Fuzzy Omnidirectional Walking Controller for the Humanoid Soccer Robot

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***Abstract*—Fast and flexible walking is necessary for humanoid robots in the Robocup soccer competition. We propose a new fuzzy-logic control scheme that would enable the robot to realize flexible walking with high standard of stability by restricting the step length and inclining the body of robot to an appropriate extent. The step controller generates the restriction of the following step length according to the fuzzy rules. While the fuzzy-logic body control scheme uses the desired walking direction and rotating angle as an input. The biped walking robot can walk to any direction quickly and efficiently without falling down according to the obtained body inclining angle. We demonstrate the effectiveness of the algorithm by successful combined walking tasks in a faithful simulation of a full-body humanoid robot. The proposed control scheme helped us to win the champion of Robocup 2009.**

***Index Terms*—Biped walking,Robocup,ZMP,Fuzzy.**

I. Introduction

In recent years, biped locomotion has become an heated research topic among researchers all over the world and many biped walking methods has been proposed [1]-[7]. However, most of the them were not suitable for a soccer robot. Because they concentrated on the typical periodic and stable biped walking and could not meet the demand in a soccer match, in which a robot need faster and more flexible locomotion. Kemalettin used natural zero moment point(ZMP) [8] references to generate the movement of center of mass(COM) [9]. The biped walking using this method seemed more natural. Takeshi carried out a control method [10] which could realize robot's emergent stop. It used a 3-D ZMP modification map as the criteria. But the variation of walking direction was still not considered. Yuan and Yingzi proposed a layered controller for biped locomotion which presented a fast and stable omnidirectional walking [11]. But the small steps looked unnatural and it was time-consuming for the robot to walk a curve to reach the target. In this paper, a novel control method is presented which realizes stable and flexible biped walking. With the body inclination action the robot can walk to planned target and pass the flags efficiently.

The Robot World Cup (RoboCup) [12] is a worldwide organization whose ultimate long-term goal is "to beat the human soccer champion by the year 2050". Robocup has several robot soccer leagues and the 3D simulation league is one of them. In the 3D simulation soccer match, teams made up of several virtual robots compete with each other. The league is a good platform for researchers who are interested in multi-agent systems and biped locomotion. In 2007 the Soccerbot model was introduced to the competition which has 20 degrees of freedom and can behave like a human. Since the following year in Suzhou, a new humanoid model NAO [13] (see Fig.1) has replaced it. Researchers of the 3D simulation league have focused their attention on the study of biped walking from then on.

In this paper, a novel biped walking controller which uses the fuzzy-logic is proposed. The controller is made up of 6 parts which are walking path planner, fuzzy step generator, gait primitive generator, fuzzy body inclination generator, limb controller and joint motor controller. The fuzzy step generator ensures that ZMP is always within the stable region when the robot changes its walking speed. It uses fuzzy-logic to restrict the next step length. If the robot needs to rotate or change walking direction, the fuzzy body inclination generator will generate proper inclination angle to compensate the centrifugal force. The soccer robot using the proposed control method can realize fast and flexible biped walking, which is especially important in a football match.

Fig. 1. The robot model NAO used in Robocup 2009

The concept of ZMP is introduced in the following section.

In section III, we describe the fuzzy omnidirectional controller and the three major parts which are fuzzy step generator, fuzzy body inclination generator and gait primitive generator are detailed. Section IV shows the result of three separate experiments, followed by conclusion and future work in Section V.

II. ZMP Equation

ZMP was first introduced by Vukobratovic and is used to evaluate the stability for biped walking. The stable region of biped walking is the convex hull of the contact points between the feet and ground. If the ZMP is inside the stable region, the robot will not fall. Considering the convenience of calculation, we divide the equation into x direction and y direction:

$$X_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{Z}_i + g_z)X_i - \sum_{i=1}^{n} m_i(\ddot{X}_i + g_x)Z_i}{\sum_{i=1}^{n} m_i(\ddot{Z}_i + g_z)} \quad (1)$$

$$Y_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{Z}_i + g_z)Y_i - \sum_{i=1}^{n} m_i(\ddot{Y}_i + g_y)Z_i}{\sum_{i=1}^{n} m_i(\ddot{Z}_i + g_z)} \quad (2)$$

Equations (1) and (2) are the formula of ZMP. In which m_i is the mass of link i,(X_{zmp},Y_{zmp},0) is the position of ZMP, and (X_i,Y_i,Z_i) is the coordinate of the mass center of link i on an absolute Cartesian coordinate system. g is the gravity.

According to equations (1) and (2)the x-component of the ZMP (X_{zmp}) is independent of the motion along the y-axis. Similarly the y-component of the ZMP (Y_{zmp}) is independent of the motion along the x-axis.

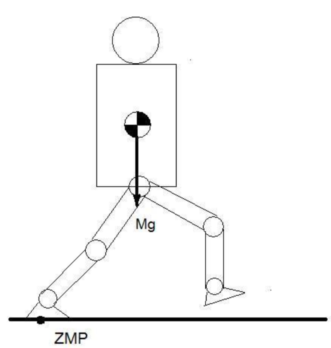

Fig. 2. The single-particle model used for the simplicity of analysis

For the simplicity of analysis, we use the single-particle model as shown in Fig.2. In this model, it is supposed that the total mass of the robot is converged to the COM. And only the z-component of the gravity is considered. Then the equations(1) and (2) can be rewritten in the following simplified form:

$$X_{zmp} = X - \frac{Z\ddot{X}}{\ddot{Z} + g_z} \quad (3)$$

$$Y_{zmp} = Y - \frac{Z\ddot{Y}}{\ddot{Z} + g_z} \quad (4)$$

Where (X_{zmp},Y_{zmp},0) is the position of ZMP, and (X,Y,Z) is the coordinate of COM on an absolute Cartesian coordinate system. g is the gravity.

III. Fuzzy logic controller for omnidirectional walking

The soccer robot needs fast and stable locomotion in the match. The structure of the walking controller is shown in Fig.3. At first, the desired position and direction are decided by robot's next action according to the situation in the field. Then the Walk Path Planner calculates the desired movement and rotation of the robot, using the information of the robot's current position and direction. The desired movement is revised by the Fuzzy Step Generator to ensure the stability of the robot. After that, the revised movement and the desired rotation are used by the Fuzzy Body Inclination Generator to generate the body inclination. The revised movement will also be sent to the Gait Primitive Generator and then the gait primitive is generated. Having the body inclination and gait primitive, the Limb Controller calculates the desired joint angles using the inverse kinematic method. At last, the joint velocities are generated. Next, the three most important part of the controller, Fuzzy Step Generator, Fuzzy Body Inclination Generator and the Gait Primitive Generator will be detailed.

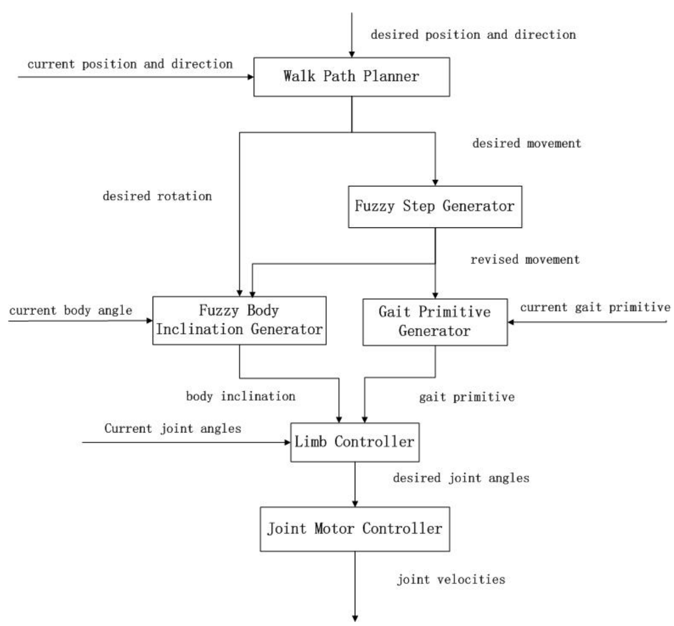

Fig. 3. The architecture of fuzzy omnidirectional controller for the NAO robot

A. Fuzzy Step Generator

During the fierce soccer match, the soccer robot accelerates and decelerates a lot to control the ball. Cooperation with teammates also needs the robot to change its walking speed frequently. The methods which use pre-designed ZMP trajectory to generate the movement of COM is useless in this situation, because there is no pre-designed ZMP trajectory in the match. Thus a novel controller is presented here which dose not need the pre-designed ZMP trajectory. The controller also meets the demand of frequent variation of walking speed. In this control method, the cycle of each step is constant and the way to accelerate and decelerate is changing the step length. The desired movement is generated by the Walk Path Planner and the Fuzzy Step Generator will revise the step length to make sure the ZMP always stays in the stable area. The step length is calculated before the next step is executed and it should not be changed when the step is executed.

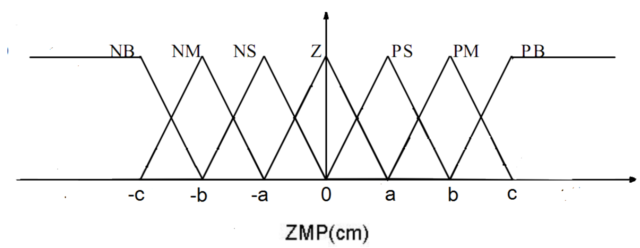

Fig. 4. Fuzzy membership functions for ZMP

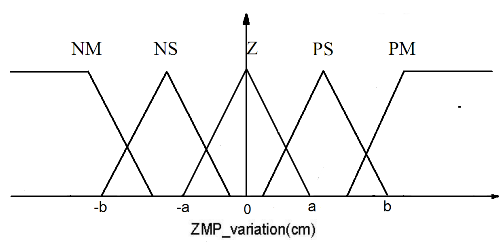

Fig. 5. Fuzzy membership functions for the variation of ZMP

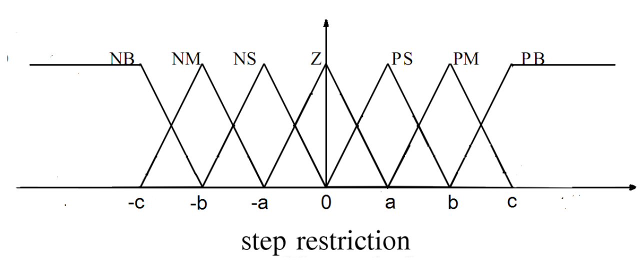

Fig. 6. Fuzzy membership functions for the restriction of step length variation

For the cycle of each step is constant, the step length represents the speed of the robot's locomotion. As shown in the ZMP equation, the location of ZMP moves when the robot changes its walking speed. For example, the ZMP will move forward when the robot decreases its step length and will move backward when the step length is increased. Without reasonable restriction of the variation, the ZMP will probably move outside the stable area, which causes the robot to fall down. In the pre-defined ZMP methods, researchers used ZMP trajectory to plan the movement of COM, and realized robot's stable walking. But the robot could only follow the pre-defined ZMP trajectory, which made it impossible for them to change their walk speeding as well as walking direction. What's more, the planning of the COM movement according to the ZMP trajectory took plenty of calculation, which was not suitable in the fierce soccer match. To ensure that the ZMP is always within the stable area, the Fuzzy Step Generator restricts the variation of the step length and controls the acceleration of the robot at the same time.

TABLE I
THE RULE BASE TO GENERATE THE RESTRICTION OF STEP LENGTH DEPENDING UPON THE ZMP AND ITS VARIATION.

ZMP' / ZMP	**NM**	**NS**	**Z**	**PS**	**PM**
NB	**PB**	**PB**	**PB**	**PM**	**PM**
NM	**PB**	**PB**	**PM**	**PM**	**PS**
NS	**PB**	**PM**	**PM**	**PS**	**Z**
Z	**PS**	**Z**	**Z**	**Z**	**NS**
PS	**Z**	**NS**	**NM**	**NM**	**NB**
PM	**NS**	**NM**	**NM**	**NB**	**NB**
PB	**NM**	**NM**	**NB**	**NB**	**NB**

Fig.4 and Fig.5 are the membership functions for the ZMP and its variation. The fuzzy sets of ZMP are:NB,NM,NS,Z,PS,PM,PB. While the variation of ZMP has following fuzzy sets:NM,NS,Z,PS,PM. Output value of fuzzy logic, which is to restrict the variation of step length, is constructed in five membership functions as shown in Fig.6. Rules are constructed in a 7x5 fuzzy table, which involves ZMP and its variation in order to stabilize the biped walking robot when it increases and decreases its walking speed. When the ZMP is PB and ZMP variation is PM, the restriction of step length variation is NB. It means that the robot can do a sharp deceleration. However, if the robot accelerates now, it will definitely fall down. The membership function for the inclination of body is defuzzified by the center of gravity method.

B. Fuzzy Body Inclination Generator

This study is to realize robot's fast omnidirectional walking with high standard of stability. So a proposed algorithm is carried out by planing the inclination of the body of robot which actually help to compensate the inertia force caused by acceleration, deceleration and body rotation to ensure that robot does not fall down when it walks to various direction with high walking speed.

Trunk of a biped robot is stable when ZMP exists in desired area which is assumed as the most stable area according to ZMP. Omnidirectional biped walking unlike walking with

TABLE II
THE RULE BASE TO GENERATE THE DESIRED INCLINING ANGLE DEPENDING UPON THE WALKING DIRECTION AND ROTATION ANGLE.

θ \ η	**NM**	**NS**	**Z**	**PS**	**PM**
NM	**NB**	**NB**	**NM**		
NS	**NB**	**NM**	**NS**		
Z	**NM**	**NS**	**Z**	**PS**	**PM**
PS			**PS**	**PM**	**PB**
PM			**PM**	**PB**	**PB**

uniform speed and direction causes variation of ZMP when a robot accelerates, decelerates or changes its walking direction. This variation is acceptable if ZMP dose not move out of the stable area. To restrict the ZMP variation we control the locomotion of the robot by letting the body incline to some extent. Fuzzy algorithm plans the exact angle the body should incline.

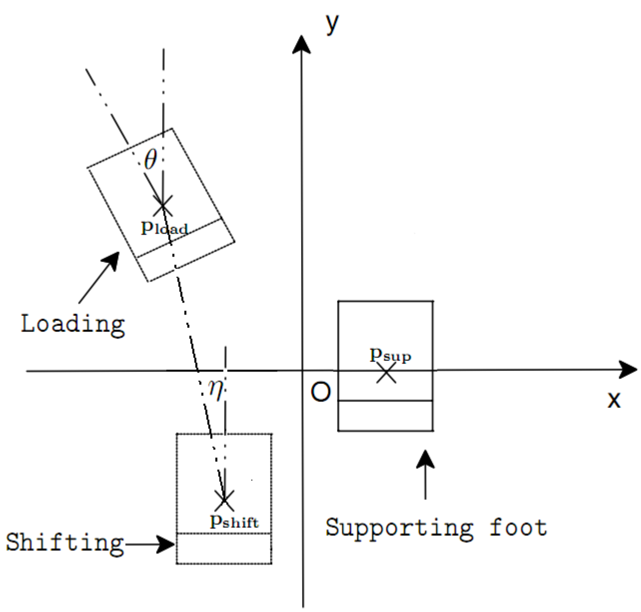

Fig. 7. The parameters of a posture for a gait primitive phase. Assuming the supporting foot is fixed on the ground while walking steadily, the local coordinate system is established according to the supporting foot: Z-axis vertical upward, Y-axis and the supporting leg towards the same.

The definition of θ and η is shown in Fig.7. Three membership functions are constructed for θ and η, where θ is desired rotation angle of following step compared to current step and η is desired angle between following walking direction and current walking direction. Each of the input variables has following fuzzy sets: NM, NS, Z, PS, PM. Membership functions consist of overlapped isosceles triangles as shown in Fig.8. All membership functions have equal base length. The universe of discourse is assumed as -a $<$ θ $<$ a and -b $<$ η $<$ b for the two variables, which the universe of discourse is decided by walking direction and by rotation angle. Output value of fuzzy logic, which is to compensate the inertia force, is constructed in five membership function

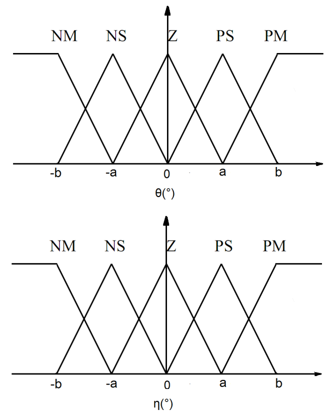

Fig. 8. Fuzzy membership functions for θ and η.

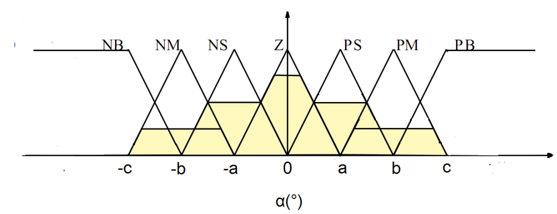

Fig. 9. Fuzzy membership functions for α and the defuzzification using the center of gravity

as shown in Fig.9. Rules are constructed in a 5x5 fuzzy table, which involves θ and η in order to stabilize the biped walking robot during its fast omnidirectional walking . If θ is N and η is N, body of robot should incline to the left. Therefore, posture of robot can keep the desired area of ZMP for stability without decreasing the walking speed. The membership function for the inclination of body is defuzzified by the center of gravity method.

C. Gait Primitive Generator

After the paraments of the following step are generated, we use a sine function to plan the gait primitive. The trajectory of a step is one fourth of a integral sine curve. Considering the energy consumption and the effectiveness of each step, the highest point of the sine curve varies with the step length. When the step length is long, the sine curve has a relatively high vertex. Similarly, when the step length is short, the vertex is low.

IV. EXPERIMENTS

In this section, two separate experiments were carried out on the Robocup 3d platform to verify the effectiveness of the fuzzy omnidirectional controller.

In the first experiment, Fig.11 and Fig.12 show the result of the robot's acceleration and deceleration without the restriction of Fuzzy Step Generator. In Fig.11, the NAO robot begun from the static state and fell down after several steps. While in Fig.12, the robot needed a emergent stop. We can see it

Fig. 10. The robot walks through flags which placed on the pitch. The robot bypasses all the flags successfully.

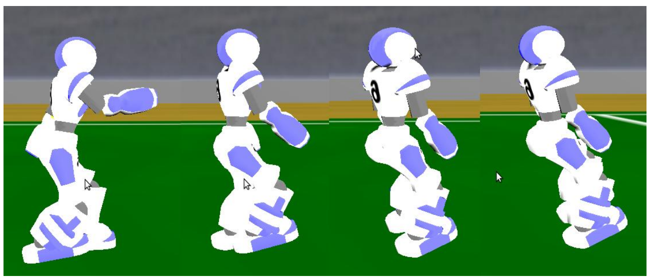

Fig. 11. Without the fuzzy step generator, the robot started from the static state and fell back after several steps.

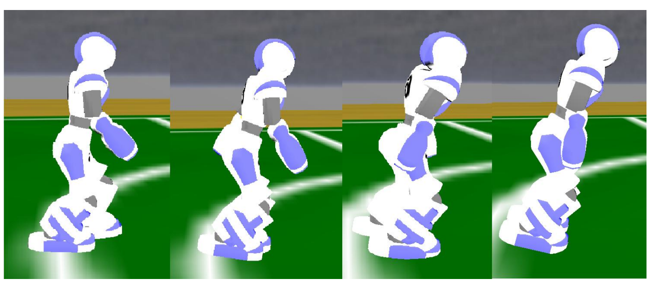

Fig. 12. Without the fuzzy step generator, The robot did a emergent stop and fell over after several steps.

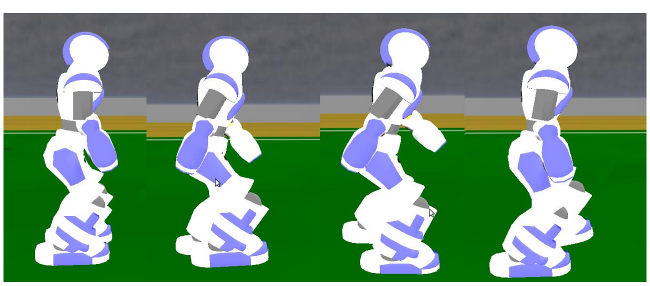

Fig. 13. Having the fuzzy step generator, the robot realized a perfect starting from the static state.

could't keep balance in this situation. It is because that without the restriction of step length variation, the robot experienced a sharp increase or decrease in speed. According to equations (3) and (4), the ZMP moved out of the stable region, which

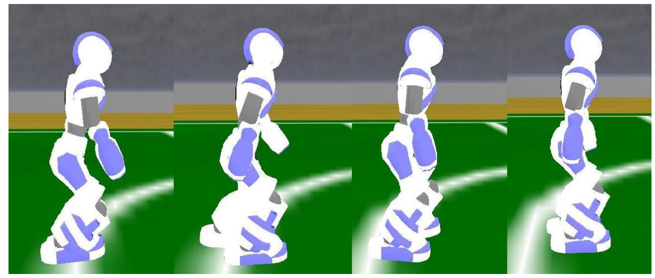

Fig. 14. Having the fuzzy step generator, the robot realized a perfect emergent stop.

caused the robot to fall down.In Fig.13 and Fig.14, the NAO robot did the same thing as in Fig.11 and fig.12 but with the restriction of Fuzzy Step Generator. In that case, the ZMP could always keep within the stable region. The result showed that the robot could perform well with the proposed controller.

Then the robot was put into a more complicated situation.(see Fig.10) It had to bypass the flags set in the field as most human football players do. In order to accomplish this task, the robot needed to change its walking speed and direction frequently. The result showed that it can do it well with the help of the fuzzy omnidirectional controller.

V. CONCLUSIONS

We proposed a fuzzy omnidirectional controller for the humanoid soccer robot. Two major parts of the controller, Fuzzy Step Generator and Fuzzy Body Inclination Generator, use fuzzy rules to generate proper paraments for stable and flexible biped walking. The Fuzzy Step Generator calculates the following step length according to the position of ZMP and its differential coefficient. Because the walking cycle is constant in this paper, the step length actually presents the speed of the robot. If the ZMP is in the front of the foot, the robot can not decelerate any more. On the contrary, it can not accelerate when the ZMP is at the back of the foot. At the same time, proper body inclination angle is generated by the Fuzzy Body Inclination Generator using the information of the turning and rotation angle. Proper body inclination can compensate the centrifugal force and keep the ZMP always in the stable region. Two experiments was carried out to confirm the effectiveness of the controller. The result showed that the robot could accomplish the tasks well. The soccer robots using the proposed control method also performed well in the soccer match.

We will improve the fuzzy omnidirectional controller to enable the variation of walking cycle, and the controller for robot's running will be the major part of our future work.

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