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An Improved ZMP-based CPG Model Considering Pitch and Roll Inclinations

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Abstract - This paper aims to provide an improved ZMP-based CPG model considering pitch and roll inclination. The proposed CPG model is optimized by Self-adaptive Differential Evolutionary Algorithm (SaDE). Simulation results are presented and the effectiveness of the CPG model is shown in snapshot of experiments.

Keywords: Bipedal robot, CPG, Pitch, Roll, SaDE.

1. Introduction

Development of humanoid robot has been made rapid progress. Different kinds of humanoid robots can walk stably on the flat horizontal plane (Huang et al., 2001; Kajita et al., 2002; Plestan et al. 2003; Lee et al., 2008; Chevallereau et al., 2009). However, not only flat plane, but also inclined plane exists in the natural environment.

Because of the decrease in the area of support polygon, the difficulty in balancing the robot during walking on an inclined plane is increased. To solve this problem, Kim et al. (2007) applied online control algorithm that considers local and global inclination of the ground. Ali (2007) utilized orientation based inverse kinematics to accomplish diagonal walking on an inclined plane. Vundavilli et al. (2009) proposed Genetic-neutral and Genetic-fuzzy system to generate walking gait for ascending and descending slope. Hong et al. (2011) used Modifiable Walking Pattern Generator (MWPG) to deal with inclined plane with pitch and roll angle. Seven et al. (2012) proposed a fuzzy system to online adjust the body pitch angle corresponding to various pitch slope angle. Besides, central pattern generator (CPG) is investigated to generate bipedal robot walking gait. CPG provides a good interaction between the robot and the environment by integrating feedback sensors (Ijspeert, 2008). Taga et al. (1991) integrated feedbacks with neural oscillators for unpredicted environment. Aoi and Tsuchiya (2007) utilized CPG model for straight and curved walking. Or (2010) presented a hybrid CPG-ZMP control system for flexible spine humanoid robot. Yu et al. (2014) proposed an improved ZMP-based CPG model based on the model proposed by Yang et al. (2007). The above-mentioned CPG models are presented to deal with horizontal flat plane or inclination in pitch angle. Therefore, this paper aims to extend the CPG model proposed by Yu et al. (2014) to deal with pitch and roll inclination.

Compared with prominent optimization technique, the performance of conventional Differential Evolutionary Algorithm (DE) is superior (Storn & Price, 1997). DE requires users to 1) tune crossover rate and scaling factor and 2) choose suitable strategy for different problems. SaDE can adaptively choose suitable parameters and strategies. Compared with other adaptive DE (Qin et al., 2009), its performance is superior. SaDE is adopted in this paper.

Mathematical model of the bipedal robot and environment are described in section 2. An improved CPG model which considers pitch and roll inclination is presented in section 3. Objective functions and constraints are portrayed in section 4. Followed by section 4, simulation results are presented. Conclusions are made in section 6.

2. Mathematical Model of Bipedal Robot and Environment

The test bed is KHR-3HV. The schematic diagram (Fig. A) of the robot is shown in Appendix.

The base of the robot is set at the pelvis. It is movable and interacts with the ground contact model (Fujimoto & Kawamura, 1998). Two assumptions are made in this simulation. 1) R/C servos are ideal and track reference trajectories ideally; 2) Mass of each link is considered to be point mass. Fig. 1 is the flow chart of the simulation environment. The ground contact model is modeled as 3-D linear spring damper system shown in Eqs. (1-3). Each corner of the foot sole is set as contact point. The position and orientation of the base are updated by Euler's integration (Fujimoto & Kawamura, 1998). The robot starts from the tail of the arrow and walks along the direction of arrow on an inclined plane (Fig. 2) with pitch slope angle (θ_{slope}) which is set as 5°. The pitch (θ_{pitch}) and roll (θ_{roll}) inclination experienced by the robot change with the orientation (α) of the robot and are calculated by Eqs. (4-5) (Ali, 2007).

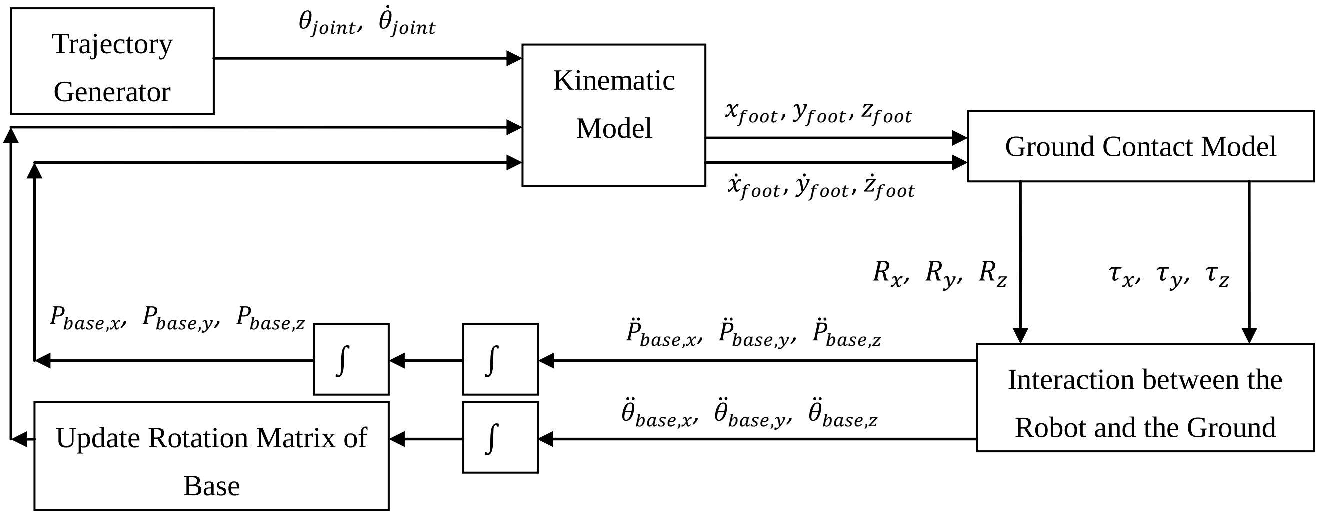

Fig. 1. Flow Chart of Simulation Environment.

$$R_{z,i} = \begin{cases} k_z(z_{foot,i} - z_{ground,i}) - d_z\dot{z}_{foot,i}, & z_{foot,i} \le z_{ground,i} \\ 0, & z_{foot,i} > z_{ground,i} \end{cases} \quad (1)$$

$$R_{x,i} = \begin{cases} k_x(x_{foot,i} - x_{o,i}) - d_x\dot{x}_{foot,i}, & z_{foot,i} \le z_{ground,i} \\ 0, & z_{foot,i} > z_{ground,i} \end{cases} \quad (2)$$

$$R_{y,i} = \begin{cases} k_y(y_{foot,i} - y_{o,i}) - d_y\dot{y}_{foot,i}, & z_{foot,i} \le z_{ground,i} \\ 0, & z_{foot,i} > z_{ground,i} \end{cases} \quad (3)$$

$$\theta_{pitch} = sin^{-1}(sin(\theta_{slope})cos(\alpha)) \quad (4)$$

$$\theta_{roll} = sin^{-1}(sin(\theta_{pitch})/tan(\pi/2 - \alpha)) \quad (5)$$

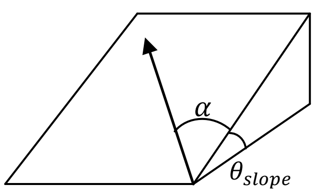

Fig. 2. Inclined Plane with Pitch Slope Angle.

3. Improved CPG Model Considering Pitch and Roll Inclination

The CPG model proposed by Yu et al. (2014) is not sufficient to overcome pitch and roll inclination since it does not consider motion in frontal plane. Due to inclination in roll direction, asymmetric motion in frontal plane is introduced in the proposed CPG model. Through satisfying Eqs. (6-7), $\dot{\theta}_{hf}$ becomes continuous at landing time (t_2 and t_5) and hence angular position, velocity and acceleration are ensured to be continuous. chl shifts CoM to the opposite direction of roll inclination to enhance the stability of walking gait. If the robot experiences zero roll inclination, chl is set as zero and $D_{i,a}$ and $D_{i,b}$ are set to be equal. Motions in frontal plane are formulated in Eqs. (8-9). Formulation of hip and knee trajectories in sagittal plane is the same as Yu et al. (2014). The ankle trajectories in sagittal plane are formulated to ensure the swing foot is parallel to the inclined plane and the trunk is upright in sagittal plane.

$$D_{4,b} = (D_{2,a} - D_{2,b})/2 \tag{6}$$

$$D_{5,b} = (D_{1,a} - 2D_{2,a} + 3D_{3,a} - D_{1,b} + 2D_{2,b} - 3D_{3,b} + 4D_{4,b})/5 \tag{7}$$

$$\theta_{rhf/lhf} = \begin{cases} \sum_{i=1}^{5} D_{i,b}\sin(i\omega(t-t_2)) + chl, & t \in [t_0, t_2]\ or\ t \in [t_5, t_6] \\ \sum_{i=1}^{3} D_{i,a}\sin(i\omega(t-t_2)) + chl, & t \in [t_2, t_5] \end{cases} \tag{8}$$

$$\theta_{raf/laf} = -\theta_{rhf/lhf} \tag{9}$$

$$\omega = \frac{\pi}{t_5 - t_2} \tag{10}$$

4. Optimization of CPG Model

Setting of SaDE is the same as Yu et al. (2014). Compared with Yu et al. (2014), since 1) ground contact model is added and 2) motion in frontal plane is considered in this study, objective functions, constraints and their weightings mentioned in Yu et al. (2014) are modified. f_1 is formulated to minimize abrupt change in trunk velocity and hence minimize abrupt change in ZMP_y. Large impact during landing may cause the robot falls over and its magnitude depends on strike velocity ($v_{strike,L/RF}$) of swing foot. f_2 is designed for searching walking gait with a relatively soft landing.

$$f_1 = \sqrt{\sum_{i=1}^{N} (V_{trunk,n} - \bar{V}_{trunk})^2 / N} \tag{11}$$

$$f_2 = \|v_{strike,RF}\| + \|v_{strike,LF}\| \tag{12}$$

S_1 and S_2 checks whether $ZMP_{x,i}$ and $ZMP_{y,i}$ exceeds the area of support polygon. S_3 is used to ensure stable standing gait by checking the projection of P_{CoM} in sagittal plane during standing is within support polygon. Correct walking direction is along positive y-axis in sagittal plane of the robot. S_4 and S_5 ensure the walking direction of robot is correct while S_6 checks the difference between the actual step length and the desired step length. Due to asymmetric motion in frontal plane, the swing height of right/left swing foot is not identical. S_7 makes sure the height of swing foot relative to the ground is within the desired range. S_8 checks the difference between desired landing time and actual landing time. S_9 ensures the hip/ankle trajectories in frontal plane is within operation range. S_{10} ensures the height of base is higher than the desired minimum height ($H_{Base/Ground,min}$). If $H_{Base/Ground,min}$ is set higher, knee joint is bent less and hence more natural and energy efficient walking gait is achieved. θ_x, θ_y and θ_z are the rotation history about x-, y- and z- axis of {B}. $|\bar{\theta}_x|$ and $|\bar{\theta}_y|$ are examined in S_{11} and S_{12} and *max*($|\theta_z|$) is examined in S_{13} to check whether they are within allowable range. The score and target vector (X) to be searched is formulated by Eqs. (28-29).

$$S_1 = \sum_{i=1}^{N} \max(|ZMP_{x,i}| - L_{\text{frontal}}, 0) \tag{13}$$

$$S_2 = \sum_{i=1}^{N} \max(\left|ZMP_{y,i}\right| - L_{\text{sagittal}}, 0) \quad (14)$$

$$S_3 = max(P_{CoM,\text{sagittal}} - L_{\text{sagittal}}, 0) \quad (15)$$

$$S_4 = max(-\bar{V}_{trunk,sagittal}, 0) \quad (16)$$

$$S_5 = max(-\bar{V}_{swing\ foot,sagittal}, 0) \quad (17)$$

$$S_6 = |L_{desired} - L_{actual}| \quad (18)$$

$$H_{SF,H} = max(max(H_{SF,RL}), max(H_{SF,LL})) \quad (19)$$

$$H_{SF,L} = min(max(H_{SF,RL}), max(H_{SF,LL})) \quad (20)$$

$$S_7 = \begin{cases} max(-(H_{SF,L} - H_{lower}),0) + max((H_{SF,H} - H_{upper}),0), & H_{SF,min} < H_{lower} \mid\mid H_{SF,max} > H_{upper} \\ 0, & H_{SF,max} \geq H_{lower} \ \&\& \ H_{SF,max} \leq H_{upper} \end{cases} \quad (21)$$

$$S_8 = \left|t_{landing,LSP} - t_2\right| + \left|t_{landing,RSP} - t_5\right| \quad (22)$$

$$S_9 = max(max(\left|\theta_{hf/af}\right|)) - \theta_{hf/af,max}, 0) \quad (23)$$

$$S_{10} = max(H_{Base/Ground} - H_{Base/Ground,min}, 0) \quad (24)$$

$$S_{11} = max(\left|\bar{\theta}_x\right| - \theta_{x,allow}, 0) \quad (25)$$

$$S_{12} = max(\left|\bar{\theta}_y\right| - \theta_{y,allow}, 0) \quad (26)$$

$$S_{13} = max(max(|\theta_z|) - \theta_{z,allow}, 0) \quad (27)$$

$$score = w_o f + w_p S \quad (28)$$

$$X = [A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3, D_{1,a}, D_{2,a}, D_{3,a}, D_{1,b}, D_{2,b}, D_{3,b}, ch, ck, chl] \quad (29)$$

5. Simulation and Experimental Results

Two cases 1) $\alpha = 45^\circ$ and 2) $\alpha = 90^\circ$ are conducted. The score of these cases are 92.0090 and 100.5142 respectively. The performance based on objective functions and constraints is shown in Table 1. Searched walking gaits are shown in Fig. 3-4 while snapshots are shown in Fig. 5-6.

Table 1. Results of Optimization.

1:	$f = [0.0286ms^{-1}; 0.1057ms^{-1}]$; $S = [1.5208m; 0.4552m; 0ms^{-1}; 0ms^{-1}; 0.0003m; 0m; 0.0053s; 0^\circ; 0m; 0m; 0^\circ; 0.1576^\circ; 0^\circ]$;
2:	$f = [0.0295ms^{-1}; 0.1077ms^{-1}]$ $S = [1.626m; 0.3464m; 0ms^{-1}; 0ms^{-1}; 0.0001m; 0.0014m; 0.0061s; 0^\circ; 0m; 0m; 0^\circ; 0.0306^\circ; 0^\circ]$;

Table 2. Searched Results of Target Vectors.

1:	$A_1 = 0.2461$; $A_2 = -0.0002$; $A_3 = 0.0052$; $B_1 = 0.2775$; $B_2 = -0.0029$; $B_3 = 0.0051$; $C_1 = 0.1767$; $C_2 = 0.0135$; $C_3 = 0.0040$; $D_{1,a} = 0.2066$; $D_{2,a} = 0.0106$; $D_{3,a} = 0.0083$; $D_{1,b} = 0.1724$; $D_{2,b} = 0.0115$; $D_{3,b} = 0.0064$; $ch = 0.5463$; $ck = 0.2746$; $chl = 0.1048$;
2:	$A_1 = 0.2121$; $A_2 = 0.0100$; $A_3 = 0.0064$; $B_1 = 0.3267$; $B_2 = 0.0067$; $B_3 = 0.0029$; $C_1 = 0.1962$; $C_2 = 0.0164$; $C_3 = 0.0003$; $D_{1,a} = 0.3051$; $D_{2,a} = 0.0231$; $D_{3,a} = 0.0031$; $D_{1,b} = 0.2706$; $D_{2,b} = 0.0151$; $D_{3,b} = 0.0046$; $ch = 0.4293$; $ck = 0.3310$; $chl = 0.0831$;

6. Conclusions

An improved ZMP-based CPG model considering pitch and roll inclination is proposed and is optimized by SaDE. According to experimental results, test bed with CPG model considering pitch and roll inclination can walk on an inclined plane in case 1 ($\alpha = 45^\circ$) and 2 ($\alpha = 90^\circ$).

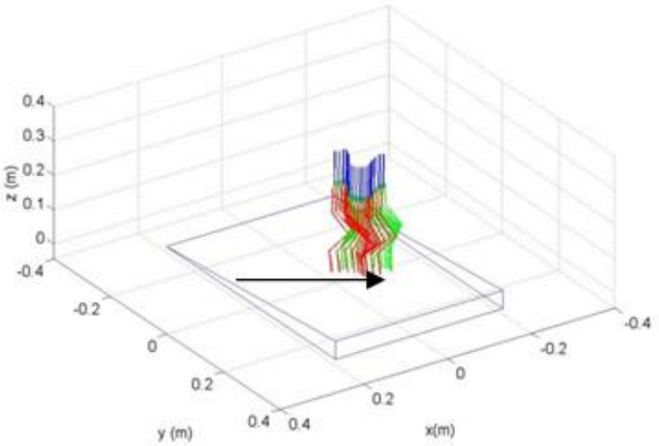

Fig. 3. Walking gait (Case 1).

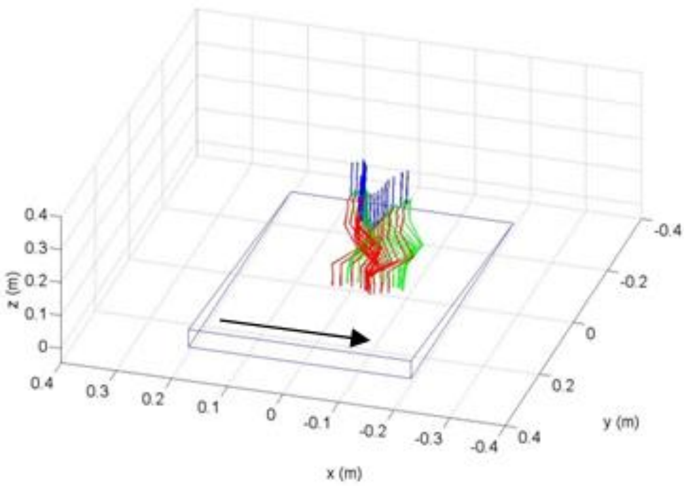

Fig. 4. Walking gait (Case 2).

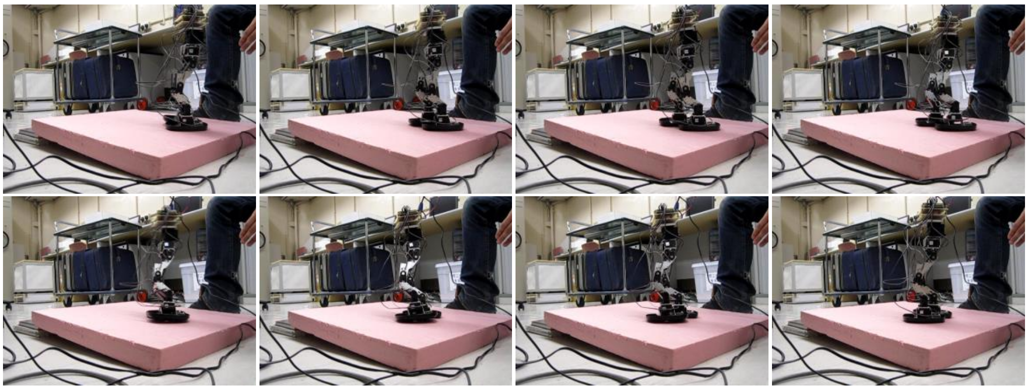

Fig. 5. Snapshots of Walking gait (Case 1).

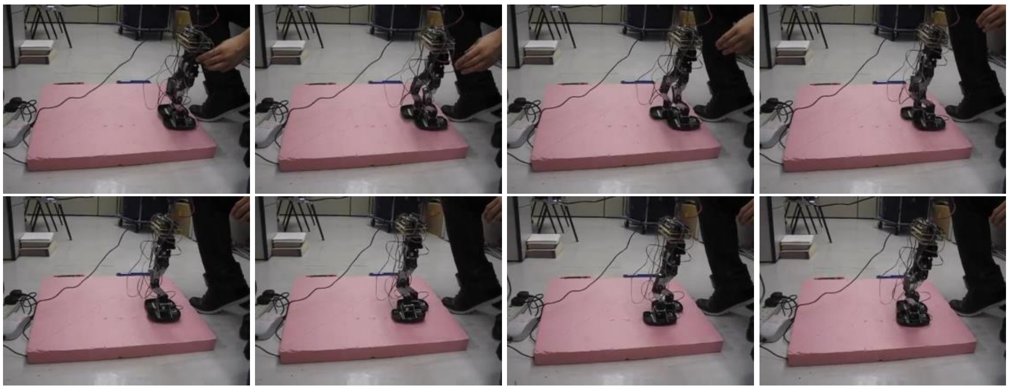

Fig. 6. Snapshots of Walking gait (Case 2).

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References

Aoi S., Tsuchiya K. (2007). Adaptive Behavior in Turning of an Oscillator-driven Biped Robot. *Autonomous Robots*, *23(1)*, 37-57

Ali F., Kawamura A. (2011). Diagonal Walking Strategy on Inclined Floor with Orientation Based Inverse Kinematics for Biped Robot. *International Journal of Mechanical & Mechatronics Engineering*, *11(4)*, 38-44

Chevallereau C., Grizzle J.W., Shih C.L. (2009). Asymptotically Stable Walking of a Five-Link Underactuacted 3D Bipedal Robot. *IEEE Transactions on Robotics*, *25(1)*, 37-50.

Fujimoto Y., Kawamura A. (1998). Simulation of an Autonomous Biped Walking Robot Including Environmental Force Interaction. *IEEE Robotics & Automation Magazine*, *5(2)*, 33-42.

Hong Y.D., Lee B.J., Kim J.H. (2011). Command State-Based Modifiable Walking Pattern Generation on an Inclined Plane in Pitch and Roll Directions for Humanoid Robots. *IEEE/ASME Transactions on Mechatronics*, *16(4)*, 783-789.

Huang Q., Yokoi K., Kajita S., Kaneko K., Arai H., Koyachi N., Tanie K. (2001). Planning Walking Pattern for a Biped Robot. *IEEE Transaction on Robotics and Automation*, *17(3)*, 280-289.

Ijspeert A.J. (2008). Central Pattern Generators for Locomotion Control in Animals and Robots: A Review. *Neural Network*, *21(4)*, 642-653.

Kajita S., Kanehiro F., Kaneko K., Fujiwara K., Yokoi K., Hirukawa H. (2002). A Real Time Pattern Generator for Biped Walking. “In Proceedings of International Conference on Robotics and Automation,” Washington, May 2002, pp. 31-37.

Kim J.Y., Park I.W., Oh J.H. (2007). Walking Control Algorithm of Biped Humanoid Robot on

Uneven and Inclined Floor. *Journal of Intelligent and Robotic Systems*, *48(4)*, 457-484.
Lee B.J., Stonier D., Kim Y.D., Yoo J.K., Kim J.H. (2008). Modifiable Walking Pattern of a Humanoid Robot by Using Allowable ZMP Variation. *IEEE Transactions on Robotics*, *24(4)*, 917-925.
Or J. (2010). A Hybrid CPG-ZMP Control System for Stable Walking of a Simulated Flexible Spine Humanoid Robot. *Neural Networks*, *23(3)*, 452-460.
Plestan F., Grizzle J.W., Westervelt R., Abba G. (2003). Stable Walking of a 7-DOF Biped Robot. *IEEE Transactions on Robotics and Automation*, *19(4)*, 653-668.
Qin A.K., Huang V.L., Suganthan P.N. (2009). Differential Evolution Algorithm with Strategy Adaptation for Global Numerical Optimization. *IEEE Transactions on Evolutionary Computation*, *13(2)*, 398-417.
Seven U., Akbas T., Fidan K.C. (2012). Bipedal Robot Walking Control on Inclined Planes by Fuzzy Reference Trajectory Modification. *Soft Computing*, *16(11)*, 1959-1976.
Storn R., Price K. (1997). Differential Evolution – a Simple and Efficient Heuristic for Global Optimization over Continuous Spaces. *Journal of Global Optimization*, *11,341*-359.
Taga G., Yamaguchi Y., Shimizu H. (1991). Self-organized Control of a Biped Locomotion by Neural Oscillators in Unpredictable Environment. *Biological Cybermetics*, *65*, 147-159
Vundavilli P.R., Pratihar D.K. (2009). Soft Computing-based Gait Planners for a Dynamically Balanced Biped Robot Negotiating Sloping Surfaces. *Applied Sort Computing*, *9(1)*, 191-208
Yang L., Chew C.M., Zielinska T., Poo A.N. (2007). A Uniform Biped Gait Generator with Offline Optimization and Online Adjustable Parameters. *Robotica*, *25(5)*, 549-565
Yu H.F., Fung E.H.K., Jing X.J. (2014). An Improved ZMP-based CPG Model of Bipedal Robot Walking Searched by SaDE. *ISRN Robotics*, *2014*.

Appendix

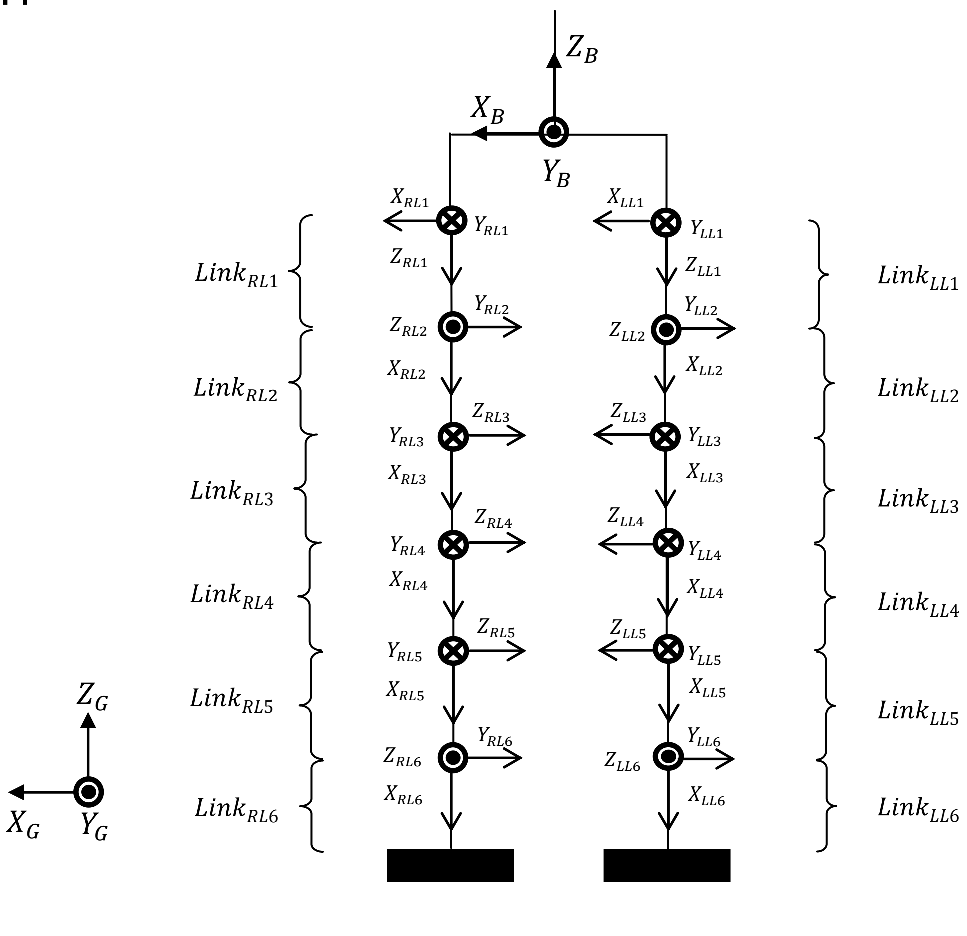

Fig. A Schematic Diagram of Bipedal Robot.

Table A. List of Symbols

$d_{x,y,z}/k_{x,y,z}$	Damping coefficient/ Spring constant in x-,y- and z- direction
H_{lower}, H_{upper}	Lower and upper bound of desired swing height relative to the ground
$H_{RSF/LSF}$	The history of swing height of right/left swing foot
$L_{sagittal/frontal}$	Allowable length of support polygon in sagittal/frontal plane
$L_{desired/actual}$	Desired/actual step length
M_{total}	Total mass of the test bed
N	Number of data
$\vec{P}_{base}/\ddot{\vec{P}}_{base}$	Position/ linear acceleration of center of mass
$\bar{V}_{trunk/swing\ foot,sagittal}$	Average velocity of trunk/swing foot in sagittal plane
w_o/w_p	Weighting of objective functions/constraints
f	$[f_1; f_2]$
S	$[S_1; S_2; S_3; S_4; S_5; S_5; S_6; S_7; S_8; S_9; S_{10}; S_{11}; S_{12}; S_{13}]$
$x, y, z_{foot,i}/\dot{x}, \dot{y}, \dot{z}_{foot,i}$	Position/ Velocity of contact point in x-,y- and z- direction
$x/y_{o,i}$	The first impact position in x-/y- direction when the contact point touches the ground
$z_{ground,i}$	Height of ground
$\ddot{\vec{\theta}}_{base}$	Angular Acceleration of center of mass
$\theta_{rhf/lhf}$	Right/left hip angle in frontal plane
$\theta_{raf/laf}$	Right/left a angle in frontal plane

Table B. Setting of Parameters

$L_{desired}$	0.05m
$[d_x, d_y, d_z]$	[20,20,300]
$[H_{lower}, H_{upper}]$	[0.008,0.012]m
$H_{Base/Ground,min}$	0.23m
$[k_x, k_y, k_z]$	[25000,25000,400000]
M_{total}	1.0300kg
w_o	[500,100]
w_p	[20,40,500,500,10000,12500,1500,50,10,1200,45,45,45]
$[t_0, t_2, t_5, t_6]$	[0,0.7,1.7,2]s
$\theta_{hl,max}$	23°
θ_{slope}	5°