Dynamically Stable Walking and Kicking Gait Planning for Humanoid Soccer Robots

Changjiu Zhou, Pik Kong Yue, and Jun Ni

School of Electrical and Electronic Engineering,
Singapore Polytechnic, 500 Dover Road, Singapore 139651
`{zhoucj, yue, JunNi}@sp.edu.sg`
`http://www.robo-erectus.org`

Abstract. Humanoid dynamic walk and kick are two main technical challenges for the current Humanoid League. In this paper, we conduct a research aiming at generating dynamically stable walking and kicking gait for humanoid soccer robots with consideration of different constraints. Two methods are presented. One is synthesizing gait based on constraint equations, which has formulated gait synthesis as an optimization problem with consideration of some constraints, e.g. zero-moment point (ZMP) constraints for dynamically stable locomotion, internal forces constraints for smooth transition, geometric constraints for walking on an uneven floor and etc. The other is generating feasible gait based on human kicking motion capture data (HKMCD), which uses periodic joint motion corrections at selected joints to approximately match the desired ZMP trajectory. The effectiveness of the proposed dynamically stable gait planning approach for humanoid walking on a sloping surface and humanoid kicking on an even floor has been successfully tested on our newly developed Robo-Erectus humanoid soccer robots, which won second place in the RoboCup 2002 Humanoid Walk competition and got first place in the RoboCup 2003 Humanoid Free Performance competition.

1 Introduction

Humanoid soccer robot league is a new international initiative to foster robotics and AI technologies using soccer games [7]. The Humanoid league (HL) has different challenges from other leagues. The main distinction is that the dynamic stability of the robots needs to be well maintained while the robots are walking, running, kicking and performing other tasks. Furthermore, the humanoid soccer robot will have to coordinate perceptions and biped locomotion, and be robust enough to deal with challenges from other players. Hence, how to generate a dynamically stable gait for the humanoid soccer robots is an important research area for the HL, especially for the new technical challenge – Balancing Challenge which will be commencing in the coming RoboCup 2004.

The problem of gait planning for humanoid robots is fundamentally different from path planning for traditional fixed-base manipulator arms due to the inherent characteristics of legged locomotion – unilaterality and underactuation [3,11,12]. The humanoid locomotion gait planning methods can be classified into two main

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categories [5]: one is online simplified model-based gait generation method; and the other is offline position based gait generation method. There are currently some ways for generating dynamically stable gaits, e.g., heuristic search approach, such as genetic algorithms (GAs) based gait synthesis [1]; problem optimisation method, such as optimal gradient method; model simplification with iteration [5], etc.

To have continuous and repeatable gait, the postures at the beginning and the end of each step have to be identical. This requires the selection of specific initial conditions, constraint functions and their associated gait parameters. However, finding repeatable gait when the constraint equations involve higher order differential equations remains an unsolvable problem. So, a natural way to solve this problem is to resort to numerical methods, e.g. Fourier series expansion and time polynomial functions. One advantage of this technique is that extra constraints can be easily included by adding the coefficients to the polynomials. Disadvantages, however, include the facts that the computing load is high for large bipedal systems and the selection of the polynomials may impose undesirable features to the joint profiles, e.g. oscillation. Moreover, the planning gait may not be human-like. To accomplish a human-like motion, it is quite natural to attempt using the Human Kicking Motion Captured Data (HKMCD) to drive the robot. However, some researches show that the HKMCD cannot be applied directly to humanoid robot due to kinematic and dynamic inconsistencies between the human subject and the humanoid, which usually require kinematic corrections while calculating the joint angle trajectory [2].

The rest of this paper is organized as follows. We will briefly present some basic constraints for the dynamically stable gait in Section 2. The humanoid soccer robot to be used for the experiment is introduced in Section 3. Most of the research on humanoids has been actively working to make a robot capable of dynamic walking on even floor. However, for the new technical challenges of humanoid league the robot is required to walk on uneven terrain such as sloping surfaces and stairs. So, we plan a dynamically stable gait for ascending a sloping surface in Section 4. In Section 5, we describe how to make use of human kicking motion capture data to drive the humanoid to perform penalty kick. Concluding remarks and some major technical challenges in this field are addressed in Section 5.

2 Robo-Erectus: A Fully-Autonomous Humanoid Soccer Robot

The Robo-Erectus (RE) project (www.robo-erectus.org) aims to develop a low-cost fully-autonomous humanoid platform so that educators and students are able to build humanoid robots quickly and cheaply, and to control the robots easily [16]. We have developed three generations humanoid soccer robots, namely RE40I, RE40II and RE40II (see Fig. 1). Our RE humanoid has participated in both the 1st and 2nd Humanoid League of RoboCup, won 2nd place in the Humanoid Walk competition at the RoboCup 2002 and got 1st place in the Humanoid Free Performance competition at the RoboCup 2003. The configuration of the hierarchical control system for the RE humanoid is shown in Fig. 2. We've also implemented reinforcement learning (see Fig. 3) to further improve the walking and kicking gait [14,15].

Fig. 1. RE40I at RoboCup 2002 (left), RE40II at the RoboCup 2003 (centre), and the newly developed RE40III (right)

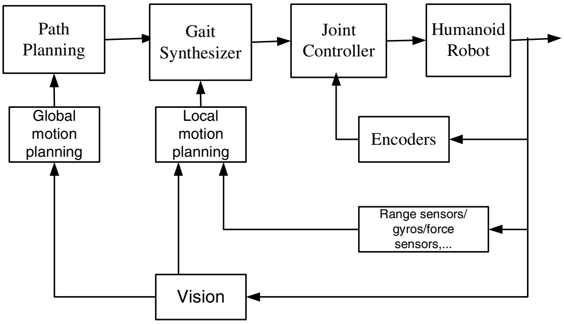

Fig. 2. Schematic diagram of the hierarchical control system for the RE humanoid robot

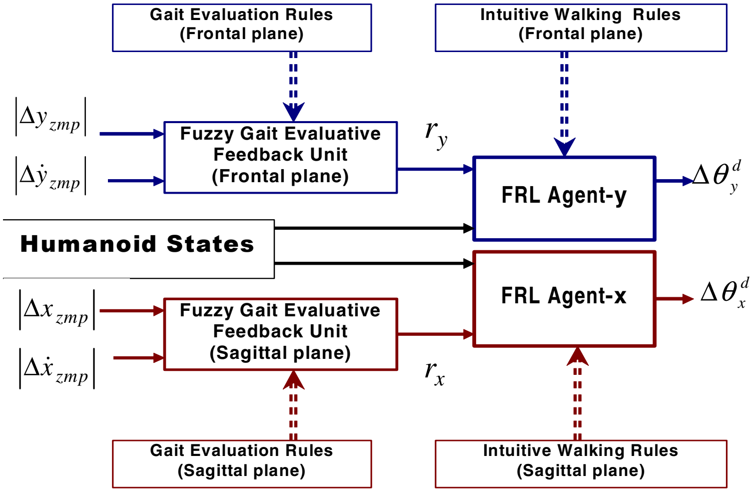

Fig. 3. Block diagram of the humanoid gait learning using two independent fuzzy reinforcement learning agents [15]

3 Dynamically Stable Gait

Since a humanoid robot tips over easily, it is important to consider stability in planning its gait. Many methods have been proposed for synthesizing walking patterns based on the concept of the zero moment point (ZMP) [11, 12]. The ZMP is defined as the point on the ground about which the sum of the moments of all the active forces equals zero. If the ZMP is within the convex hull (support polygon) of all contact points between the feet and the ground, the bipedal robot can walk dynamically.

Humanoid dynamics can be modelled using a multi-body system model consisting N chains involving the body parts, such as head, arms, trunk and pelvis. Each chain consists of n_i links (i = 1, 2, …, N) interconnected with single DOF joints. The support-foot can only be controlled indirectly by ensuring the appropriate dynamics of the mechanism above the foot.

The humanoid robot is a highly redundant system with many extra degrees of freedom (DOF). Its gait consists of large number of unknown parameters. This allows us to formulate constraint equations for synthesizing gait. In this paper we formulate an optimization problem to determine the unknown parameters of the gait to achieve dynamic locomotion, i.e. to obtain a good match between the actual and the desired ZMP trajectories as follows

$$Minimize \quad \int_{t_i}^{t_f} \left\| P_{zmp}(t) - P_{zmp}^{d}(t) \right\|^2 dt \tag{1}$$

subject to the boundary conditions of both $p(t)$ and $\dot{p}(t)$ at time t_i and t_f, where P_{zmp} is the actual ZMP, and P_{zmp}^{d} is the desired ZMP position.

Due to the large number of the unknown parameters for the above optimization problem, we need to specify some constraints [2,4,8]. The following are some constraints that need to be considered.

Sabilization of the gait (ZMP constraint): The control objective of the humanoid dynamically stable gait can be described as

$$P_{zmp} = \left(x_{zmp}, y_{zmp}, 0\right) \in S \tag{2}$$

where ($x_{zmp}, y_{zmp}, 0$) is the coordinate of the ZMP with respect to O-XYZ. S is the support polygon.

Smooth transition constraint: The equation of motion of the centre of the humanoid can be described as

$$m_{cm} a_{cm} = f_L + f_R + m_{cm} g \tag{3}$$

Where m_{cm} and a_{cm} are the mass of the robot and the acceleration of the COM, respectively. f_R and f_L represent the ground reaction forces at the right and left foot. During single-support phase, the foot force can be obtained from (3) as one of f_R and

f_L will be zero. However, during double-support phase, only the total of the ground reaction forces is known. Hence, how to resolve the leg reaction forces appropriately to minimize the internal force has to be considered. This can ensure a smooth transition of the internal forces during placement and take-off [2].

Geometrical constraints: The swing limb has to be lifted off the ground at the beginning of the step cycle and has to be landed back at the end of it.

Maximum clearance of the swing limb: During swing phase, the foot of the swing limb has to stay clear off the ground to avoid accidental contact.

Repeatability of the gait: The requirement for the repeatable gait demands that the initial posture and velocities be identical to those at the end of the step.

Continuity of the gait: The horizontal displacements of the hip during the single and double support phases must be continuous.

Minimization of the effect of impact: During locomotion, when the swing limb contacts the ground (heel strike), impact occurs, which contacts sudden changes in the joint angular velocities. By keeping the velocity of the foot of the swing limb zero before impact, the sudden jump in the joint angular velocities can be eliminated.

4 Dynamic Walking Gait for Ascending Sloping Surfaces

For RE humanoid, we have developed a gait planner which is able to generate gait for the robot walking on both plat and uneven terrain, such as stairs and sloping surfaces. Note that, one of the major problems in controlling humanoids is the difficulty in choosing proper gait for a particular terrain.

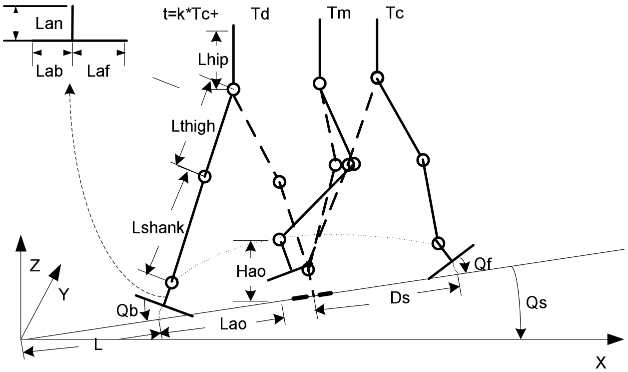

Fig. 4. The humanoid and gait parameters and coordinate on the slope

In this paper, we only consider how to generate a dynamically stable gait for humanoid ascending sloping surfaces, which will be a new technical challenge for

Humanoid League from 2004. To simply our analysis, we assume that the *k*th step begins with the heel of the right foot leaving the slop at t= k*T_c, and ends with the heel of the right foot making the first contact with the slope at t= (k+1)*T_c, as shown in Fig. 4.

We prescribe some joint trajectories, e.g. both foot trajectories, and then derive all joint trajectories by inverse kinematics with consideration of the constraints discussed in Section 3. These constraints can ensure that the gait is dynamically stable and also satisfies some geometric and periodical requirements. We also need some more constraints for the sloping surface. Eqs (4) to (7) show some constraints on ankle and hip joints.

$$x_a(t)=\begin{cases} L*\cos Q_s+k*D_s*\cos Q_s+L_{an}*\sin Q_s, & t=k*T_c \\ L*\cos Q_s+k*D_s*\cos Q_s+L_{an}*\sin(Q_s-Q_b)+L_{af}*(\cos Q_s-\cos(Q_s-Q_b)), & t=k*T_c+T_d \\ L*\cos Q_s+k*D_s*\cos Q_s+L_{ao}*\cos Q_s, & t=k*T_c+T_m \\ L*\cos Q_s+(k+2)*D_s*\cos Q_s-L_{an}*\sin(Q_s+Q_f)-L_{ab}*(\cos Q_s-\cos(Q_s-Q_b)), & t=(k+1)*T_c \\ L*\cos Q_s+(k+2)*D_s*\cos Q_s-L_{an}*\sin Q_s, & t=(k+1)*T_c+T_d \end{cases} \tag{4}$$

$$z_a(t)=\begin{cases} L_{an}*\cos Q_s-L_{af}*\sin Q_s+(L_{an}*\sin Q_s+L_{af}*\cos Q_s)*tgQ_s+x_a(t)*tgQ_s, & t=k*T_c \\ L_{an}*\cos(Q_s-Q_b)-L_{af}*\sin(Q_s-Q_b)+(L_{an}*\sin(Q_s-Q_b)+L_{af}*\cos(Q_s-Q_b))*tgQ_s+x_a(t)*tgQ_s, & t=k*T_c+T_d \\ H_{ao}+x_a(t)*tgQ_s, & t=k*T_c+T_m \\ L_{an}*\cos(Q_s+Q_f)+L_{ab}*\sin(Q_s+Q_f)+(L_{an}*\sin(Q_s+Q_f)-L_{ab}*\cos(Q_s+Q_f))*tgQ_s+x_a(t)*tgQ_s, & t=(k+1)*T_c \\ L_{an}*\cos Q_s+L_{ab}*\sin Q_s+(L_{an}*\sin Q_s-L_{ab}*\cos Q_s)*tgQ_s+x_a(t)*tgQ_s, & t=(k+1)*T_c+T_d \end{cases} \tag{5}$$

$$x_h(t)=\begin{cases} L*\cos Q_s+k*D_s*\cos Q_s+x_{ed}, & t=k*T_c \\ L*\cos Q_s+(k+1)*D_s*\cos Q_s-x_{sd}, & t=k*T_c+T_d \\ L*\cos Q_s+(k+1)*D_s*\cos Q_s+x_{ed}, & t=(k+1)*T_c \end{cases} \tag{6}$$

$$z_h(t)=\begin{cases} H_{\min}+x_h(t)*tgQ_s, & t=k*T_c+0.5*T_d \\ H_{\max}+x_h(t)*tgQ_s, & t=k*T_c+0.5*(T_c-T_d) \\ H_{\min}+x_h(t)*tgQ_s, & t=(k+1)*T_c+0.5*T_d \end{cases} \tag{7}$$

From the above via points and the constraints, the walking gait on sloping surface can be generated using the spline interpolation. The gait is dynamically stable as the ZMP constraints (2) is applied.

Based on the planned gait for ascending the sloping surface, we have conducted both simulation and experimental studies.

Fig. 5(a) shows the horizontal displacements of the hip and both right and left ankle joints. It can be seen that the trajectories are smooth, i.e. the velocities are continuous for both single and double support phases. The horizontal displacement of the ZMP for different slope angles is shown in Fig. 5(b). One can see that the ZMP remains approximately at the centre of the stability region for the smaller slope angles, which ensures the largest stability margin and greatest stability. However, for bigger slope angle, e.g. 15 degrees, the dynamic stability cannot be guaranteed. In Figs. 5 (a) and (b), the angular velocities for both right ankle and right knee joints are given. It shown that the sudden changes in the angular velocities due to landing impact are reduced when the slope angle is smaller, e.g. less than 10 degrees. However, the landing impact is very obvious for the bigger slope angle.

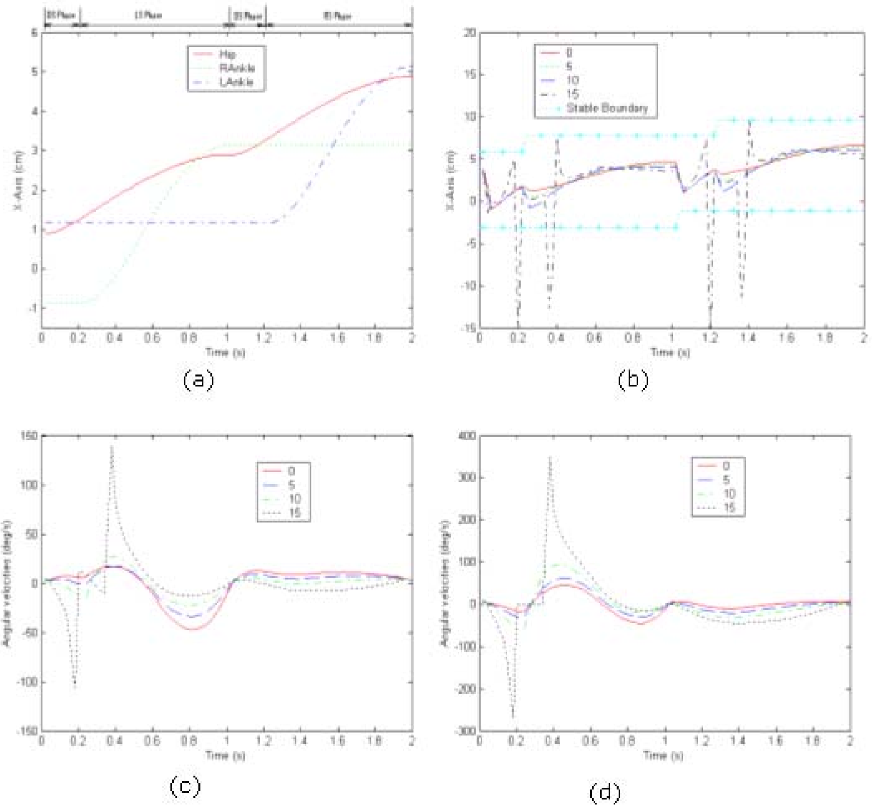

Fig. 5. (a) Movements of the hip and ankle joints: (b) Comparison of the ZMP trajectories for different slope angles ($Q_s = 0^o, 5^o, 10^o, 15^o$); (c) Right ankle joint angular velocities for different slope angles; (4) Right knee joint angular velocities for different slope angles

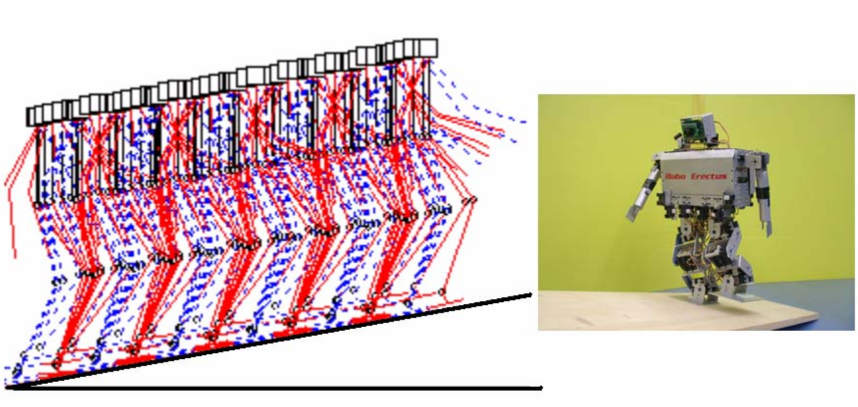

Fig. 6. RE40II ascending a sloping surface during the experiment

Fig. 6 shows the stick diagram of humanoid walking on the sloping surface.

By considering the humanoid performance constraints, a fuzzy reinforcement learning agent [14,15,16] has been used to further improve the gait. Fig. 7 shows humanoid walking sequence on flat platform (after learning). The turning sequence after learning is shown in Fig. 8. We are currently working on further improving the gait for ascending slope using reinforcement learning.

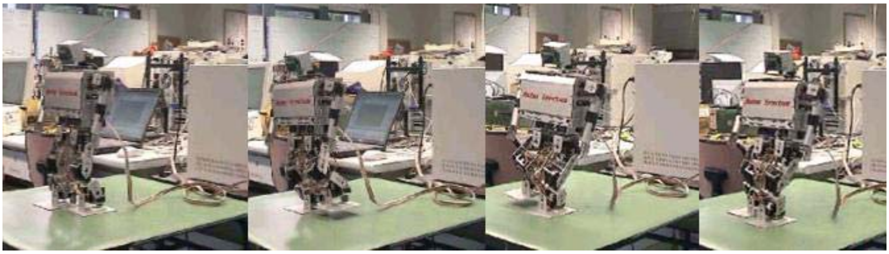

Fig. 7. The humanoid walking sequence (after learning)

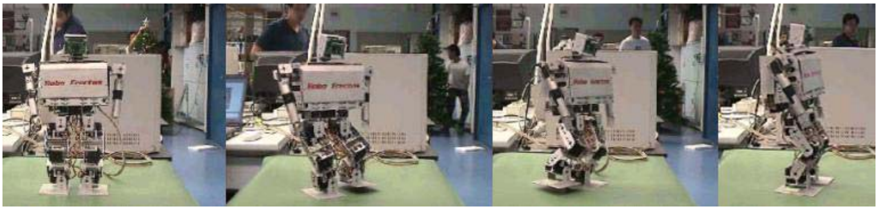

Fig. 8. The Humanoid turning sequence (after learning)

5 Planning Dynamic Kicking Pattern Based on Human Kicking Motion Captured Data

To plan humanoid kicking trajectory, we have to consider some kicking constraints [16], e.g. the Maximum Kicking Range (MaxKR), the Effective Kicking Range (EKR), the Minimum Kicking Moment (MinKM) and so on. The challenge for the humanoid dynamic kick is that the ZMP must stay in the support polygon, which is the stance foot, during the kicking phase. In our previous research [16], by considering all the kicking parameters, an initial kicking pattern was generated using Kicking Pattern Generator developed by our Humanoid Robotics Group. However, the kick is clearly not a human-like one.

In this paper, we propose a new method to generate dynamically stable kicking pattern for humanoid soccer robot. To accomplish a human-like kick, it is quite natural to attempt using the Human Kicking Motion Captured Data (HKMCD) to drive the robot. However, by using human kicking data to prescribe the motion of the lower limbs, two immediate problems arise when using HKMCD directly. Firstly, a complex dynamic model is required. Secondly, the designer has no freedom to synthesize the joint profiles based on tangible gait characteristics such as walking speed, step length and step elevation. Please also note that there are kinematic and dynamic inconsistencies between the human subject and the humanoid, which usually require kinematic corrections while calculating the joint angle trajectory [2].

The adaptation of the HMKCD for the humanoid soccer robot uses mainly periodic joint motion corrections at selected joints to approximately match the desired ZMP trajectory. By optimisation with constraints, we can maximize the dynamic stability against sliding during kicking.

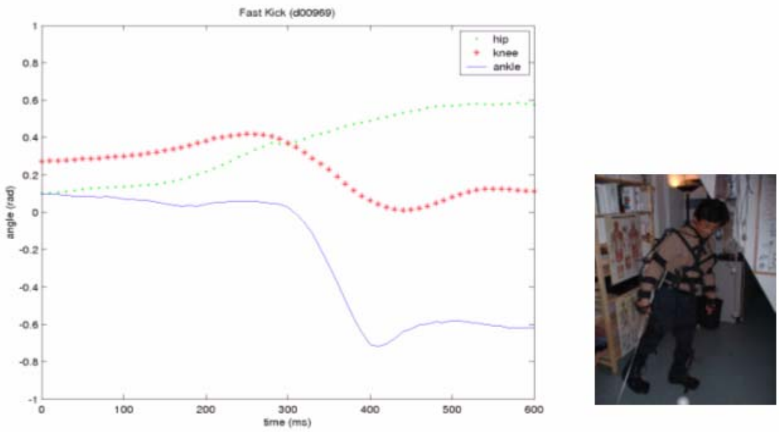

Fig. 9. Human kicking motion captured data (the experiment was conducted in Prof. Stefan Schaal's Computational Learning and Motor Control (CLMC) Lab at University of Southern California; and the data was captured by his PhD students Michael Mistry and Peyman Mohajerian)

The HMKCD was collected in the Computational Learning and Motor Control (CLMC) Lab at University of Southern California. The Sarcos SenSuit simultaneously measures 35 degrees of freedom (DOF) of the human body. It can be used for real-time capturing of full body motion, as an advanced human-computer interface, or to control sophisticated robotic equipment. The complete SenSuit is worn like an exoskeleton which, for most movements, does not restrict the motion while an array of lightweight Hall-sensors reliably records the relative positions of all limbs. For the arms, we collect shoulder, elbow and wrist DOF, for the legs, hip, knee and ankle data is recorded. In addition, the Sensuit measures head as well as waist motion. The experiment setup and result is shown in Fig. 9. At left, it is joint trajectories for the kicking leg recorded from a fast kick demonstration. At right, it is the human kicker who wore the Sarcos Sensuit.

By using optimization with ZMP constraints, we obtained the corrected joint trajectories which are shown in Fig. 10. The ZMP trajectories during humanoid kick are given in Fig. 11. It can be seen that by using the original HKMCD (left), the ZMP is out of the support polygon during the ending phase of the kick. From the ZMP constraints (2), it is clear that the original HKMCD cannot drive the robot to perform a stable kick. However, after correcting the HKMCD with ZMP constraints, the corrected ZMP trajectory is always inside the support polygon so that the dynamically stable kicking gait can be obtained. We have also conducted an experiment of humanoid kick using the corrected HKMCD. The kicking sequence is shown in Fig. 11. The striker's kicking posture is more or less "human-like".

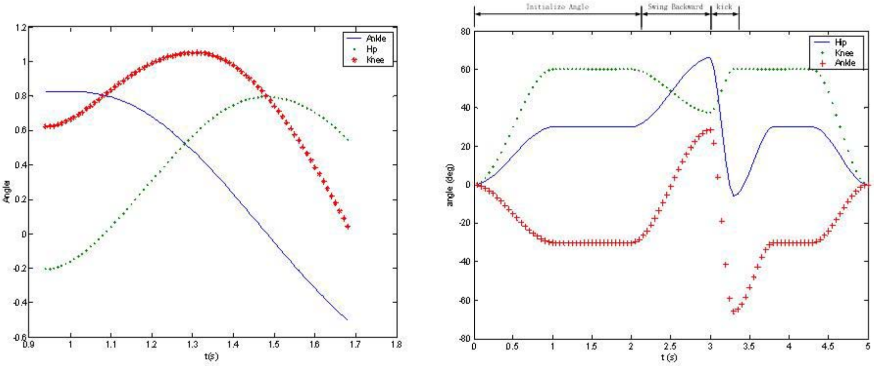

Fig. 10. Corrected joint trajectories for humanoid kick (At left, it is the joint trajectories for kicking phase. At right, it is the joint trajectories for a complete kicking cycle)

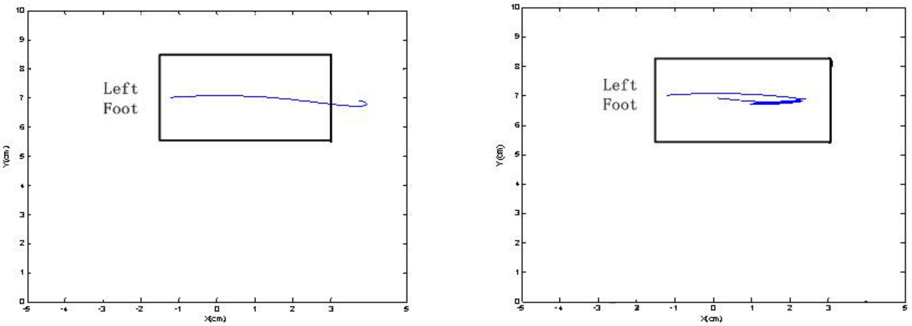

Fig. 11. Original and corrected ZMP trajectories (At left, the original ZMP trajectory is not always within the support polygon. At right, the corrected ZMP trajectory is always inside the support polygon so that the dynamic kicking gait is obtained)

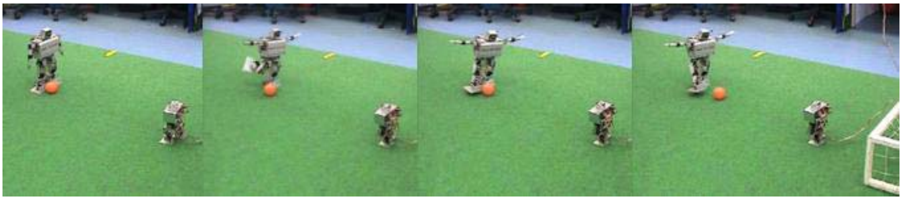

Fig. 12. The humanoid kicking sequence (using the corrected human kicking motion capture data)

6 Concluding Remarks

Humanoid dynamic walk and kick are two main technical challenges for the current Humanoid League. In this paper, we conduct a research that aims at generating dynamically stable walking and kicking gait for humanoid soccer robots with consideration of different constraints using two methods. One is synthesizing gait based on constraint equations. The other is generating feasible gait based on human kicking motion capture data (HKMCD), which uses periodic joint motion corrections at selected joints to approximately match the desired ZMP trajectory. The effectiveness of the proposed dynamically stable gait planning approach for humanoid walking on a sloping surface and humanoid kicking on an even floor has been successfully tested on our newly developed Robo-Erectus humanoid soccer robots.

The Robo-Erectus project aims to develop a low-cost humanoid platform so that educators and students are able to build humanoid robots quickly and cheaply, and to control the robots easily. We are currently working to further develop this platform for educational robots, service robots and entertainment robots.

By using the proposed fuzzy reinforcement learning approach, we also demonstrate that the robot is able to start walking from an initial gait generated from perception-based information on human walking, and learn to further tune its walking and kicking behavior using reinforcement learning. Note that humans do not just learn a task by trial and error, rather they observe other people perform a similar task and then emulate them by *perceptions*. How to utilize perception-based information to assist imitation learning [9] will be a new challenge in this filed. We will also look at how to make use of human motion capture data to drive humanoid soccer robots to perform more soccer-playing tasks, e.g. passing, throwing, catching and so on.

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