless, this algorithm works most of the time because it takes advantage of the large stability margin resulting from the large supporting polygon of the double-leg supporting phase.

4.2 Algorithm 2: Transition Utilizing Spline Function

The second proposed algorithm utilizes spline functions. This algorithm consists of two processing steps. The first step is for generation of angle trajectories of transitional motion. The second step is for conversion of the generated trajectories into dynamically stable one.

Step 1: Generation of transitional motion

The objective of this step is to generate a set of equations to interpolate trajectories obtained from gait modules. The advantage of this algorithm is to guarantee gait module switching with continuous ZMP transition. This feature is realized by taking second-order derivatives of joint angle trajectories into consideration. We utilize cubic spline functions with four nodes for this purpose.

$$\theta_i = \begin{cases} \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \alpha_3 t^3 & (0 \le t < h) \\ \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 t^3 & (h \le t < 2h) \\ \gamma_0 + \gamma_1 t + \gamma_2 t^2 + \gamma_3 t^3 & (2h \le t < 3h) \end{cases} \quad (13)$$

$$h = \frac{1}{3} T_t$$

where

$\alpha_k, \beta_k, \gamma_k$: Coefficients of spline functions

T_t : Transitional period

The following boundary constraints are introduced to keep the continuity of ZMP.

< Boundary Conditions >

- Joint angles at t=0 and t=3h are predetermined from the switching gaits
- Joint angular velocities are continuous at t=0, t=h, t=2h and t=3h
- Joint angular accelerations are also continuous at t=0, t=h, t=2h and t=3h

Step 2: Trajectory stabilization

Transitional motion generated in Step 1 may become unstable dependent on the transition period and boundary conditions. The generated joint angle trajectories are checked for their stability and, if necessary, are modified into stable motion pattern based on the ZMP criterion.

Processing flow of the trajectory stabilization is shown in Fig.4. As described in Fig.4, the motion pattern converter consists of a CoG velocity controller and a referential CoG velocity distributor. The stabilization is processed using these two-step operation.

The transitional angle trajectories from Step 1 and the reference ZMP are supplied to the CoG velocity controller first. CoG of the humanoid is computed by kinematical calculation with the supplied trajectories. In addition, a single-mass model of the humanoid that represents simplified dynamics of the humanoid is applied to obtain the referential CoG velocity. This referential CoG velocity realizes the reference ZMP and stabilizes the transition motion. The referential CoG velocity distributor distributes the CoG velocity to each joint angle by utilizing CoG Velocity Jacobian (Sugihara2002).

This algorithm can realize smooth gait module transition with ZMP continuity. Another advantage of this algorithm is the freedom in the timing of transition. This algorithm can change gait modules in single-supporting phase as well. However, this algorithm requires more calculation effort than algorithm 1.

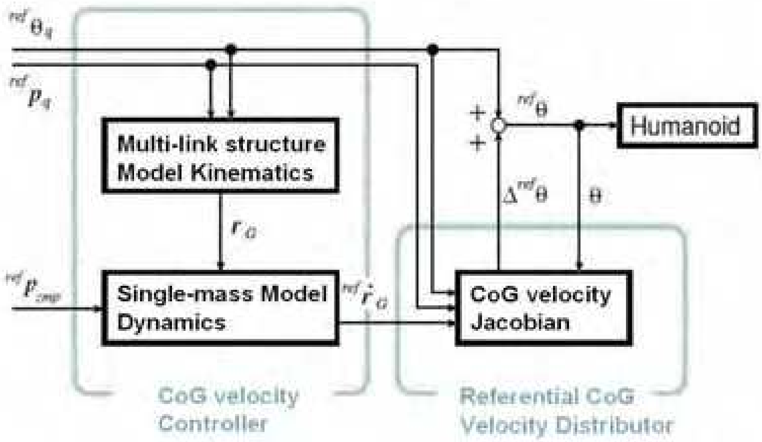

Figure 4. Block diagram of the transitional motion stabilizer

5. Experimental System

The developed and implemented system that realizes the proposed method is explained.

5.1 Hardware Configuration

Hardware configuration of the control system of the robot and a view of the biped walking robot Mk.3 (Furuta2000) used in experiments are shown in Fig.5. Mk.3 was designed for evaluation of gait generating algorithms and walk stability.

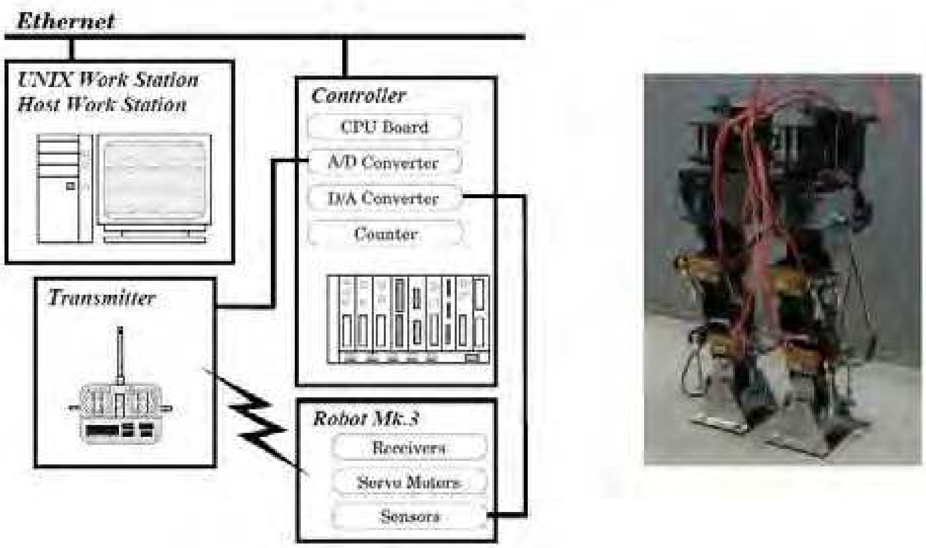

Figure 5. Hardware configuration of the experimental system and humanoid Mk.3

This control system consists of a host computer, a real time controller and a humanoid Mk.3. The reference angle trajectories for links of the robot are distributed wirelessly to motor modules of the robot via a transmitter and receivers. The real time controller uses a commercial real time OS called VxWorks. All sensor values are sent as feedback to the real time controller.

5.2 Developed Gait Modules

Three gait modules based on three kinds of gait generation methods, the "Multi-linked inverted pendulum method (Furuta1997)", the "multi-phase gait (Toda2000)" generating method and the static walk, are constructed and stored in the experimental Gait Library. Although the multi-linked inverted pendulum method has the smallest energy consumption, its movements can easily become unstable since there is no double-leg supporting phase. The stability of this method therefore is established only on level grounds. On the contrary, robots with the multi-phase gait generator can continue walking on rough grounds within limits since certain stabilization of movements during the double-leg supporting phase is possible. However, energy consumption is comparatively large. The static walk has the highest stability margin and can walk through rough grounds within a larger limit than the multi-phase gait. Since the walk cycle is long, however, the walk speed is low and energy consumption is large.
The performance of these gait modules are evaluated in preliminary experiments on even ground, on inclined ground with 5-degree climb and on yielding ground (covered with two sheets of cardboard). Success rate of 10-step walking as the achievement rate, walking speed and the supplemental energy as the energy efficiency for locomotion are measured in the preliminary experiments. These results are summarized in Table 1.

Features \ Gait		Multi-Linked Inverted Pendulum	Multi-Phase Gait	Static Walk
Supplemented Energy [N·m /step]	Sagittal	0.49	1.2	0.84
	Lateral	0.42	0.70	1.0
Walking Speed [m / sec]		0.062	0.071	0.025
Success Rate [%] (ratio)	Even Ground	90 (18/20)	90 (18/20)	90 (18/20)
	Inclined Ground	15 (3/20)	80 (16/20)	80 (16/20)
	Yielding Ground	10 (2/20)	35 (7/20)	80 (16/20)

Table 1. Results of evaluation of gait modules in preliminary experiments

5.3 Experimental Gait Selector

As we have explained in Subsection 3.2, walking state can be judged by monitoring the angular moment of the humanoid because the developed gait modules are based on the ZMP criterion. The flow chart of Gait Selector according to the design policy in Subsection

3.2 is shown in Fig.6. Note that, in this figure, gait modules on the right hand side are more efficient but less stable than those on the left hand side. The right most module, which is for defensive fall, in Fig.6 is selected in the case when stabilization of walk is impossible.

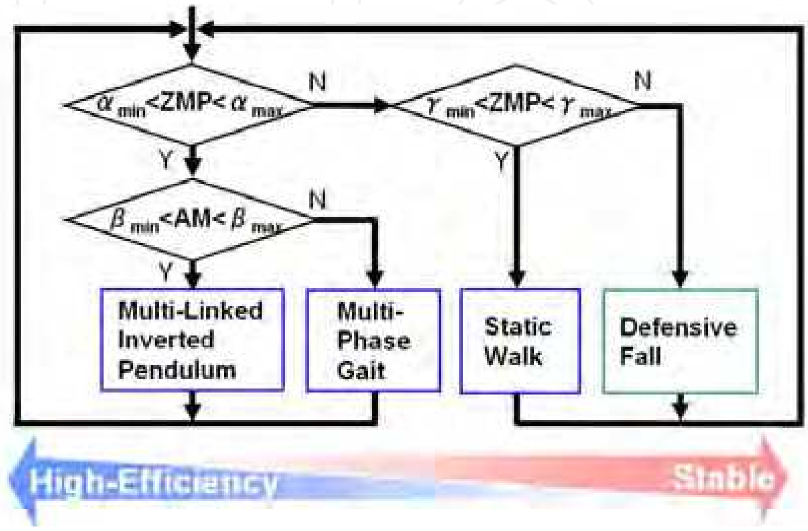

Figure 6. Flow chart of gait selection

At the gait selection, the system first obtains a measured ZMP and determines walk stability margin. If the ZMP deviation is over a threshold determined by $\alpha_{\min}$ and $\alpha_{\max}$, imminence of falling is judged. Defensive fall is selected if the stability margin of ZMP equals zero, namely, the outside of thresholds ($\gamma_{\min}$ and $\gamma_{\max}$). Otherwise, static walk is selected because of the best stability characteristic. If ZMP deviation is within a band defined by the two thresholds $\alpha_{\min}$ and $\alpha_{\max}$, then the next gait is selected based on the angular momentum. It is noted that the angular momentum is an index that can express the degree of rotational motion of a robot, just as ZMP is an index that is able to determine the condition of contact between the sole and ground. Therefore, magnitude of the forward motion of a humanoid can best be evaluated by the angular momentum. Since there is an appropriate range of the angular momentum for steady walk, the measured angular momentum is tested if it lies within a set of minimum and maximum thresholds given by $\beta_{\min}$ and $\beta_{\max}$. If that is the case, then the multi-linked inverted pendulum method is selected as the gait module. If the angular momentum is out of the threshold, multi-phase gait that is more stable than the multi-link inverted pendulum method is selected as the next gait module.

It is known that the evaluation variables used in these criteria are very sensitive and are affected by even microscopic ground conditions. A part of this over sensitivity can be reduced by elimination of high-frequency components of the sensed data. The average of sensor values over 0.080 second interval preceding the gait selection is used for this purpose. A weak point of this operation is the possibility of missing a sharp maximum of ZMP and, as a result, missing the onset of instability. However, this can be overcome by adopting enough stability margins through tactically chosen thresholds.

The following set of threshold values is used:

$$\begin{aligned}
\alpha_{\min} &= -6.0 \quad [mm] \\
\alpha_{\min} &= \ \ 10 \quad [mm] \\
\beta_{\min} &= -0.15 \quad [kgm^2/\sec] \\
\beta_{\min} &= -0.030 \quad [kgm^2/\sec] \\
\gamma_{\min} &= -40 \quad [mm] \\
\gamma_{\min} &= \ \ 40 \quad [mm]
\end{aligned} \tag{14}$$

Here, the range of α is set at 16 [mm] that is 20% of 80[mm], the actual sole length in traveling direction of Mk.3. In addition, both the thresholds $\alpha_{\min}$ and $\alpha_{\max}$ are shifted forward by 2[mm]. It is because the vertical projection of the center of gravity deviates 2[mm] in the forward direction with our robot. $\gamma_{\min}$ and $\gamma_{\max}$ are set at 40 [mm], sole edge positions, because they represent the limit of stability. For the case of the thresholds of angular momentum, they should be decided based on the desired values derived from the planned motion. Here, the values in the table for the thresholds $\beta_{\min}$ and $\beta_{\max}$ are determined based on the preliminary experiments. The reason for this is a hardware problem. We found that backlashes at gears of the robot have adverse effects on the measured angular momentum through these experiments. It is noted that those thresholds depend only on robot hardware parameters such as the size of the sole, accuracy of sensors, and other physical parameters and not on environmental conditions. Environmental conditions are taken into consideration through real time measurements and gait switchings.

5.4 Installed Gait Transition Algorithm

We have chosen algorithm 1 that was explained in Section 4, namely, transition in double-supporting phase, as the gait transition algorithm. This is because that processing power of the hardware is not enough to execute gait transition with algorithm 2. We have chosen higher priority for real-time operation of gait transition here. It is noted that this transition operation is to be completed within 0.40[sec], which is chosen from the hardware constraint.

6. Experiments

Two purposes of this experiment are the evaluation of the developed experimental system and demonstration of effectiveness of the proposed method.

6.1 Experimental Set-ups

The developed system was implemented onto the control system of the original humanoid robot Mk.3. Gyroscope sensors on each leg link and universal six-axis force sensors installed between the sole and foot were used. Measurement of angular momentum was from gyroscope sensors and measurement of ZMP was from universal force sensors. Measured values were used for judgment of gait module selection at the gait selection brunching points.
The robot is commanded to walk on two kinds of changing road surfaces. In the first case, the surface changes from an upward slope with angle of 5[deg] to an yielding surface (covered with two sheets of cardboard). In the second case, the surface changes from a flat

horizontal ground to an upward slope with angle of 5[deg]. The robot is commanded to walk ten steps in both cases, approximately five steps on each surface.
During the evaluation experiments, ZMP and angular momentum were recorded. At the same time, information on gait selection and overall operation was collected. The obtained data were used for verification of the intended operation of the developed experimental system. Next, success rates of the planned walk, amount of the supplemented energy and traversal time to complete the commanded walk were compared between the proposed method and conventional single gait generation scheme in order to evaluate effectiveness of the proposed method. Major parameter values used for gait generation are listed in Table 2.

Gait	Stride[m]	Period[sec]
Static Walk	0.050	2.0
Multi-Phase Gait		0.70
Multi-Linked IP		0.80

Table 2. Parameter settings of each gait module

Here, selection and change of gait were performed every two steps and at the start of the walk cycle. The reason for every two steps is that gait transition at every step implies that the gait selection of next step must be done while the transient effect of gait change is still prevailing and this will cause errors in selection of gaits.

6.2 Result of the Verification Experiments

Typical trajectories of gait selection, the measured angular momentum and the ZMP from one each of two cases are shown in Result I (Fig.7) and Result II (Fig.8).

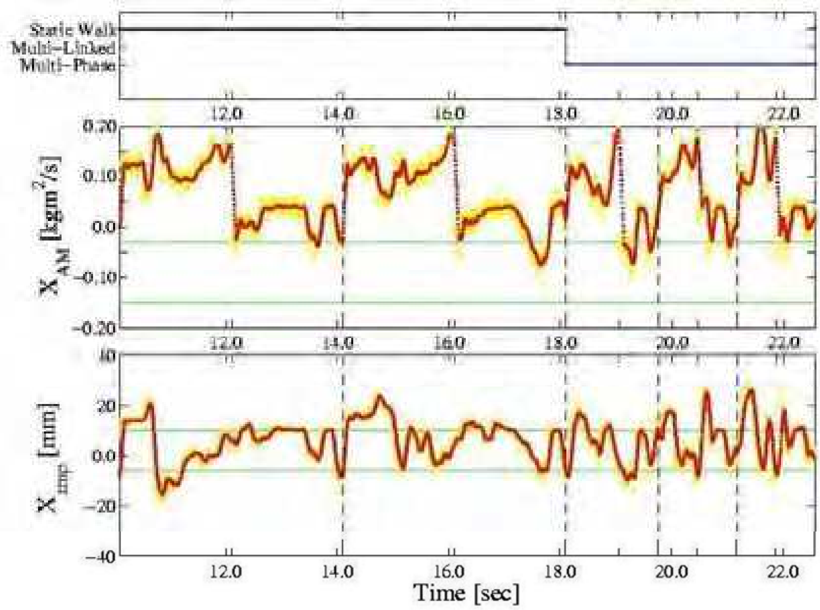

Figure 7. Gait module selection and sensor values I: Walking through an upward slope of 5[deg] and encountering an yielding surface at time 18.1[sec]

Blue lines in the top figures show the selection of gaits. Middle graph is the angular momentum. The lowermost graph is the measured ZMP. Values shown in yellow are the instantaneous measurement of sensors and the red curves are the running average over the 0.080[sec] time duration and are used as indices of gait selection. Green lines show the minimum and maximum thresholds. Vertical dashed lines point the timing of gait selection. In Result I, at the first and second gait selection timings (10.1[sec], the left end of the graph, and 14.1[sec]), static walk was chosen because the averaged ZMP deviated from the range of thresholds. The robot moved onto the yielding surface at the third timing (18.1[sec]) of gait selection. The ZMP came back within the limits of the threshold at this timing but the angular momentum stayed outside of the threshold. It is observed that the selected gait was changed to the multi-phase gait in response to this. In summary, the static walk with the highest stability margin was chosen on the upward slope and the multi-phase gait was chosen on the yielding surface based on a comparatively wider stability margin.

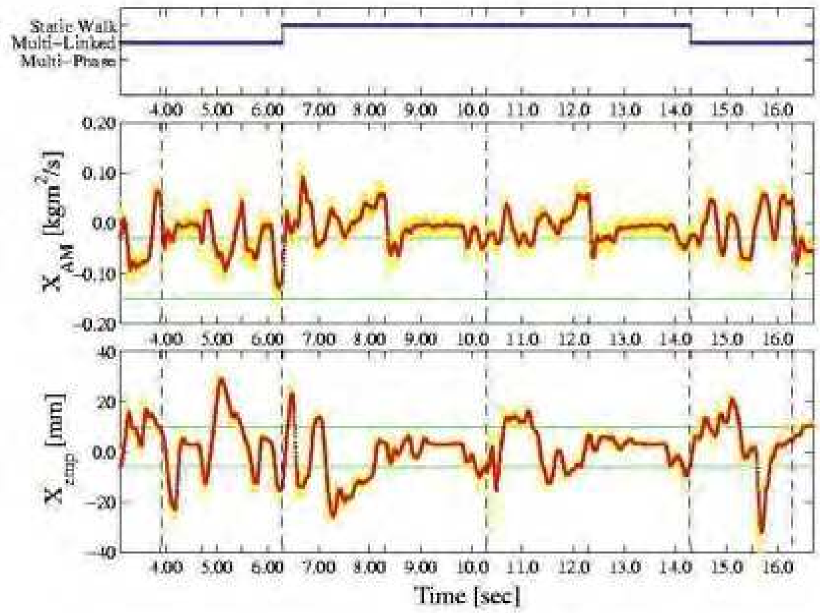

Figure 8. Gait module selection and sensor values II: Walking through a flat horizontal ground and encountering an upward slope at time 6.30[sec]

In Result II, the gait of multi-linked inverted pendulum method was chosen on the initial horizontal ground since the ZMP and the angular momentum were judged to be within the limits of the thresholds. At the second gait selection timing (6.30[sec]) when the robot proceeded to the upward slope, the ZMP deviated out of the threshold. Therefore, static walk with highest stability was chosen. At the fourth timing (14.3[sec]) of gait selection, the gait of multi-linked inverted pendulum method was chosen since the angular momentum returns within the threshold.

The results of these two cases exhibit the gait selection corresponding to the road surface condition is successfully realized using sensor information.

6.3 Effectiveness of the Proposed Method

The sensor-based gait generation and conventional single gait generation are compared in Table 3.

	Success Rate	Traversal Time	Total Energy	Walking Velocity	Energy Efficiency
	[%]	[sec]	[Nm]	[m/sec]	[m/Nm]
Static	16/20	20.0	19.4	0.0250	0.0258
MPG	7/20	7.00	19.0	0.0714	0.0263
MLIP	3/20	8.00	9.10	0.0625	0.0549
SBG-I	10/20	12.4	19.0	0.0403	0.0263
SBG-II	10/20	13.2	15.3	0.0379	0.0327

Table 3. Mobility performance of each gait

The success rates in the upper three lines; static (Static), multi-phased (MPG) and multi-linked (MLIP) gaits, are the averages of success rates on the two experimental walk surfaces discussed in the last subsection over 10 trial walks. All other values; traversal time, total supplemented energy, walking velocity and energy efficiency, are computed based on the reference trajectory generated by those algorithms for the commanded stride and walk period. The lines marked Sensor-Based Gait I and II (SBG-I and SBG-II) in this table correspond to the cases with the proposed Sensor-Based Gait Generation system on the two walk surfaces.

The experimental results in this table show that the walking velocity and the energy efficiency of walk are both enhanced without reducing the success rate of walk in each sensor-based gait. Therefore, it is concluded that the humanoid can acquire sufficient mobility and can make use of the advantages of each gait by adopting the proposed system.

The high success rate of walk comparable to the static gait only case, however, was not obtained in neither of the experiments. The major cause of this is the instability during the transition from a gait to another. This indicates the necessity to improve the transitional motion by utilizing new hardware and/or better algorithm. Installation of higher-end CPU with the transitional algorithm 2 would be a viable approach. By doing this, success rates equivalent to the static walk can be expected in both Sensor-Based Gait I and II cases. It is also noted that it is impossible to increase energy efficiency of the sensor-based gait more than that of the multi-linked inverted pendulum method. This is because the Gait Selector is designed to consider not only the energy efficiency but also the walking stability as the criteria for walk selection.

It is also noted that the success rate is no more than 80% even for the case of static gait in the series of experiments. The reason for this is that no balance control was implemented in the experiments in order to evaluate the effect of the proposed system only.

7. Conclusion and Future Works

A Sensor-Based Gait Generation method was introduced and an experimental system was built. Then, the system was implemented onto an original humanoid robot to evaluate operations and to demonstrate effectiveness of the proposed method. Experimental results exhibited successful gait selection corresponding to the road surface condition obtained from sensor information. Additionally, walking velocity and the energy efficiency are both enhanced without reducing the success rate of walking.

The design approach for Gait Selector based on both ZMP and the angular momentum adopted in this study is a sufficiently general and valid one. The developed Gait Selector should be applicable to many gaits and humanoids. However, more conditional branchings based not only on ZMP and the angular momentum but also on some combinations of them may be necessary depending on such factors as robot hardware, types of gaits and criteria for robot motion evaluation. The fundamental reason for the lack of a fixed design method is that the selection of gait is inherently rooted in factors such as hardware specifications and characteristics of each gait. At present, therefore, we have to redesign the Gait Selector such as that in Fig.6 according to the procedure described in Section 3.

Future studies should be targeted to simplify the design procedure of Gait Selector. The more gait modules and ground conditions are installed into the system, the more complicated parameter tuning must be required. One possibility of avoiding this problem would be to introduce simple learning capability for Gait Selector design. A discrimination method that only utilizes sensor value histories of 3-axis accelerometer to identify several ground conditions (Miyasita2006) was already reported. They employ simple decision tree constructed based on acceleration data that are obtained during several trial motions on each ground condition. There is a possibility of direct acquisition of transition rules by utilizing histories of ZMP and angular momentum with all combinations of a gait module and a ground condition.

Apart from the improvement of the design of Gait Selector, there also is a room for improvements by adding new gait generation modules and improving the success rate of walk through the enhancement of the transition scheme for gait module changes. These are more straightforward tasks if the required additional computational power is available.

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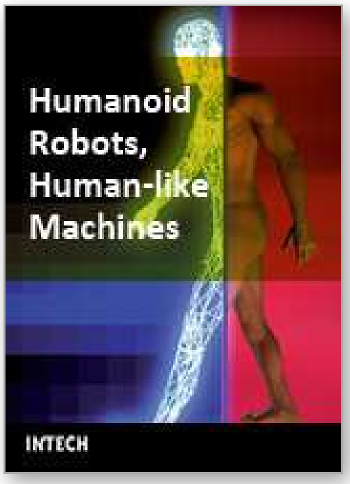

Humanoid Robots, Human-like Machines
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In this book the variety of humanoid robotic research can be obtained. This book is divided in four parts: Hardware Development: Components and Systems, Biped Motion: Walking, Running and Self-orientation, Sensing the Environment: Acquisition, Data Processing and Control and Mind Organisation: Learning and Interaction. The first part of the book deals with remarkable hardware developments, whereby complete humanoid robotic systems are as well described as partial solutions. In the second part diverse results around the biped motion of humanoid robots are presented. The autonomous, efficient and adaptive two-legged walking is one of the main challenge in humanoid robotics. The two-legged walking will enable humanoid robots to enter our environment without rearrangement. Developments in the field of visual sensors, data acquisition, processing and control are to be observed in third part of the book. In the fourth part some "mind building" and communication technologies are presented.

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