Comparison of PID and Fuzzy Logic Controllers in Humanoid Robot Control of Small Disturbances

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Abstract. Presence of permanent perturbations during walk requires simultaneous control of dynamic balance preservation and correction of internal synergy to bring it as close as possible to reference one. It is not answered yet in full extent how control for each of these tasks have to be synthesized. In this paper is discussed use of PID and fuzzy control for these purposes. In simulation experiment we applied for dynamic balance preservation only PID controller, but for internal synergy compensation two different controllers (PID and fuzzy) were applied. Obtained results were compared and discussed.

Keywords: Humanoid robots, ZMP (Zero Moment Point), dynamic balance, fuzzy control.

1 Introduction

Although the problem of bipedal gait has been in the focus of researchers for almost forty years, not all aspects of the control synthesis have been satisfactorily addressed yet. From humanoid robot control system is required to ensure simultaneous realization of a coordinated and functional motion of the joints (realization of the given gait type) and constant preservation of dynamic balance (preventing the robot's overturning during the walk).

All robot's movements are controlled in joint state space (internal synergy), whereas the verification of the realization efficiency is based on the robot's behavior in the external (Cartesian) coordinates (external synergy). In order to have the control task realized in one and verified in another state space it is necessary to have a unique relationship between these two spaces. During the regular gait, this unique relationship is ensured by fulfilling the requirement for preserving dynamic balance, which is manifested as the requirement that at least terminal link of the kinematical chain of the supporting leg (or of both legs in the case of double-support phase) is immobile with respect to the ground. This requirement is fulfilled if ZMP [1-6] is permanently within support area [7,8], either in single or double support phase.

Each deviation in the motion of the joints (deviation of internal synergy from the reference one) causes a deviation of the ZMP from its reference position, jeopardizing

A. Gottscheber et al. (Eds.): EUROBOT 2008, CCIS 33, pp. 42–53, 2009.

thus dynamic balance [5,6,8]. It is well known that the disturbances can be compensated for in different ways, depending of their type, complexity of the humanoid's mechanical structure (number of DOFs and their disposition) and, of course, disturbance intensity[1] [9]. Corrective actions can be planned and undertaken with the aim of preserving dynamic balance or bringing closer internal synergy to the reference one. It may easily happen that the compensation action aimed at bringing closer internal synergy to the reference produces as a side effect additional increase in deviation of the ZMP from the reference, jeopardizing thus dynamic balance. Thus, it can be stated that additional task of the control system part aimed to bring closer internal synergy to the reference one is not to jeopardize dynamic balance "too much". In "fine tuning" of the control system for internal synergy recovery priority should not be given to fast decrease of system deviation from reference motion (deviation decrease can be realized in one or even more half-steps), but priority should be "not-jeopardizing" of dynamic balance.

Since there is no use to perfectly realize the internal synergy while the humanoid is falling, we hope that it is quite straightforward that the priority must be given to preventing the humanoid's falling, i.e. to compensating for the ZMP deviation. Only then when the humanoid is not explicitly endangered (there is no direct threat of falling) the compensation activity can be “shared” between tasks of the following internal synergy and minimization of the ZMP deviation from its reference position.

In our previous paper [9] we already investigated control structure of PID regulator applied in each of these tasks. In this paper, for compensation of the ZMP deviation was designed PID regulator with variable feedback gains. For internal synergy compensation were compared two approaches: again PID regulator and fuzzy regulator. Obtained results are compared.

2 Description of Mechanical Structures of the Mechanism

In this section we describe the kinematical schemes of robot's mechanical configuration [9] that was used in the present work. The basis for deriving the mechanism's mathematical model is the software for forming the dynamic model of a branched, open or closed, kinematical chain whose links are interconnected with joints having only one DOF. The structure of the mechanism having 54 DOFs, used in the present work, is shown in Fig. 1. The first kinematic chain represents the legs (links 1-27), the second chain extends from the pelvis and comprises the trunk and the right hand (links 28-51), and the third chain (links 52-54) forms the left shoulder and arm. The multi-DOF joints were modeled as a set of "fictitious" links (massless links of zero-length) interconnected with the joints having one DOF. For example, the hip joints, which are in reality spherical joints with three DOFs, are modeled as sets of three one-DOF joints whose axes are mutually orthogonal. Thus the right hip is modeled by

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[1] Small disturbances are defined as disturbances that can be compensated for during the realization of internal synergy (the deviations of internal synergy are constantly diminishing), whereas in the case of large disturbances tracking of internal synergy is temporarily abandoned, compensation action realized with the aim to avoid falling down (e.g. by stepping aside), and, when dynamic balance is re-established, the tracking of internal synergy is continued. In this paper only small disturbances are considered.

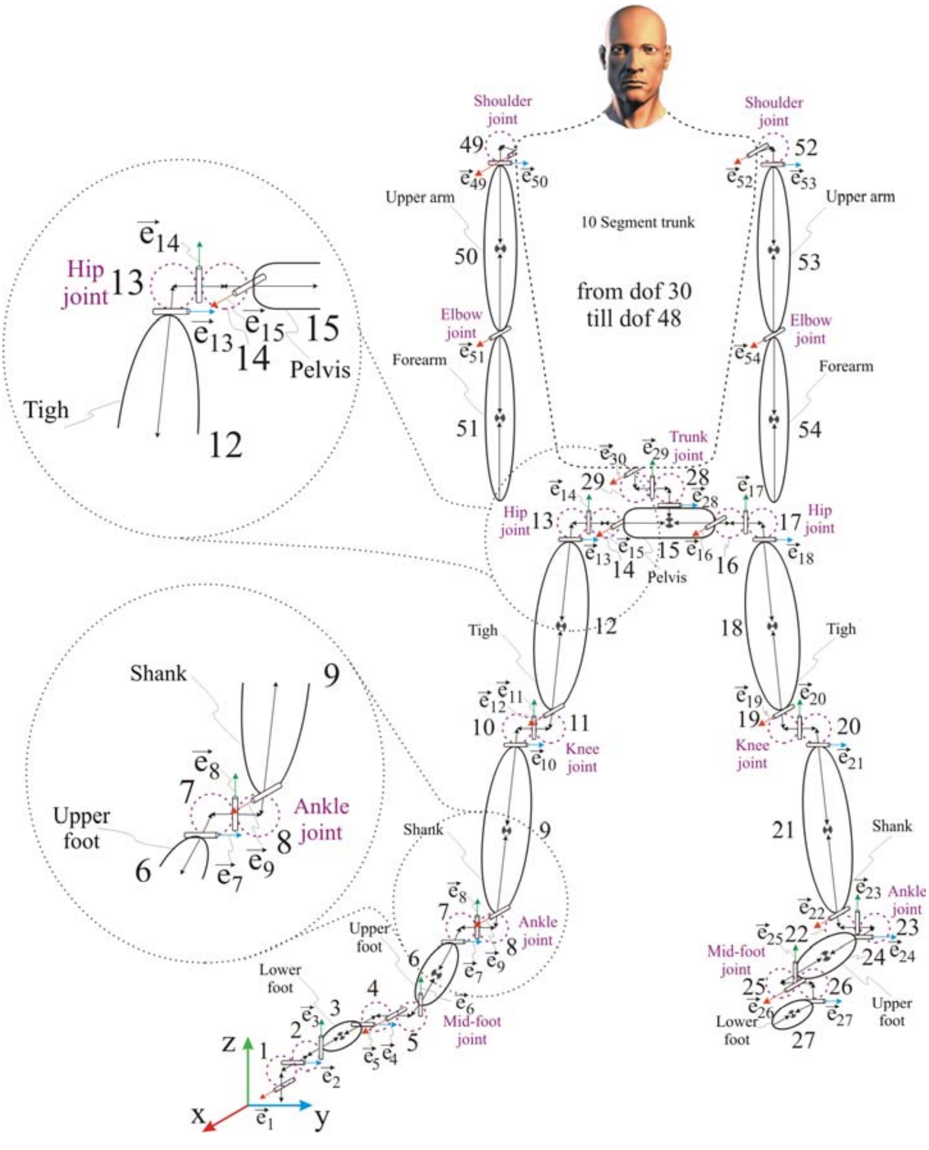

Fig. 1. Schematic of the robot's basic mechanical configuration having 54 DOFs

a set of simple joints 13, 14 and 15 (with the unit vectors of rotation axes $\boldsymbol{e}_{13}$, $\boldsymbol{e}_{14}$ and $\boldsymbol{e}_{15}$), and the left hip by the set of joints 16, 17 and 18 (the unit vectors $\boldsymbol{e}_{16}$, $\boldsymbol{e}_{17}$ and $\boldsymbol{e}_{18}$). The links connecting these joints (for the right hip the links 13 and 14, and for the left links 16 and 17) were needed only to satisfy the mathematical formalism of modeling a kinematic chain. The other links (those that are not part of the joints with more DOF's) whose characteristics correspond to the links of an average human body (link 9 corresponds to the shank, link 12 to the thigh, etc.) are presented by solid lines in Fig. 1. In the same figure, the links that were needed only for modeling "complex" joints with more DOFs (having no mass and with the moment of inertia and length being equal zero) are presented by dashed lines, to indicate their “fictitious” nature.

Of special importance is the way of modeling the foot-ground contact in order to determine the exact position of the ZMP during the motion and observe the moment when the mechanism is out of dynamic balance. The loss of dynamic balance means that the mechanism collapses by rotating about one of the edges of the supporting foot, and this situation, obviously, has to be prevented. The contact of the mechanism with the ground is modeled by two rotational joints, determined with the unit vectors e_1 and e_2 (Fig. 1), mutually perpendicular. At the ZMP for dynamically balanced motion, it is constantly ensured that $\mathbf{M_Y} = 0$ $((\mathbf{M_X} \perp \mathbf{M_Y}) \wedge (\mathbf{M_X}, \mathbf{M_Y} \in XoY))$. It should be especially emphasized that the mechanism feet were modeled as the two-link ones. In Fig. 1 the anterior part of the right foot (toes) is presented by link 3, and its main part (foot body) by link 6. The toes of the left foot are presented by link 27 and the foot body by link 24. The trunk is divided into several links (in this work it was modeled as being composed of 10 links) interconnected with the joints having two DOFs each (rotation about the y-axis (inclining forward-backward) and rotation about the x-axis (inclining left-right)).

The motion of all the links of the locomotion system was determined on the basis of the semi-inverse method using predescribed motion of the legs and predefined trajectory of ZMP shown on Fig. 2. for one half step.

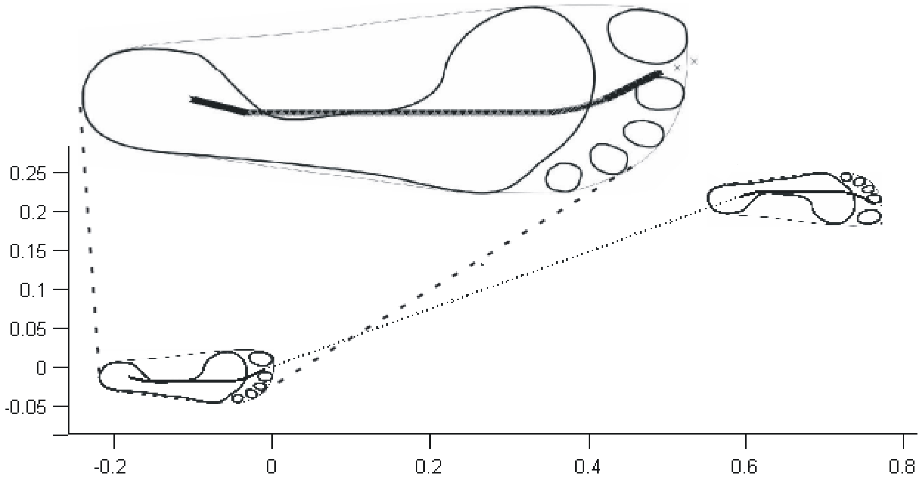

Fig. 2. Reference trajectory of ZMP for one-half step

In this way we obtained the reference motion (motion without any disturbance) of the mechanism.

3 Simulation Experiment

In this section control structure is adopted and simulation experiment are described.

3.1 Description of Experiment and Control System for Dynamic Balance

In simulation experiment deviation in joints reference angles (perturbation) were introduced at the beginning of the simulated motion. In hip and ankle (joints with unit vectors $\boldsymbol{e}_9$, $\boldsymbol{e}_{15}$, $\boldsymbol{e}_{16}$ and $\boldsymbol{e}_{22}$) were added +5° or -5° to obtain system posture as shown in Fig. 3. As a consequence of change in system posture deviation in ZMP position will also appear. Simulation lasted one half-step.

Control aim was to eliminate angular deviations in system joints while walking. This means that two tasks have to be performed simultaneously: elimination of deviation in joint angles and preservation of dynamic balance.

Accordingly, in each time instant t_i, the total control input at each joint consists of two parts: reference control (obtained for the motion without disturbances) and correction part, which depend of the disturbance intensity. In other words,

$$u_{n_i}^{(t_i)} = u_{\text{reference } n_i}^{(t_i)} + \Delta u_{\text{at joint } n_i}^{(t_i)} . \tag{1}$$

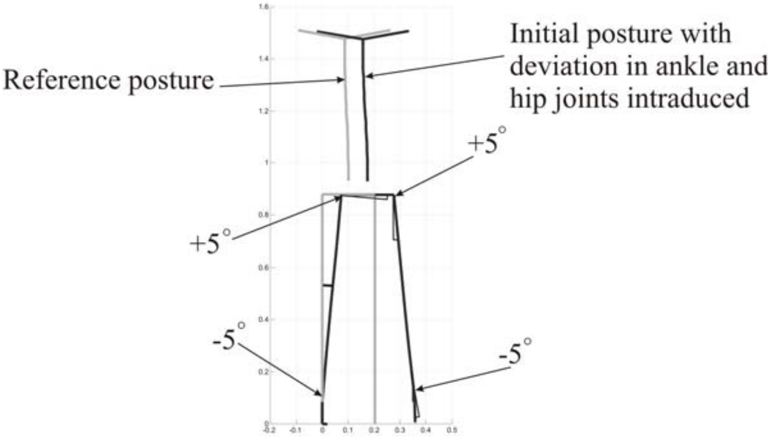

Fig. 3. Angular deviations at joints at the beginning of the simulated motion

The corrective part $\Delta u_{\text{at joint } n_i}^{(t_i)}$ consists also of two parts:

- The most important task is to prevent system to overturn. Thus, one part of the corrective control serves to minimize the ZMP position deviation from the reference $\Delta u_{\text{ZMP at joint } n_i}^{(t_i)}$, i.e. this control should preserve dynamic balance. This task can be allocated to one or more mechanism's joints.
- The other part of the corrective control ($\Delta u_{\text{local at joint } n_i}^{(t_i)}$) should ensure minimization of the deviation of the actual synergy from the reference one at each joint. This part of the corrective control we call local control, as the regulators involved act at the individual joints (locally).

The task of compensating for ZMP deviation should not be assigned to every joint at the same time, but may be allocated only to certain joints. Therefore, if we want to compensate for the ZMP deviations in the x-direction with the aid of the joint n_i, the control law will be of the form:

$$\begin{aligned}\Delta u^{(t_i)}_{\mathrm{ZMP\,at\,joint}\,n_i} = k_{\mathrm{pZMP}n_i} \cdot \Delta\mathrm{ZMP}^{(t_i)}_x + k_{\mathrm{iZMP}n_i} \cdot \sum_{i=1}^{t_i} \Delta\mathrm{ZMP}^{(i)}_x + \\ + k_{\mathrm{dZMP}n_i} \cdot \left(\Delta\mathrm{ZMP}^{(t_i)}_x - \Delta\mathrm{ZMP}^{(t_i-1)}_x\right)\end{aligned} \quad (2)$$

where $k_{\mathrm{pZMP}n_i}$ is the position feedback gain at the joint n_i, for the compensation of ZMP deviation; $k_{\mathrm{iZMP}n_i}$ and $k_{\mathrm{dZMP}n_i}$ are integral and derivative feedback gains at the joint n_i, also for compensating the ZMP deviation; $\Delta\mathrm{ZMP}^{(t_i)}_x$ stands for the deviation of ZMP in the direction of the x-axis at a time instant t_i. Analogously to (2) corrective control for ZMP deviation in y-direction can be obtained in form:

$$\begin{aligned}\Delta u^{(t_i)}_{\mathrm{ZMP\,at\,joint}\,n_i} = k_{\mathrm{pZMP}n_i} \cdot \Delta\mathrm{ZMP}^{(t_i)}_y + k_{\mathrm{iZMP}n_i} \cdot \sum_{i=1}^{t_i} \Delta\mathrm{ZMP}^{(i)}_y \\ + k_{\mathrm{dZMP}n_i} \cdot \left(\Delta\mathrm{ZMP}^{(t_i)}_y - \Delta\mathrm{ZMP}^{(t_i-1)}_y\right)\end{aligned} . \quad (3)$$

It should be borne in mind that the axis of the joint performing compensation should be perpendicular to the direction of ZMP deviation. Thus, Eq. (2) is applied in joints 7 (ankle), 13 (hip) and 28 (trunk), while Eq. (3) is applied in joints 9 (ankle), 15 (hip) and 30 (trunk). At joints of the leg in swing phase compensation obtained for leg in support phase has been applied. For example, compensation obtained for joint 15 (hip of supporting leg), is also applied at joint 16 (hip of the leg in swing phase).

Table 1. Feedback gains for ZMP compensation and the corresponding increments and decrements

Feedback gain	Joint	Min.	Max.	Increment	Decrement
	7 and 13	1	9	0.1	0.01
k_{pZMP}	9 and 15	5	13	0.1	0.01
	28 and 30	2	10	0.1	0.01
k_{iZMP}	all joints	3	3.08	0.0001	0.00001
k_{dZMP}	all joints	2	2.8	0.001	0.0001

To ensure priority of the preservation of the dynamic balance over internal synergy compensation coefficients in Eqs. (2) and (3) are not constant, but depend on ZMP deviation intensity in x and y direction. If ZMP is in 5mm wide zone with respect to ZMP reference position coefficient is set to its minimal value. As ZMP exit out of the 5 mm zone feedback gains start increase by increments specified in Table 1 up to its maximal value. If ZMP return to 5 mm zone it decrease by decrement from Table 1 up to its minimal value. In Table 1 are, for all joints involved in dynamic balance preservation, specified minimal and maximal feedback gains, as well as corresponding increments and decrements.

3.2 PID and Fuzzy Regulator

Regulators for internal synergy compensation were applied at same joints as regulators for ZMP deviation compensation, i.e. at joints 7, 9, 13, 15, 28 and 30. Also, compensation obtained for joints of the leg in support phase was applied at joints of the leg in swing phase. For all other joints only reference control was applied.

Two approaches were applied in internal synergy compensation: PID regulator and fuzzy logic regulator. In both cased "additional amount of control" ($\Delta u^{(t_i)}_{\text{local at joint } n_i}$) was added to reference control.

PID regulator for internal synergy compensation is defined in following way:

$$\Delta u^{(t_i)}_{\text{locali at joint} n_i} = k_{p n_i \text{ local}} \cdot \Delta q^{(t_i)}_{n_i} + k_{i n_i \text{ local}} \cdot \sum_{i=1}^{t_i} \Delta q^{(i)}_{n_i} + k_{d n_i \text{ local}} \cdot \left(\Delta q^{(t_i)}_{n_i} - \Delta q^{(t_i - 1)}_{n_i}\right). \qquad (4)$$

Coefficient in (4) are not constant, but also depend on ZMP position: if ZMP is within 5mm zone coefficients increase by defined increment up to maximal values, but if ZMP is out of the 5mm zone coefficients decrease by defined decrement up to minimal values (Table 2). In this way is ensured that when dynamic balance is not endangered priority is given to achieving reference internal synergy. Otherwise, priority is given to fall prevention.

Another approach applied was to design fuzzy controller. Block diagram of fuzzy controller is shown on Fig. 4. Controller is of mamdani type and has two inputs and one output. Inputs for controller are the error in joints and error derivation in joints 7, 9, 13, 15, 28 and 30:

Table 2. Feedback gains for local regulators and the corresponding increments and decrements

Feedback gain	Joint	Min.	Max.	Increment	Decrement
$k_{p\ \text{local}}$	All joints	10	200	0.1	10
$k_{i\ \text{local}}$	All joints	2	3	0.0005	0.05
$k_{d\ \text{local}}$	All joints	3	8	0.002	0.2

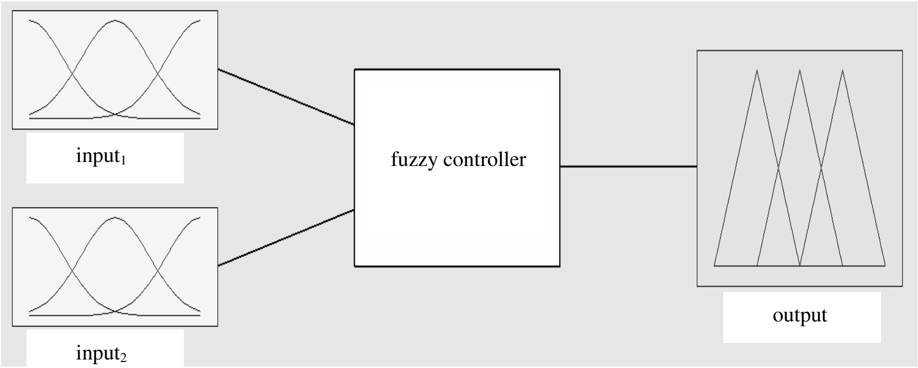

Fig. 4. Block diagram of fuzzy controller

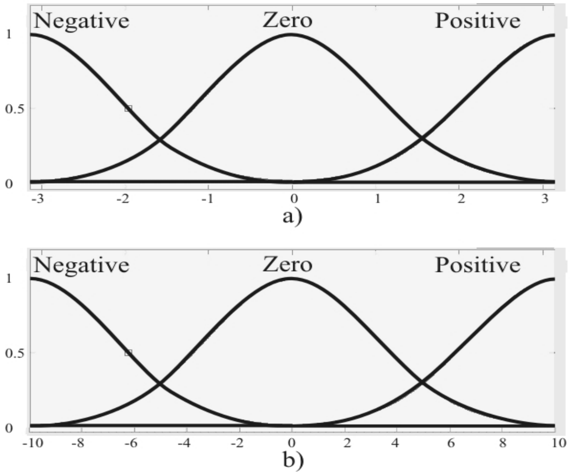

Fig. 5. Membership functions for input$_1$ a), input$_2$ b)

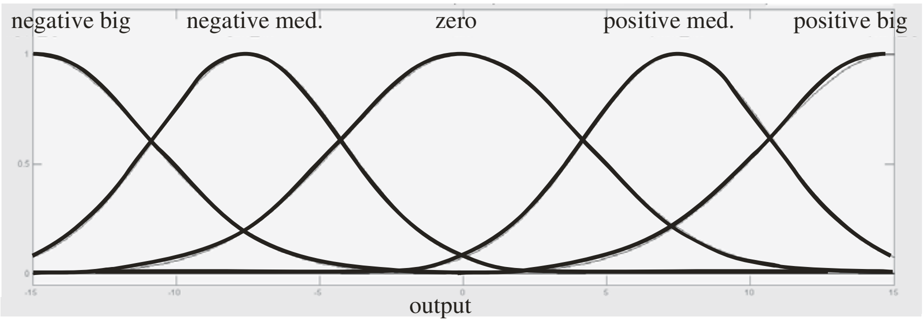

Fig. 6. Membership functions for output

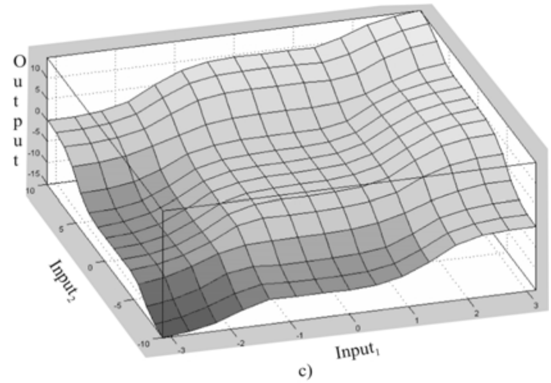

Fig. 7. Transfer surface for adopted fuzzy controller

$$\text{input}_1^{(t_i)} = \Delta q_{n_i}^{(t_i)} \quad \text{and} \quad \text{input}_2^{(t_i)} = \left(\Delta q_{n_i}^{(t_i)} - \Delta q_{n_i}^{(t_i-1)}\right). \tag{5}$$

Membership functions for inputs are shown in Fig. 5. In Fig. 6. are shown membership functions for output. All membership functions (for inputs and output) are Gaussian curve membership function.

The following "IF-THEN" rules are introduced in to controller:

IF input$_1$ is negative and input$_2$ is negative THEN output is negative big
IF input$_1$ is negative and input$_2$ is zero THEN output is negative med.
IF input$_1$ is negative and input$_2$ is positive THEN output is zero
IF input$_1$ is zero and input$_2$ is negative THEN output is negative med.
IF input$_1$ is zero and input$_2$ is zero THEN output is zero
IF input$_1$ is zero and input$_2$ is positive THEN output is positive med.
IF input$_1$ is positive and input$_2$ is negative THEN output is zero
IF input$_1$ is positive and input$_2$ is zero THEN output is positive med.
IF input$_1$ is positive and input$_2$ is positive THEN output is positive big

As a result of introduced "IF-THEN" rules and input and output membership functions we can generate a transfer surface (Fig. 7.).

When fuzzy controller is used corrective control $\Delta u_{\text{local at joint } n_i}^{(t_i)}$ is defined as:

$$\Delta u_{\text{local at joint } n_i}^{(t_i)} = k_{\text{fuzzy}} * \text{output}^{(t_i)} \quad . \tag{6}$$

where $\text{output}^{(t_i)}$ is fuzzy controller output, k_{fuzzy} is coefficient whose intensity depend on ZMP deviation from its reference position and it changes from 0.1 to 1. When ZMP is out of 5 mm zone k_{fuzzy} decrease up to its minimal value by decrement 0.05, but in case ZMP deviation is less than 5mm, k_{fuzzy} increase till 1 by increment 0.025.

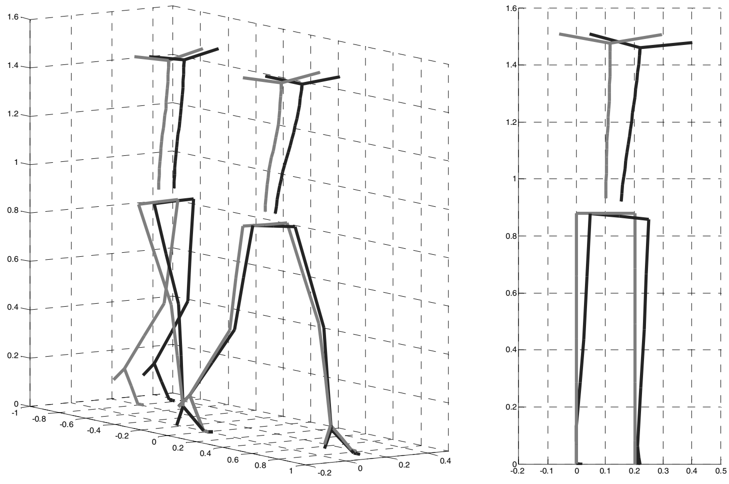

Fig. 8. Reference and actual biped postures at the beginning and at the end of half-step. For internal synergy compensation was used PID regulator. a) perspective view, b) sagittal plane.

3.3 Results

In Fig. 8. is shown stick diagram of the locomotion system on the beginning and the end of the simulated half step if for internal synergy deviation compensation is used PID regulator. In Fig. 9 is shown same situation, but in case for internal synergy deviation compensation is used fuzzy regulator.

Due to completeness in Figs. 10 and 11 are shown reference and actual ZMP positions in case as local regulator are used PID and fuzzy regulator.

From Figs. 10 and 11 can be seen ZMP trajectory during simulated period, as well as feet position during single-support phase and at the beginning of double-support phase. It is clear that both approaches ensure preservation of dynamic balance what is

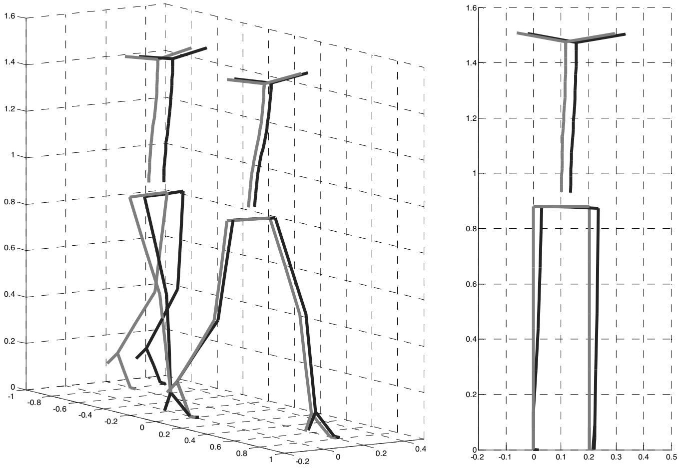

Fig. 9. Reference and actual biped postures at the beginning and at the end of half-step. For internal synergy compensation was used fuzzy regulator: a) perspective view, b) sagittal plane.

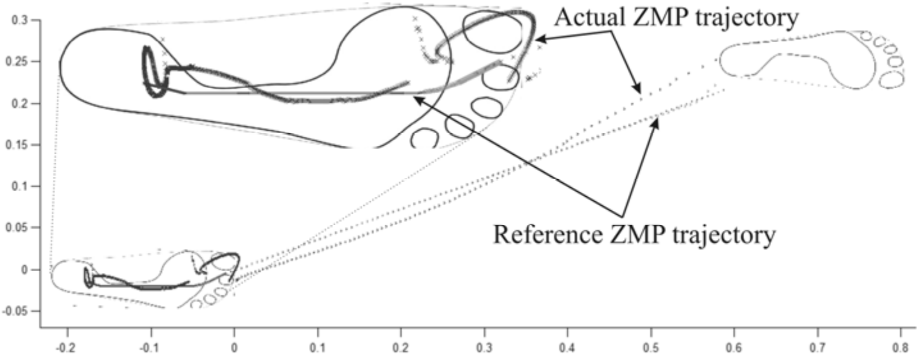

Fig. 10. Reference and actual ZMP position during one-half step; PID local regulator was used

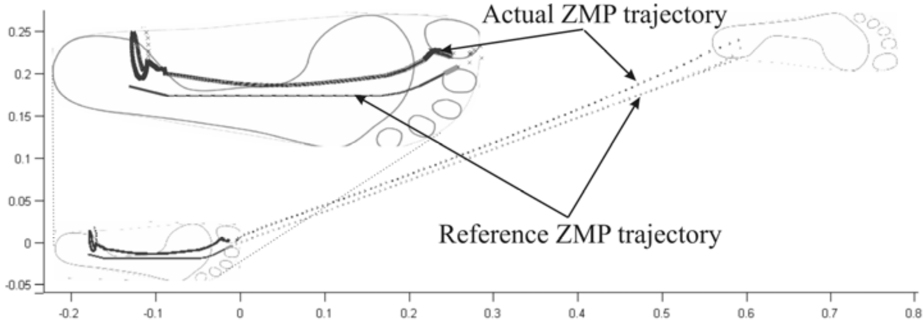

Fig. 11. Reference and actual ZMP position during one-half step; fuzzy local regulator was used

the most important requirement in humanoid robots control synthesis. But, from Figs. 8 and 9 it can be seen that at the end of half step posture in case fuzzy regulator was applied is closer to reference posture. In addition, in Figs. 10 and 11 is shown that that ZMP trajectory during half-step is much more "calm", as a consequence of more “smooth” compensation motion of internal synergy i.e. with smaller intensity of forces induced in the process of compensation. This is very good example that by more appropriate compensation of internal synergy as a side effect preservation of dynamic balance can be improved.

4 Conclusion

In this paper comparison of use of PID and fuzzy controller in compensation of small disturbances of internal synergy was performed. Both controllers were applied in parallel with controller whose task was to preserve dynamic balance, i.e. to prevent mechanism overturn during walk. In both cases simulation experiment was successful. But, fuzzy controller showed somewhat more promising characteristics in sense of more smooth compensation (movements without rapid accelerations) what reflects on the ZMP trajectory under foot. Thus, some more detailed investigation in this direction is planned in the future for example use of fuzzy controller for dynamic balance or use of neural network based controllers.

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