# Biped Robot Walking Control on Inclined Planes with Fuzzy Parameter Adaptation

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**Abstract:** The bipedal structure is suitable for a robot functioning in the human environment, and assuming assistive roles. However, the bipedal walk is a poses a difficult control problem. Walking on even floor is not satisfactory for the applicability of a humanoid robot. This paper presents a study on bipedal walk on inclined planes. A Zero Moment Point (ZMP) based reference generation technique is employed. The orientation of the upper body is adjusted online by a fuzzy logic system to adapt to different walking surface slopes. This system uses a sampling time larger than the one of the joint space position controllers. A newly defined measure of the oscillatory behavior of the body pitch angle and the average value of the pelvis pitch angle are used as inputs to the fuzzy adaptation system. A 12-degrees-of-freedom (DOF) biped robot model is used in the full-dynamics 3-D simulations. Simulations are carried out on even floor and inclined planes with different slopes. The results indicate that the fuzzy adaptation algorithms presented are successful in enabling the robot to climb slopes of 5.6 degrees (10 percent).

***Keywords:*** humanoid robots, bipedal walk, inclined plane.

## 1. INTRODUCTION

The humanoid structure has certain advantages for a robot working in the human environment with assistive roles. A bipedal humanoid robot can avoid typical obstacles in the human environment via the locomotion on lower limbs. Other advantages can be listed too. However, there are disadvantages of the bipedal structure too. Walking on two legs is a difficult task. This is due to the many degrees of freedom to be controlled under coupling effects and nonlinear dynamics. The last four decades witnessed intensive research on humanoid robot walking control. A number of successful projects and results are reported (Hirai et al., 1998, Sakagami, 2002, Kaneko et al., 2002, Kim et al., 2007, Hyon and Cheng, 2006, Ogura et al., 2006).

One of the most challenging problems in this field is the robust balance of the walk, not only on even floor but on surfaces with irregularities and slopes too. Studies on bipedal walking on inclined or uneven surfaces are reported (Kajita and Tani, 1996a, Hirukawa et al., 2007, Kajita and Tani, 1996b, Yokoi et al., 2001, Taskiran et al., 2009). An inclined plane presents a very typical floor condition encountered in human daily life. Though such planes are mostly part of the city and outdoor environments, since the indoor floors are not perfectly even, the inclined planes can be found at our homes and offices too. This paper presents a fuzzy logic parameter adaptation system for walking control on inclined planes. A smooth walking trajectory is generated based on the ZMP stability criterion and the Linear Inverted Pendulum Model (LIPM) as in (Kajita et al., 2003, Erbatur and Kurt 2009, Taskiran et al., 2010). Independent joint PID controllers are employed to track references. The robot above the legs is assumed to have two rigid bodies. One of them, the lower one is termed in this paper as the pelvis link. The second one is the upper body positioned above the pelvis. The angle of the upper body with respect to the pelvis link is called the "body pitch angle" and the angle of the pelvis link with respect to a vertical line is called the "pelvis pitch angle." A measure of the oscillatory behavior of the pelvis pitch motion is introduced. This measure and the average pelvis pitch angle are used as the input of a fuzzy logic system which computes the body pitch angle parameter online, to be applied as a reference position to the robot controller. The rule base is constructed in such a way to compensate the disturbance effects of changing slopes by shifting the upper body weight forward and backward. The paper also discusses an inverse kinematics solution for generating the effect of the upper body pitch motion for robots which do not have a pitch joint between the pelvis and upper body, but possess "spherical" hip joints. We call this approach the "method of the virtual pelvis." Full dynamics 3D simulation studies with a 12 DOF robot model are carried out in order to test the proposed fuzzy parameter adaptation system.

The rest of this paper is organized as follows. The next section defines the problem of walking on planes with changing grades, the above mentioned pitch angles and the measure of oscillatory behavior in the pitching motion. Section 3 describes the fuzzy adaptation system. The method of virtual pelvis is introduced in Section 4. Section 5 introduces the simulation platform and presents the simulation results of walking on changing slopes. The paper is concluded in Section 6.

## 2. THE PROBLEM DEFINITION AND BALANCE INDICATORS

Figure 1 shows a typical biped robot walking on flat floor and on inclined planes with changing slopes. The motion of the robot is defined in a fixed coordinate frame called the world frame. The robot walking direction coincides with the x-direction of the world frame. Another frame is attached at the pelvis link of the robot. This link can be considered as a "central" one since the legs and possibly waist links are connected to the pelvis. Initially (before the start of the walk), the pelvis frame axes are aligned parallel with the corresponding world frame axis. However, this parallel alignment changes during the walk due to various effects including gravitational forces, foot to ground interaction, changing slopes and coupling effects between the links. The pelvis pitch angle which is the angle the z-axis of the pelvis frame makes with a vertical line is an indicator of the balance of the walk. Assuming that a gait with zero pelvis pitch angle is planned in the reference generation, the online measurement of this angle can provide feedback indicating whether the robot is following this reference. It can also detect a falling forward or backward. However, our simulation and experimental results (Erbatur et al., 2008, Erbatur et al., 2009, Taskiran et al., 2010,) suggest that the pelvis pitch angle is oscillating during the walk. Even in a steady and stable walk the pelvis pitch angle trajectory can be in the form of a periodic signal with peak values of a few degrees. Therefore, a single measurement of the angle can be misleading in deciding upon the balance condition of the robot. In order to infer whether the robot goes on with a steady walking pattern or is in the trend of falling, the average rather than the instantaneous value of the pelvis pitch angle is more suitable. Averaging can be done in many different ways. One question to be answered is related to the length of the averaging window. Another concern is the sampling period for the data to be averaged. Usually, joint space controller sampling times of one to ten milliseconds are employed in robotic applications. Using a long averaging window from the current sampling instant back with a low sampling period in the order of the joint control sampling period would require large storage space and consume online computational resources. There is a trade-off in the accuracy of the averaging computation and the efficient use of the computational power. Employing the number of samples $N$ used in the average computation and the pelvis pitch angle sampling period $T_p$ as design parameters, the average value $\bar{\beta}$ of the pelvis pitch angle $\beta$ in Fig. 2 is computed as

$$\bar{\beta}(kT_p) = \frac{1}{N}\sum_{l=0}^{N-1}\beta\big((k-l)T_p\big) \qquad (1)$$

where $k$ is the sampling index. In addition to the average value of $\beta$, the frequency and size of the oscillations of this angle are also indicators of the stability of the walk. Simulations and measurements during experiments with bipedal robots indicate that the frequency and peak values of the angle change drastically when encountered disturbances like irregularities on the floor, slope changes or external forces applied to the robot body. The following pelvis pitch angle activity indicator (or measure of the oscillatory behavior) inspired from the sliding mode robot position control chattering indicator in (Erbatur et al., 1996, Erbatur and Kaynak 2001 and Erbatur and Calli, 2009) and denoted by $\Gamma$ is suggested in this paper.

$$\Gamma(kT_p) = \sum_{l=0}^{N-1}\Big|\beta\big((k-l)T_p\big) - \beta\big((k-l-1)T_p\big)\Big| \qquad (2)$$

In (2), $|\cdot|$ signifies the absolute value function. Among many actions which can enhance the stability during the walk, studied in this paper is the online adjustment of the body pitch angle (the angle $\theta$ shown in Fig. 2) parameter. Note that, while $\beta$ is an angle between a link (pelvis) of the robot and the environment (a vertical line), $\theta$ is an angle between two links (pelvis and upper body) of the robot. In other words, $\beta$ is a measured parameter which, due to the underactuation between the robot feet and the ground surface, can only be controlled indirectly, whereas $\theta$ can be controlled directly and accurately via a joint position controller. (Park, 2003) uses this angle as a balance control variable for a 2D (saggital plane) biped model. One of the benefits of increasing this angle is an addition to the robot moment of inertia about the yaw axis (pelvis frame z-axis) by moving some percentage of the robot weight far from this axis. In this way, disturbance torques due to foot swing motion and foot-ground interaction have a more diminished effect on the rotary motion about the yaw axis. Yaw moment compensation techniques using this fact are studied in (Fujimoto and Kawamura, 1998). Bending the body forward or stretching backward moves the robot center of mass (COM) of the robot forward and backward, respectively, too.

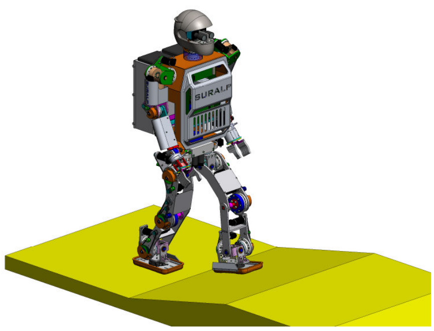

Fig. 1 Bipedal robot walk on changing slopes

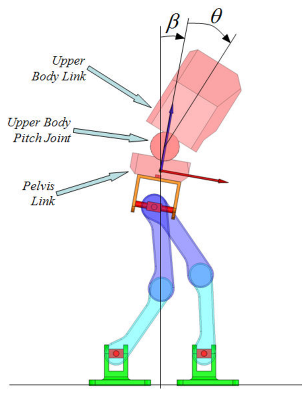


Fig. 2 Legs, pelvis and the upper body

The location of the COM with respect to the support polygon determines static stability, whereas the time history of the COM determines the location of the ZMP, the location of which is a widely used stability criterion for biped robots. Motivated by these significant effects of the body pitch angle on the balance of the robot, in the next section we develop a fuzzy logic system which adjusts this parameter online by evaluating the average $\overline{\beta}$ of the pelvis pitch angle and the activity $\Gamma$ of this angle as its inputs.

## 3. THE FUZZY PARAMETER ADAPTATION SYSTEM

The main idea of the parameter adaptation system can be summarized as: (i) *When high levels of pelvis pitch activity* $\Gamma$ *is observed, the upper body should be rotated forward (by increasing the body pitch angle* $\theta$ *between the pelvis and the upper body) to counter disturbance effects.* (ii) *The body pitch angle* $\theta$ *should be decreased if the pelvis pitch activity* $\Gamma$ *is low. This is since, ideally, an upright posture is preferred for the upper body in many tasks. This study regards the upright posture as the default one, and if no disturbing effects are observed the robot should return to its default upper body orientation mode.* The guidelines (i) and (ii) on their own can be used to devise body pitch angle adjustment methods. However, these two guidelines use only the information about the pelvis pitch activity in the system. Another source of valuable information is the average $\overline{\beta}$ of the pelvis pitch angle. The following guidelines describe the role of $\overline{\beta}$ in the body pitch angle adjustment used in this paper: (iii) *When the average value of pelvis pitch angle is positive, assuming that a flat pelvis trajectory is planned, we can infer that this is a posture inclined to a fall towards front, to the walking direction. In this case, the body pitch angle should be decreased (and even made negative) to compensate for the gravity effect of the forward leaned pelvis link.* (iv) *In a similar way to the guideline 3 above, when the average value of pelvis pitch angle is negative, the body pitch angle should be increased to compensate for the gravity effect of the backward leaned pelvis link.* The four guidelines above can be used in various ways to construct a tuning mechanism for $\theta$. An analytic relation between $\overline{\beta}$, $\Gamma$ and $\theta$ could be one of the choices. The method proposed in this paper employs fuzzy systems for the online tuning of $\theta$. Fuzzy systems are natural choices to exploit verbal descriptions (like the four guidelines above) of the plant or problem to obtain control or adaptation mechanisms. Table 1 and Fig. 3 describe the nine fuzzy rules used in the tuning. In Table 1 the subscript "$P1$" of the rule strength $\theta_{P1}$ stands for positive small. "$\theta_{P2}$" is also positive and small, however, it is bigger than $\theta_{P1}$. $\theta_{P3}$ is bigger than $\theta_{P2}$. Similarly defined are $\theta_{P4}$ and $\theta_{P5}$ with increasing magnitudes. $ZZ$ symbolizes "zero" and $N1$ is negative small. The numerical values of the rule strengths and the corner positions of the trapezoidal membership functions in Fig. 3 are tabulated in the simulation results section, in Table 4. The rules are summarized in Table 1. An example for a rule is: "*Rule 11: If* $\Gamma$ *is small and* $\overline{\beta}$ *is negative, then* $\theta$ *is positive of grade 3 (*$\theta_{P3}$*).*" The choice of the rule base and the membership functions satisfies the conditions (i) - (iv) above. The truth value of a rule is obtained by multiplying the membership values of $\Gamma$ and $\overline{\beta}$ fuzzy sets involved in the rule. For example, from Table 1, the truth value of Rule 11, denoted by $w_{11}$, is computed as

$$w_{11} = \mu_{Small\,\Gamma}(\Gamma)\mu_{Negative\,\overline{\beta}}(\overline{\beta}). \tag{3}$$

In general, the truth value of rule Rule $ij$ is denoted by $w_{ij}$ and computed in a way similar to the computation of $w_{11}$. Let the rule strength matrix $\Theta$ be defined from Table 1 as

$$\Theta = \begin{bmatrix} \theta_{p3} & \theta_{p4} & \theta_{p5} \\ \theta_{p1} & \theta_{p2} & \theta_{p4} \\ \theta_{N1} & \theta_{ZZ} & \theta_{p2} \end{bmatrix}. \tag{3}$$

Using this matrix, the defuzzification is carried out by the expression

$$\theta = \left( \sum_{i=1}^{3}\sum_{j=1}^{3} w_{ij}\Theta_{ij} \right) \Big/ \left( \sum_{i=1}^{3}\sum_{j=1}^{3} w_{ij} \right). \tag{4}$$

As mentioned above the computed $\theta$ value is applied as the reference angular position of the joint between the pelvis and upper body links. The next section briefs a practical consideration: What if the robot does not possess a pitch joint between its pelvis and upper body?

**Table 1. The Fuzzy Rule Base**

| | | $\Gamma$ | | |
|---|---|---|---|---|
| | | Small $\Gamma$ | Medium $\Gamma$ | Big $\Gamma$ |
| $\overline{\beta}$ | Negative $\overline{\beta}$ | $\theta_{P3}$ *Rule 11* | $\theta_{P4}$ *Rule 12* | $\theta_{P5}$ *Rule 13* |
| | Zero $\overline{\beta}$ | $\theta_{P1}$ *Rule 21* | $\theta_{P2}$ *Rule 22* | $\theta_{P4}$ *Rule 23* |
| | Positive $\overline{\beta}$ | $\theta_{N1}$ *Rule 31* | $\theta_{ZZ}$ *Rule 32* | $\theta_{P2}$ *Rule 33* |

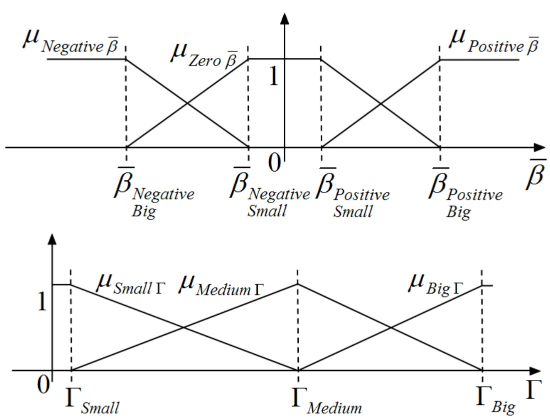


Fig. 3 The membership functions

## 4. VIRTUAL PELVIS

Fig. 4 shows the kinematic arrangement of the robot SURALP designed at Sabancı University Robotics Laboratory (Erbatur et al., 2008, Erbatur et al., 2009). This kinematic arrangement does include a waist yaw axis, however no pitch axis is present. There are many other examples of robots which do not feature a pitch joint between the pelvis and the upper body. In this section, a method which enables the application of the adaptation mechanism in the previous section to humanoids without such a joint is presented. The idea of the method is based on the introduction of a virtual pelvis link illustrated in Fig. 5. Consider the walk without the pitch motion between the pelvis and upper body. Assume that the references of the feet are defined in an upper body-fixed frame. The position and orientation references can be expressed in the form of a reference homogenous transformation matrix $H_r$ as

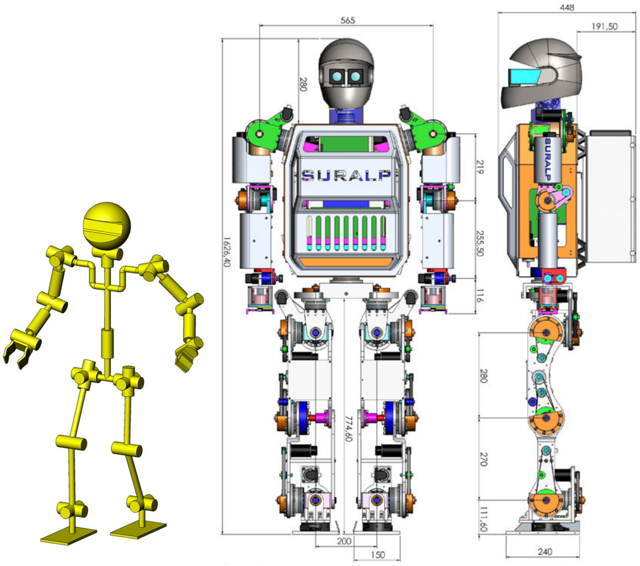

Fig. 4 The kinematic arrangement of SURALP.

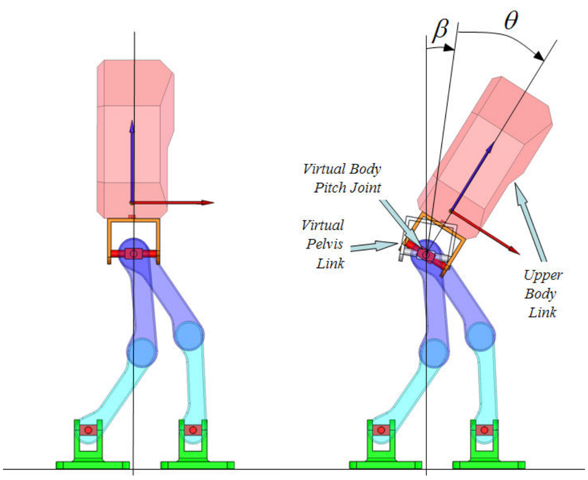


Fig. 5 a) Walk with upright upper body posture. b) Upper body leaned forward. Body and virtual pelvis angles are shown.

$$H_r = \begin{bmatrix} \begin{bmatrix} & & \\ & R_r & \\ & & \end{bmatrix} & \begin{bmatrix} \\ d_r \\ \\ \end{bmatrix} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix}, \tag{5}$$

where $R_r$ is the reference orientation matrix and $d_r$ is the reference position of a foot. Suppose that the foot orientation reference matrix $R_r$ is such that the feet are parallel to the upper body. Fig. 5a shows such a posture. The body fixed coordinate frame is shown in this figure too. By applying a pure pitch rotation operator on the homogenous transformation matrix $H_r$, new, rotated foot references can be obtained:

$$H_{r_{new}} = \begin{bmatrix} \begin{bmatrix} & & \\ & R_{y,-\theta} & \\ & & \end{bmatrix} & \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} H_r \,. \tag{6}$$

Here, $R_{y,-\theta}$ is the basic rotation matrix about the $y$-axis by the angle $-\theta$. The $y$-axis of the body-fixed coordinated frame in Fig. 5 points into the page. The reference posture resulting from the rotation of the foot references in Fig. 5a about this axis by the angle $-\theta$ is shown in Fig. 5b. Assuming that the feet will keep their contact with the ground, the effect of rotating the feet with respect to the body fixed coordinate frame is to rotate the body by the angle $\theta$. Hence, upper body pitch motion can be generated by planning a rotated version of the upright body references, even for robots without a pitch joint at the waist. Note that the angle $\theta$ in Equation 6 can be used as the adapted pitch angle $\theta$ in Equation 4. However, the adaptation mechanism in Section 3 requires the pelvis pitch angle $\beta$ as its input and this angle, different from the upper body pitch angle, is yet to be defined for robots without a waist pitch joint. Actually for such robots the pelvis and the upper body links can be considered to be the same. However, if we measure the pitch orientation angle of the robot by an inertial measurement system mounted at the upper body of the robot and subtract from it the rotation angle $\theta$ explained above, we can find an offset angle which can be considered as the pitch orientation angle of a virtual pelvis link:

$$\beta = \beta_{body} - \theta \tag{7}$$

Here $\beta_{body}$ is the pitch angle measured by the inertial measurement system at the upper body. The virtual pelvis link is shown in Fig. 5b.

## 5. SIMULATION RESULTS

The biped model used in this paper consists of two 6-DOF legs and a trunk connecting them. Three joint axes are positioned at the hip. Two joints are at the ankle and one at the knee. Link sizes and masses of the biped are given in Table 2. Simulation studies are carried out with this robot model. The details of the simulation algorithm and contact modeling can be found in (Erbatur and Kawamura, 2003). Parameters used for reference generation are presented in Table 2. The control algorithm is a simple one based on independent joint PID position controllers. The joint position references are generated through inverse kinematics from CoM and swing foot references in world frame coordinates. The PID controller gains are obtained via trial and error. The controller structured this way, except for the servo control loops, is an open-loop one. However, it achieves walking when stable reference trajectories (like the ones obtained in the previous section) are employed. The simulation and PID controller cycle time employed is 0.5 milliseconds. The cycle time of the fuzzy adaptation routine is however set to 200 milliseconds. The value of the number of samples, $N$, in these equations equals to 10. The simulation results obtained with the fuzzy parameter adaptation system are shown in Figures 6 and 7. The walking surface of the simulation environment contains two parts:

**Table 2. Masses and Dimensions of the robot links**

| *A. Link* | Dimensions (LxWxH) [m] | Mass [kg] |
|---|---|---|
| Trunk | 0.2 x 0.4 x 0.5 | 50 |
| Thigh | 0.27 x 0.1 x 0.1 | 12 |
| Calf | 0.22 x 0.05 x 0.1 | 0.5 |
| Foot | 0.25 x 0.12 x 0.1 | 5.5 |

**Table 2. Trajectory Generation Parameters**

| Parameter | Value |
|---|---|
| Single support period | 0.6 s |
| Double support period | 0.9 s |
| ZMP reference in y | 7 cm |
| ZMP motion under the | 4 cm |
| Step size | 10 cm |
| Step height | 2 cm |

**Table 4. Rule Strengths and Membership Function Corner Locations**

| Rule Strength | Numeric Value (Degrees) | Corner | Numeric Value (Degrees) |
|---|---|---|---|
| $\theta_{bN1}$ | −3 | $\overline{\beta}_{\substack{Negative\\Big}}$ | −5 |
| $\theta_{bZZ}$ | 0 | $\overline{\beta}_{\substack{Negative\\Small}}$ | −0.25 |
| $\theta_{bP1}$ | 1 | $\overline{\beta}_{\substack{Positive\\Small}}$ | 0.25 |
| $\theta_{bP2}$ | 4 | $\overline{\beta}_{\substack{Positive\\Big}}$ | 5 |
| $\theta_{bP3}$ | 5 | $\Gamma_{Small}$ | 1 |
| $\theta_{bP4}$ | 8 | $\Gamma_{Medium}$ | 5 |
| $\theta_{bP5}$ | 12 | $\Gamma_{Big}$ | 10 |

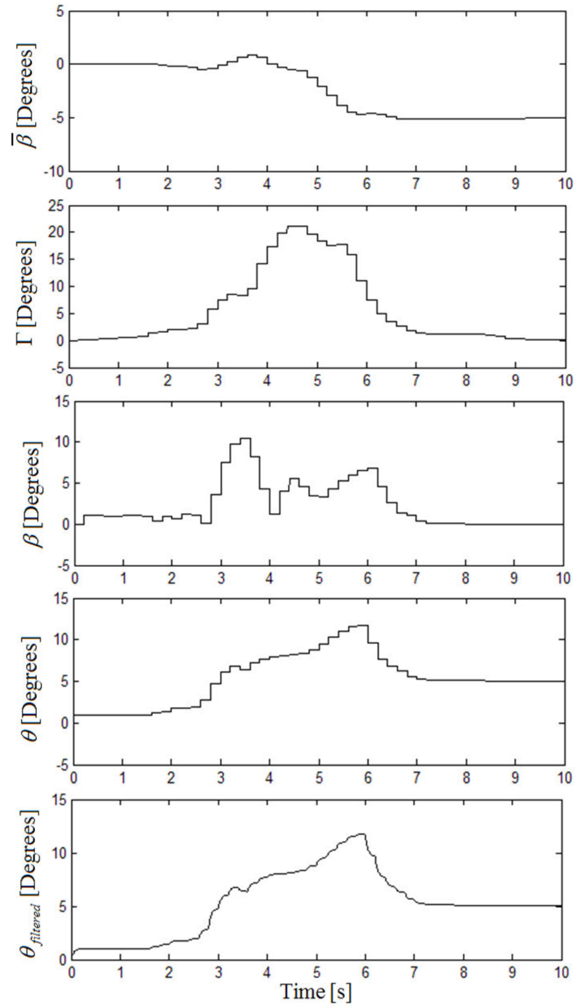

Fig. 6 Body and pelvis angles during the simulation

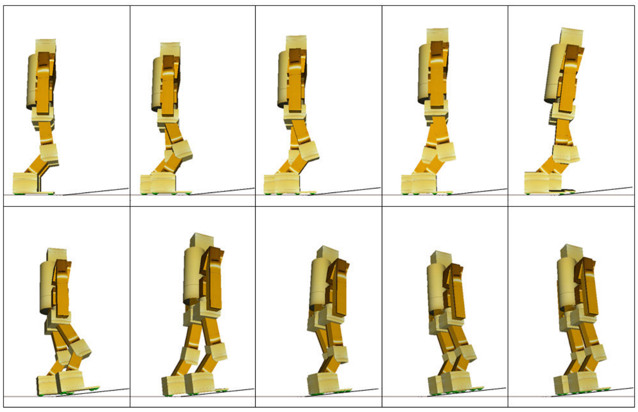
Fig. 7 The robot on the inclined plane, side views

An even surface and a plane inclined with 5.6 degrees (10% grade). Initially, the simulation starts with the robot in upright posture at a distance of 12 cm to the inclined plane. It can be observed from Fig. 6 that the robot reaches to the inclined plane after approximately 2 seconds is elapsed from the start of the walk. The $\overline{\beta}$ graph shows that the average oscillation of the upper body of the robot is small during this period. After the feet establish contact with the inclined plane $\overline{\beta}$ and

$\Gamma$ parameters start indicating an increasing activity of the pelvis pitch angle. The fuzzy parameter adaptation system acts according to the fuzzy rule base and finds the appropriate $\theta$ angle. This angle is first increased as a response to the activity $\Gamma$ and kept high due to the increasing magnitude of the average pelvis pitch angle $\overline{\beta}$. When, however, the activity in the pelvis pitch angle drops after the sixth second with the end of the walk, the $\theta$ parameter is dropped to a lower value. This value is still larger than the original value of $\theta$. This is a response of the fuzzy adaptation mechanism to the sensory observation that robot is standing on the inclined plane at the end of its walk. It can be noted from Fig. 6 that the generated curve for $\theta$ is in the form of a staircase. The side view snapshots of the robot from the simulation window are shown in Fig. 7. Simulation studies are carried out with the same control method by deactivating the fuzzy adaptation too. It is observed that the robot fails to climb onto the inclined plane and falls without the fuzzy pitch angle adaptation algorithm.

## 6. CONCLUSION

Bipedal walk on uneven surfaces is an important research area. Inclined planes are typically encountered in our living environment. This case is studied in this paper. A fuzzy logic adaptation system for the body pitch orientation angle reference generation is proposed. A novel pitch angle activity measure and the average of the body pitch angle are the inputs of the fuzzy adaptation system. The model of a 12-DOF biped walker is used in the simulations which demonstrate the performance of the adaptation algorithm under various slope conditions. Simulation results indicate that the fuzzy logic system is successful in obtaining a stable walk in the transition from a horizontal plane onto an inclined one with a slope of 5.6 degrees. Our future research is motivated into the implementation of the algorithm on our humanoid robot SURALP.

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