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Realization of Miniature Humanoid for Obstacle Avoidance with Real-Time ZMP Preview Control Used for Full-Sized Humanoid

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Abstract— **Many walking pattern generators for humanoid robots require predefined trajectories for the robot to track. This inflexibility limits the range of real-world environments that the robot can navigate through. For environments with obstacles and inconsistent terrain, the ability to change the walking trajectory becomes valuable. Using a miniature humanoid, a three-dimensional inverted pendulum model and ZMP preview control with ZMP and Foot generator were used to implement a real-time ZMP preview controller. We show the simulation results walking on obstacle field which validates that this approach can generate the all types of walking pattern based on the distance estimated based on the sensor data to the target to step without the predefined trajectory.**

I. INTRODUCTION

In the past decade, humanoid has been actively researched. The Honda ASIMO and Waseda University's WABIAN [1] are examples of humanoids that have been designed to realize human motions such as dynamic walking, running, and dancing. Many different types of humanoids have been constructed in the past decade for research including Tohoku University's MS DanseR (Mobile Smart Dance Robot) [2], and the KAIST Hubo [3].

A plethora of commercial and custom-built mini-sized humanoids have been also developed. They have been extensively used as research platforms, substituting for full-sized humanoids to reduce cost and development time. For example, Robonova-1 (manufactured by Hitec) was used to perceptually interpret music and consequently dance to the beat [4]. DARwIn [5] developed by Virginia Tech uses off-the-shelf parts and an x86 processor running real-time LabVIEW to explore artificial intelligence and cooperative behavior. Also a miniature humanoid named ATLAS [6] designed by Drexel University was implemented to walk dynamically using an algorithm based on a full-sized humanoid. Although many different types of humanoids and human motion have been implemented and realized, dynamic bipedal walking, a key ability of humanoids, is still an open problem.

Fig. 1. The miniature humanoid named Mini-Hubo developed in 2010

The most important issue in dynamic walking of humanoids is to find a stable hip trajectory. It is very difficult to define the stable hip trajectory since dynamic walking of human consists of the position and acceleration of the center of mass, as well as three different walking states. Zero Moment Point (ZMP) control, one of the most popular approaches for stable bipedal walking was proposed by Vukobratovic et al. in 1970 [7]. The definition of ZMP is a point on the ground where the equivalent moment acting on the foot is zero. With this idea many different methods for hip trajectory have been also proposed [8][9][10][11][12][13].

A common method to generate a reliable hip trajectory in [8][9][10][11][12][13] is to define the ZMP trajectory first and to combine it with the dynamics of a humanoid. This approach is already validated and used for many types of full-sized humanoids for dynamic walking.

However, to properly generate a stable hip trajectory by this idea, the ZMP typically needs to be specified a priori. A fixed ZMP trajectory limits where the next steps can be placed, affecting performance in navigation and obstacle avoidance. This restriction is critical for the humanoids to be utilized within a human environment.

To increase the pattern generator's flexibility, we employed a 3-Dimensional Linear Inverted Pendulum Model (3D-LIPM) [9] as a model of the robot's dynamics and ZMP preview control [8] was used to generate the hip trajectory. We added ZMP and Foot generator designed. By generating the ZMP trajectory as a function of the desired path, Our approach makes it possible to walk on obstacle field without any predefined path and walking trajectory.

In section II, we describe the mechanical design and system configuration of a miniature humanoid called mini-Hubo. The generic walking pattern generation algorithm based on 3D-LIPM and ZMP is explained briefly in section III. The original ZMP preview controller is demonstrated as well as the real time ZMP preview controller is described in section IV. In section V, reliable walking patterns to avoid detected obstacles are developed. These walking patterns were demonstrated at the 2010 AAAI Robotics Exhibition, demonstrating obstacle avoidance with the mini-Hubo. Conclusions is described in sections VI.

II. CONSTRUCTION OF A MINI HUMANOID ROBOT

A. *Mechanical Design*

We adapted a mini-sized humanoid robot called mini-Hubo (Fig 1) for dynamic walking. The key design considerations of the miniature humanoid are to minimize weight, have strong actuators to produce demanded forces, and centralize mass in the . Minimization of weight is most critical, because it reduces power and torque requirements to perform a given motion. The cost of adding weight is stronger (and heavier) actuators, which in turn requires larger batteries and support structure.

Our mechanical design for mini-Hubo considered these issues in implementation. The mini-Hubo' Dynamixel RX-28 digital servos are widely used in many humanoid research labs. Weighing only 72g, the servo generates 28.3 kg-cm holding torque, with adjustable control gains. The total weight of mini-Hubo is 3.0 Kg including only 550g weight of brackets. By centering the Lithium Polymer (LiPo) battery directly above the hip joint, the center of mass is balanced in the Sagittal plane.

The Mini-Hubo has 22 Degrees Of Freedom (DOF) total in its arms and legs. The six total DOF in each leg allow very similar motion to human legs. Eight ultrasonic sensors around the torso and a 320x240 pan/tilt CMOS camera in the head provide data used for obstacle avoidance.

B. *System Design*

The system architecture of mini-Hubo follows that of Hubo [3]. We utilize a FitPC for the main computer which is a small and portable computer involving Intel Atom 1.6Ghz processor. The main computer is accessed by remote control based on Window XP. Each Dynamixel servo and CMOS camera communicate with the main computer via RS-485 and USB respectively. Visual C++ and MATLAB were used as a main program to process the data and generate all trajectories for the motion of mini-Hubo.

III. WALKING PATTERN GENERATION

A. *model and ZMP equation*

One of the most popular approaches for stability of bipedal walking is the walking trajectory generation based on ZMP stability criterion [7] with robot's dynamic model. Current walking pattern generation algorithms based on the ZMP criterion generate reliable hip trajectories by solving ZMP equation with the predefined ZMP trajectory. Thus the ZMP trajectory is specified with an assumption that the ZMP is on the convex hull of the support foot, which is shown in Fig.2.

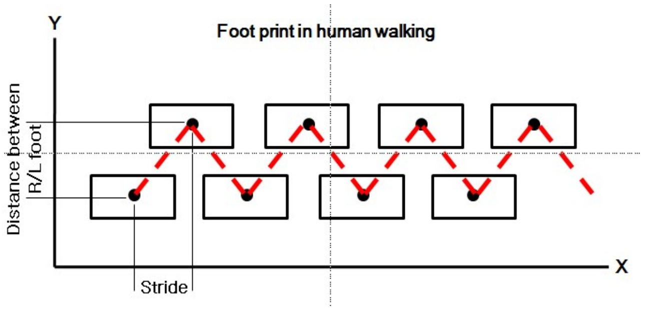

Fig. 2. Possible ZMP trajectory on each foot step

The dotted line is the ZMP trajectory by the assumption. The hip position related to the ZMP trajectory can be calculated by solving the ZMP equation. The ZMP equation is derived depending on the dynamic model of the humanoid. In [10][11], they constructed the whole dynamic equation of the humanoid regarding each joint as a point mass. In contrast, [12][13] modeled a three dimensional inverted pendulum model for the dynamics of humanoid, which simplifies the ZMP equation.

After producing the hip and foot trajectories, inverse kinematics is applied to produce each joint trajectory. However, the actual ZMP is not always placed at the position predefined since the predefined ZMP trajectory does not account for external disturbances, which cause the actual ZMP to deviate. To overcome this, many position and orientation controllers were proposed such as ZMP compensator with inertia measurement [14] and the ZMP disturbance observer controller [15].

B. *ZMP Equation based on 3D Linear Inverted Pendulum Model*

More specific dynamic equations produce better walking motion and stability with fewer controllers, but require more processing power. A simple linear inverted pendulum is employed based on ZMP criterion to minimize the computational burden. The dynamics of mini-Hubo are based on a 3D Linear Inverted Pendulum Mode (3D-LIPM) shown in Fig. 3(left). XYZ is the global Cartesian coordinate and m is a point mass. The resulting equations of motion of the pendulum model are non-linear, but can be linearized by assuming a massless bar and constant height[6][9][16] as shown below.

$$\ddot{x} = \frac{g}{z_c}x + \frac{1}{mz_c}\tau_y \tag{1}$$

$$\ddot{y} = \frac{g}{z_c}y + \frac{1}{mz_c}\tau_x \tag{2}$$

Where m is the point mass of pendulum, z_c is the height of point mass, and g is the gravitational acceleration. τ_y and τ_x are the torque around y-axis and x-axis respectively.

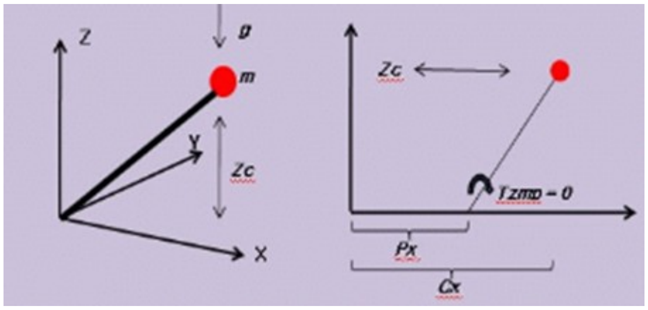

Fig. 3. Coordinate system of (left) 3D linear inverted pendulum mode, and (right) Zero moment point

(1) and (2) are linear and we can derive ZMP equation from (1) and (2) by the definition of ZMP [6][9][16].

$$p_y = c_y - \frac{z_c}{g}\ddot{c}_y \tag{3}$$

$$p_x = c_x - \frac{z_c}{g}\ddot{c}_x \tag{4}$$

Where p_x and p_y are ZMP in x-y plane and c_x and c_y are the coordinates of the point mass. Fig. 3(right) shows the definition of ZMP as an image. ZMP is defined as the point at which the equivalent point load of the foot has zero net moment. The torque generated by the reaction force due to the acceleration of the point mass is the same as the torque generated by the gravitational acceleration of the point mass. The mathematical expression is shown in (5) as below.

$$\tau_{zmp} = mg(c_x - p_x) - mc_x z_c \tag{5}$$

IV. ZMP PREVIEW CONTROLLER

The ZMP equation is derived based on 3D-LIPM in previous section [6][8][9][16]. Now we need to generate the reliable hip trajectory from the ZMP equation. The ZMP preview controller is one of the methods to produce the proper hip trajectory proposed by S. Kajita et al. [8] with the idea of previewable optimal control published in 1985 [17]. This controller requires the future reference ZMP trajectory to track current reference ZMP trajectory without the delay.

A. ZMP preview controller

[8] defined a new control input to represent ZMP equations as a state-space. The new input is a time derivative of the horizontal acceleration of the center of mass, defined in (6).

$$\frac{d}{dt}\ddot{c} = u \tag{6}$$

c is the position of the center of mass and u is the new control input. Now the ZMP equation in x direction can be transformed to state-space representation in (7).

$$\begin{aligned}
\frac{d}{dt}\begin{bmatrix} c_x \\ \dot{c}_x \\ \ddot{c}_x \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} c_x \\ \dot{c}_x \\ \ddot{c}_x \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u_x \\
p_x &= \begin{bmatrix} 1 & 0 & -\frac{z_c}{g} \end{bmatrix}\begin{bmatrix} c_x \\ \dot{c}_x \\ \ddot{c}_x \end{bmatrix}
\end{aligned} \tag{7}$$

The state-space representation for y direction can be transformed by the same manner as (7). Now (7) needs to be discretized as follow.

$$\begin{aligned}
X(k+1) &= AX(k) + Bu(k) \\
P(k) &= CX(k)
\end{aligned} \tag{8}$$

Where T is the sampling time and the discrete-time state space model for the lateral direction can be realized in the same manner. To find an optimal gain, the performance index is defined as

$$\begin{aligned}
X(k) &= \begin{bmatrix} c_x(kT) & \dot{c}_x(kT) & \ddot{c}_x(kT) \end{bmatrix}^T \\
u(k) &= u_x(kT) \\
p(k) &= p_x(kT) \\
A &= \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \\
B &= \begin{bmatrix} \frac{T^3}{6} \\ \frac{T^2}{2} \\ T \end{bmatrix} \\
C &= \begin{bmatrix} 1 & 0 & -\frac{z_c}{g} \end{bmatrix}
\end{aligned}$$

Where T is the sampling time and the discrete-time state space model for the lateral direction can be realized in the same manner. To find an optimal gain, the performance index is defined in 9

$$J = \sum_{i=k}^{\infty} Q_e e(i)^2 + \Delta X^T(i) Q_x \Delta X(i) + R\Delta u^2(i) \tag{9}$$

Where $e(i) = p(i) - p^{ref}(i)$ is the ZMP error, Q_e, $R > 0$ and Q_x is a 3x3 symmetric semi-definite matrix. $\Delta X(k) = X(k) - X(k-1)$ is the incremental state vector and $\Delta u(k) = u(k) - u(k-1)$ is the incremental input. The optimal controller to minimize (9) is given by [8].

$$u(k) = -G_i \sum_{i=0}^{k} e(k) - G_x X(k) - \sum_{j=1}^{N_L} G_p(j) p^{ref}(k+j) \tag{10}$$

Where G_i and G_x are the optimal gains of the system, and G_p is an optimal gain for previewed inputs calculated by Discrete Algebraic Riccati Equation (DARE). N_L is the size of future inputs which is the future reference ZMP trajectory. The adequate size of N_L is found in [8]. The decision of the weight, Q_e, Q_x, and R, is a straightforward work. According to [8], the appropriate values for them are $Q_e = 1.0$, $Q_x = 0$, and $R = 1.0 \times 10^{-6}$.

B. Real-Time ZMP Preview Controller

The ZMP preview controller is a walking controller to generate the reliable the hip trajectory subject to a known reference ZMP trajectory. It uses the future reference ZMP trajectory as one of the control inputs to track the current reference trajectory without delay. In other words, this controller can produce the proper hip trajectory as long as the future ZMP trajectory is given. With this idea, we add ZMP and Foot generator to produce the ZMP and foot trajectory

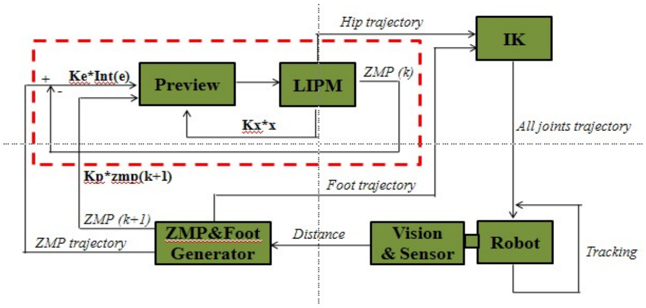

Fig. 4. The block diagram of real-time ZMP preview controller

for next foot step based on the next foot location estimated by sensor data. The block diagram of real time ZMP preview controller is shown in Fig. 4.

The dot box in Fig. 4 is the same as the ZMP preview controller but we replace the preview ZMP trajectory in the original with the ZMP trajectory from the ZMP and foot trajectory generator. Once the next foot location is defined based on the sensor data, the controller generates the hip trajectories automatically. Then inverse kinematics is applied to hip from ZMP preview controller and foot trajectories from ZMP and Foot generator to produce all joint trajectories in legs.

1) ZMP and Foot Generator: When the next foot location is determined, the distance in forward and lateral direction from a humanoid to the location can be estimated. The both distance can be regarded as the step distance in both direction. Thus ZMP and foot trajectories for both direction can be defined using the distance estimated.

Foot trajectory can be modeled directly from human walking. For human walking, the swing foot motion in the forward direction (x-direction) can be realized as a curve as seen in Fig. 5 [13]. This curve can be defined simply as a cycloid function as follows.

$$A_z(t) = h_z \sin(\frac{\pi}{S_t} t) \tag{11}$$

$$A_x(t) = S_{dx}(\frac{t}{S_t} - \frac{1}{2\pi} \sin(\frac{2\pi}{S_t} t)) \tag{12}$$

Where A_z and A_x are the ankle position in Z (upward) and X (forward) direction respectively, S_{dx} and S_t are the step distance in X direction, and step time, respectively. h_z is maximum height of the ankle. The foot trajectory in Y (lateral) direction also can be generated with the same manner in (12). Fig. 6 shows the reliable foot trajectory in forward walking with D is the step distance, S_{dx} , and T is the step time, S_t.

The ZMP trajectories can be derived from foot trajectories and foot prints in Fig. 2 since the location of ZMP is assumed to be on the center of support foot when single support phase and of right and left foot when double support phase.

V. SIMULATION

The field of the obstacle run is 4ft (width) by 8ft (length) defined in Fig. 7. The eight obstacles including 'wall' and

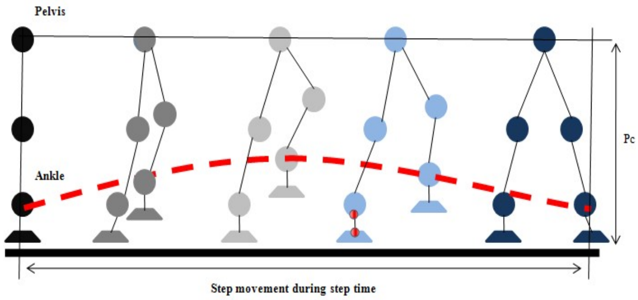

Fig. 5. The proper foot trajectory in human walking

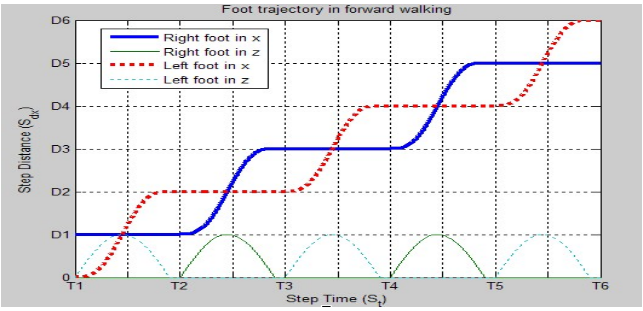

Fig. 6. Right and left foot trajectory

'step over and on' obstacles are randomly placed. To avoid 'wall' obstacles, the humanoid needs to go straight and to turn clockwise or counterclockwise. Thus we define two cases and generates the proper foot and hip trajectory using real-time ZMP preview controller.

To generate the hip trajectories using our approach, the step time and the distance between foot should be determined at first. Mini-Hubo described in Section 2 has 0.15m between each feet and a 1 second step time.

A. *Case 1 - Walking Forward*

When there is no obstacle in the immediate path, the humanoid should walk forward in steps shorter than the maximum step length (limited by the hip height). In this case there is no movement in the local Y (lateral) direction. Thus ZMP and foot trajectories only generated in the X (forward) direction.

In case 1 (Fig. 8), the robot is assumed to walk 0.15m in forward direction. Based on the location for the next step,

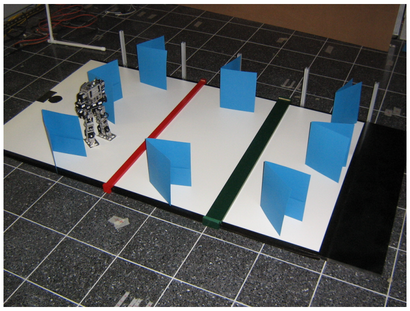

Fig. 7. Mini-Hubo on the field of obstacle run

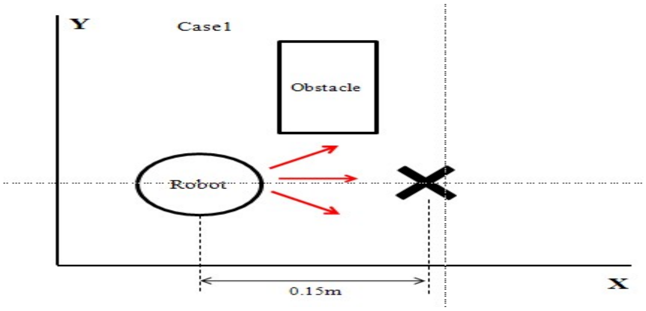

Fig. 8. The case for walking 0.15m to forward when no obstacle on the path

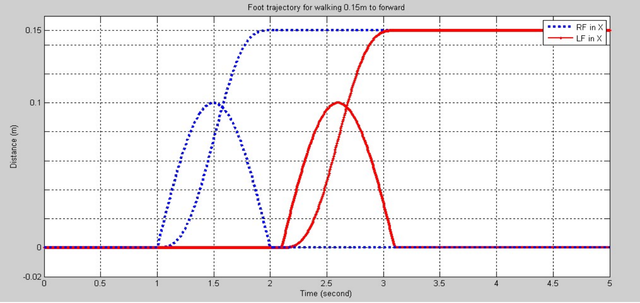

Fig. 9. Right and left foot trajectories generated from ZMP and foot generator based on the distance specified previously

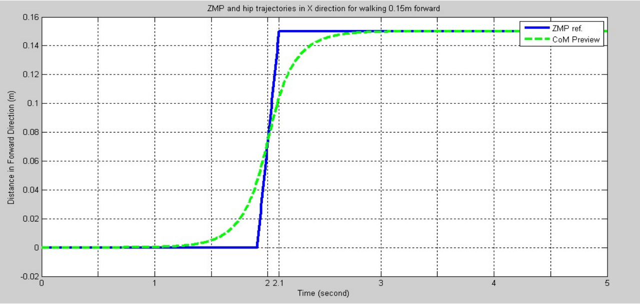

Fig. 10. The reliable hip(dot) trajectory in forward direction for 0.15m walking forward

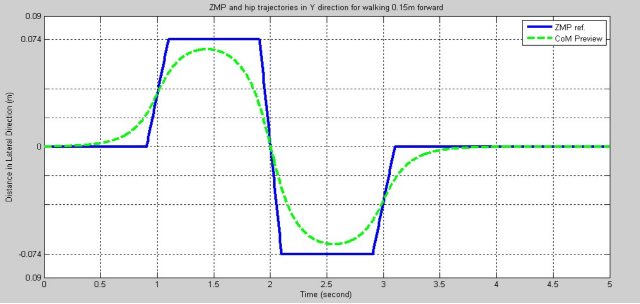

Fig. 11. The reliable hip(dot) trajectory in forward direction for 0.15m walking forward

the ZMP and Foot generator produces the foot trajectories of both foot using the step time and maximum height of foot, which was set to 0.1m previously. Fig. 9 shows both foot trajectories for a step cycle generated from ZMP and Foot generator. The dotted lines represent the right foot trajectories in X and Z (like sinusoidal) directions, on the other hand the non-dotted lines shows the left foot trajectories in X and Z direction with 1 second of step time (single support phase) and 0.1 second of double support phase.

Based on foot trajectories, the ZMP trajectories (non-dotted) in X and Y directions are defined and the proper hip trajectories (dotted) using ZMP preview controller are generated as seen in Fig. 10 and Fig. 11, respectively. According to Fig.9, Fig. 10 and Fig. 11, when the right foot is lifted at 1 second the ZMP is on the left foot which is 0.074m away from the center of standing position. Then when the right foot lands at 0.15m from the starting position the left foot is took off and the ZMP is on the right foot. Finally the left foot lands beside the right foot and the ZMP is located on the center of right and left foot.

B. Case 2 - Changing Direction

When there is an obstacle on the path, the humanoid should change the direction to avoid the obstacle. The real-time ZMP preview controller can generate the proper foot and hip trajectories whenever the distance to the location where to go is estimated. Fig. 12 shows the situation to avoid an obstacle. The target is determined based on the sensor information and the distance to the target can be estimated. In this case the humanoid should walk 0.12m to forward and 0.04m to lateral direction.

Fig. 13 shows the right and left foot trajectories in X, Y, and Z directions. All parameters are the same as used in forward walking except for the distance in X direction and movement in Y direction. The dotted lines are the motion of right foot and non-dotted lines are for left foot. The lines merging with 0.12m are both foot trajectories for walking forward and 0.08m are both foot trajectory for lateral direction. The lines like sinusoidal are for Z direction.

Also Fig. 14 and Fig. 15 show the ZMP trajectories produced based on the foot trajectories in Fig. 13, and hip trajectories by ZMP preview controller in forward and lateral direction, respectively.

Like Fig. 11, when the right foot is lifted at the standing position (1 second) the ZMP is located on the left foot. Then the right foot lands at (0.12m, 0.154m) in X and Y directions, respectively, so the ZMP is located at (0.12m, 0.154m) where is on the right foot. Lastly, the ZMP is located at (0.12m, 0.08m) where is the center of right and left foot.

VI. CONCLUSIONS

We have augmented a miniature humanoid named mini-Hubo with an improved walking controller for obstacle avoidance. It was modeled using a simple 3D linear inverted pendulum with ZMP stability criterion. For pattern generation, we employed the ZMP preview controller with ZMP and Foot generator. Based on the sensing data, the distance

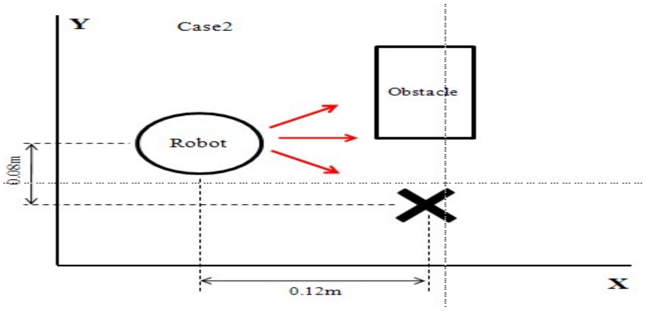

Fig. 12. The case for turn to avoid an obstacle

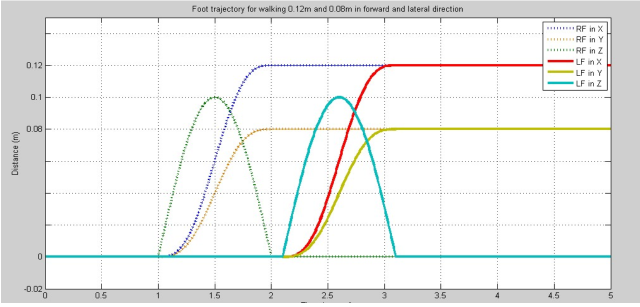

Fig. 13. Right and left foot trajectories for moving to (0.154m, 0.08m) in X and Y direction, respectively

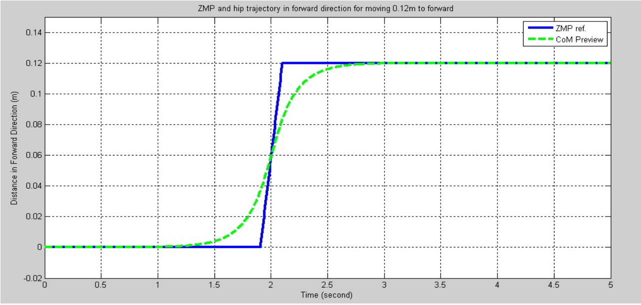

Fig. 14. The reliable hip(dot) trajectory in x (forward) direction for moving 0.12m in X direction

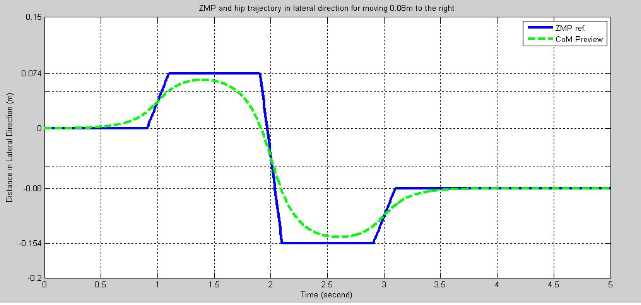

Fig. 15. The reliable hip(dot) trajectory in y (lateral) direction for moving -0.08m in Y direction

to the target can be estimated. The ZMP and Foot trajectory generators produced reliable trajectories for the next step. The future desired ZMP trajectory is used as an input of ZMP preview controller, with which the controller generates the proper hip trajectories for the next step.

We showed two simulation results on a flat obstacle field, showing promise for future endeavors into more complex environments. Ongoing research on dynamic model and pattern generation will help reduce the gap between reality and simulation. The final goal of our project is to show that the humanoid can adjust its walking pattern in a general environment without falling down.

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