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Humanoid Robot Locomotion Control based on Perceptive Model

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***Abstract* - A humanoid locomotion control method with human-like perceptive model is described in this paper. Traditionally the locomotion problem of biped robot is divided into temporal periodic gait generation and real-time stabilizing control. However due to unmeasurable accumulated errors from simplified dynamic model and other uncertain disturbances, the spatial and temporal deviation from the motion plans askes for a new perceptive locomotion planning and control system which is decoupled with time, rather than adhering to a rigid time schedule regardless of current dynamic balance state. This method also gives the right of interpretation of non-time motion plan of gait to the motion control layer based on a designed perceptive reference, which is directly ensure dynamic balancing and high response rate to the errors. The simulation and experiment on a full-size humanoid robot show the success of the method.**

I. Introduction

Compared with wheeled robots, the humanoid robot is expected to pass through cluttered and uneven environments. The ability to swiftly and robustly keep balanced while walking under unknown environments and unexpected disturbances is a critical need. This goal is even more challenging because the humanoid walking robot is impulsive hybrid nonlinear dynamic system, whose rich dynamics needs the guarantee of dynamic balance at every moment of whole body motions and has to be simplified with unpleasant accumulated model errors.

Traditionally the humanoid locomotion is treated as a temporal periodic process and real-time balance controllers would try their best to meet the assumptions of a planned gait. However due to errors from internal simplified dynamic model or sensors and external unexpected disturbances or contacts, the time-based reference trajectories in gait ought to be modified really frequently to fit the deviation perfectly. Nevertheless, considering the smoothness of the motion and the limited computation resource, the modifications of time-based trajectories are mostly suggested to exist only at the intervals of the steps [1] [2], which limits its robustness and adaptability. Also in many cases, directly specifying the relationship of time and motion evolution is over-constrained and structurally destabilizes the stability of the system. Obviously humans perform better at keeping balance at such conditions. Therefore, our goal is to propose a locomotion planning and control method decoupled from time, which synchronizes different parts of the humanoid robot with a perceptive reference and takes advantages of some human-like motion generation principles that is believed to provide biological system robust and adaptive balance ability while walking as in the Fig.1.

Findings from neurobiology [3] indicated human gait does not exactly repeat a single cycle, instead, it tends to show different yet homologous patterns with relationship to each step's current balance situation and the person's physical ability and etc. A series of observations [4] of passive biped robot walking also verifies this, which also question the temporal cycle assumption on the humanoid walking. This paper therefore proposes a method where the reference stepping motion is generated continuously based on sensory balance information, rather than planning the reference trajectories as functions of time. In this case, the perceptive motion plan incorporates the gait and the intrinsic sensory information, which relaxes such strict time-dependence and makes the robot robust against unexpected disturbances.

The humanoid robot used in this paper is developed with THORMANG3 as a prototype at the Shen Zhen Robotics Academy as in Fig. 2. It weighs about 39.8 kg and is about 137.5 cm tall and has 29 actuated degrees of freedom. All joints are driven by brushless motors with absolute angular sensors. In each foot, six-axis force/ torque sensors (FTS) are equipped. Additionally, an Inertial Measurement Unit (IMU) is installed near the CoM. Also the sponge mats are added at the contact surfaces of the feet to absorb part of the strike when the foot is landing.

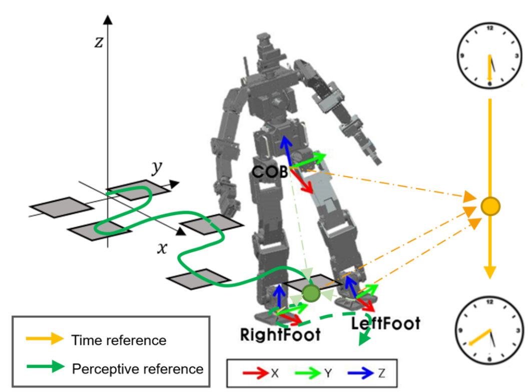

Fig. 1. **Synchronization Between Motions of Feet and Center of Body (CoB) via Time or Perceptive Reference.** Time increases evenly regardless of anything, but the perceptive reference carries sensory balance-related information and increases or stop continuously based on locomotion situations.

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The rest of the paper would be organized as follows. In Section II a brief overview of related work would be shown. The detailed definitions and content of perceptive gait planning would be shown in Section III. The control of perceptive gait plan is presented in Section IV. And the simulation and experiment result of proposed method are shown in Section V. Section VI concludes this paper and state future works.

Fig. 2. The full-size humanoid robot with 29 DoFs

II. Related Work

Mostly a stable locomotion of humanoid robot is realized by reference motion trajectories of limbs with closed-loop controllers to provide real-time modifications [5-7]. The analytic relationship of center of mass (CoM) trajectory and desired ground reference point, such as zero moment point (ZMP), trajectory is based on simplified robot dynamic model. And the dynamic balance of the robot is ensured when the support polygon, which is provided by landed feet or single foot, includes the current ZMP. So a continuous proper synchronization of motions between the legs (feet) and torso is the key to make sure the balance. In a well-known environment, many successful gait planning algorithm use time as the intermedia to realize the synchronization [8-10], however it cannot efficiently deal with the unexpected temporal advance or lag progress of one of motion trajectories. This situation can probably happen in an unknown environment when earlier or later foot contacts exit because of the uneven terrain or position deviation of real ZMP because of accumulated error caused by simplified dynamic model. It would be better to use sensory information instead of time as the intermedia of synchronization of the gait planning.

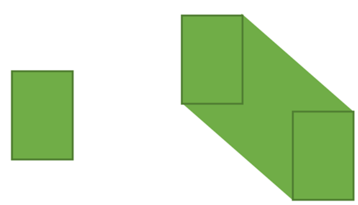
Several research also realizes this and utilizes sensory information in legged gait planning and control feedback [11-13] to stabilize the system. Based on the neurobiology knowledge, gait phase of a neural oscillator would be reset as soon as ground contact of the swing leg is detected. This would improve the stability of a central pattern generators (CPG) controlled stability of a walking robot. However, the event-based phase switching mechanisms widely used in legged robots [14-18] only use sensor information discretely by defining some "event-based" waking phase transition triggers which mainly solves early or late contacts and still adopt temporal periodicity framework. Others would rapidly regenerate the reference trajectories with walking cycle duration modification [5][6],

In this work, the locomotion plan is continuously associated with the balance-related sensory reference, which directly and fundamentally ensures the dynamic balance is ensured in the perceptive locomotion plan. Then the execution of the locomotion plan is continuously based on real-time sensed perceptive reference, which reflects actual balance spatial status affected by unmeasurable errors and uncertain disturbances, instead of time-based reference, which just keeps increasing evenly.

III. Perceptive Gait Planning

A. Perceptive Motion Reference

Instead of the time, it is necessary to consider the nature of the system and the objectives of the relevant tasks to properly design the perceptive reference [19]. The main goal of the biped walking mission is dynamic balancing, which can be ensured by many ground reference points [20] With the corresponding balance standards. In this paper, a ZMP-based balance criterion is chosen, which means that the biped can be dynamically balanced as long as the ZMP remains within the supporting polygon (SP) as in Fig. 3 [21]. As a substitute for time, the selected perceptive motion reference must be a one-dimensional monotonically increasing independent variable [19], so the horizontal position of ZMP- (p_x, p_y) is chosen to calculate the perceptive reference-ZMP in its reference path - s. In the real-time closed loop process, the actual ZMP will always deviate from the reference path due to external disturbances, internal models, hardware or other errors. In order to calculate the optimal s^* with the smallest ZMP position error from the actual value on the ZMP reference path to the desired value, an orthogonal projection of the actual ZMP to the reference ZMP path is performed, and the projection ZMP on the path can uniquely determine the value of the. Under any condition. Furthermore, the best motion reference is updated only when the travel distance of the projected ZMP is greater than the previous distance, thereby ensuring its monotonous increase.



(a) Single support foot (b) Double support feet

Fig. 3. Support Polygon (green area) of Humanoid robot when the robot is supported by single foot (a) or by double feet (b)

For limbs such as the foot and CoM, there is a correspondingly defined perceptive motion reference, such as the distance traveled by the left foot, right foot or CoM on its reference path - s_{lf}, s_{rf}, s_{CoM}, which are related with s by the appropriate transfer function to ensure the ZMP balance criterion. In this way, key the balance information is passed to each limbs and CoM planner for a coordinated locomotion. The details will be discussed in the chapter C Perceptive Task, Trajectory Planning.

B. Dynamic Model and balance criteria

The dynamic motion of the linear inverted pendulum model (LIPM) in Cartesian right-hand coordinates (Fig. 4) can be described as (1) and (2) using the $(\tau_x, \tau_y, \mathrm{F})$ inputs generated by the leg actuators.

$$m(-z_0\ddot{y}_0 + y_0\ddot{z}_0) = \tau_x - mgy_0 \tag{1}$$

$$m(z_0\ddot{x}_0 - x_0\ddot{z}_0) = \tau_y - mgx_0 \tag{2}$$

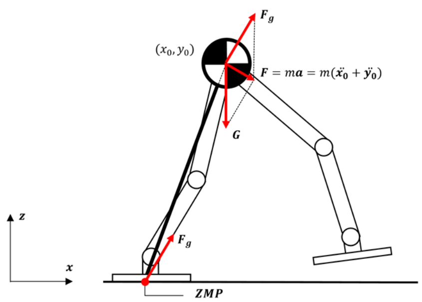


Fig. 4. Inverted linear pendulum model and ZMP

In the next chapter, when referring to the constraint - $z_0 = k_1x_0 + k_2y_0 + z_c$ associated with biped walking, you can rewrite (1) and (2) as:

$$\ddot{x}_0 = \frac{g}{z_c}x_0 - \frac{k_y}{z_c}(x_0\ddot{y}_0 - \ddot{x}_0y_0) + \frac{\tau_y}{mz_c} \tag{3}$$

$$\ddot{y}_0 = \frac{g}{z_c}y_0 - \frac{k_x}{z_c}(x_0\ddot{y}_0 - \ddot{x}_0y_0) - \frac{\tau_x}{mz_c} \tag{4}$$

Where g is the gravitational acceleration and τ_x, τ_y represents the torque around the x and y axes. On the other hand, the original definition of ZMP - $\vec{r_i}\,(p_x, p_y)$ is the point on the ground/contact surface about which the horizontal component of the moment of ground/contact surface reaction force [19] and inertial [20] - $\vec{\tau}_{inertia+gravity}$ is zero as:

$$\vec{\tau}_{inertia+gravity}(\overrightarrow{r_{zmp}})|_{horizontal} = 0 \tag{5}$$

Given the mass distribution of whole body kinematics and humanoid robots, the definition of zero moment point (ZMP) can be described by equation (1) - detailed description is:

$$\sum_{i=1}^{N}\left[(\vec{r_i} - \overrightarrow{r_{zmp}}) \times m_i\vec{a_i} + \frac{d(\rightrightarrows I_i\overrightarrow{\omega_i})}{dt}\right]_{horizontal} = [(\overrightarrow{r_{CoM}} - \overrightarrow{r_{zmp}}) \times m\vec{g}]_{horizontal} \tag{6}$$

Where $\overrightarrow{r_{CoM}}$ is CoM, m is the total mass, $\vec{r_i}$ is the ith link, m_i is the mass of the ith link, $\vec{a_i}$ is the linear acceleration of the ith link, and I_i is the ith link for the inertial tensor link CoM , $\overrightarrow{\omega_i}$ is the angular velocity of the ith link.

$$p_x = x_0 - \frac{z_c}{g+\ddot{z}_0}\ddot{x}_0 - \frac{\tau_y}{m(g+\ddot{z}_0)} \tag{7}$$

$$p_y = y_0 - \frac{z_c}{g+\ddot{z}_0}\ddot{y}_0 - \frac{\tau_x}{m(g+\ddot{z}_0)} \tag{8}$$

Considering that LIPM cannot represent the torque about CoM, and most of it is reduced by the ankle balancer, so τ_x and τ_y are set to zero. For now, ZMP can be described as (5), (6).

$$p_x = x_0 - \frac{z_c}{g+\ddot{z}_0}\ddot{x}_0 \tag{9}$$

$$p_y = y_0 - \frac{z_c}{g+\ddot{z}_0}\ddot{y}_0 \tag{10}$$

C. Perceptive Task, Trajectory Planning

First, the walking mission can be planned as a series of walking modules in the task level. The length of the sequence is the number of steps. And each of its elements contains a class object with 5 members: step type as in the Fig. 5, step direction, steering angle, step size, step size. Please note that the complete and valid part of the walking mission sequence must follow the following principles according to the person's gait pattern.

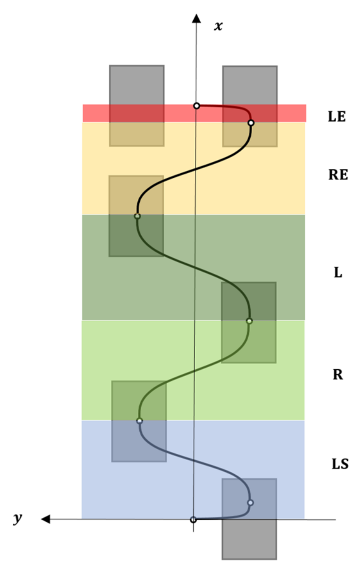


Fig. 5. **Path planning of reference ZMP (black curves) for 5 steps.** 7 points are marked as knots for 5 kinds of walking modules: LS left foot swing starts, L left foot swings, R right foot swings, LE left foot swings to the end, RE right foot swings to the end)

In the effective order, only one direction can be selected. For the selected step, such as forward, backward, left or right: the complete and effective gait planning must start with LS, the last two lines are LE, then RE. In the middle of the ZMP reference path, R and L alternate, and R is the start and end of the sequence of the middle part of the walk task module. For the selected step direction, such as "Left": R and L must alternate, and L will be the beginning and end of the entire sequence of walking task modules. Instead, for the selected step direction, such as "right": R and L must alternate, and R will be the start and end of the entire sequence of walking task modules. The order of the walking task modules. As a basic guarantee for smooth motion of the limbs, the main consideration for reference to the ZMP path $-p_y$ is its smoothness. Therefore, p_y consists of segments of the fifth-order polynomial function of the ZMP value on the x-axis, consisting of - p_x, and the start nd end conditions for each segment are:

$$
\begin{aligned}
p_y &= f_i(p_x) \\
&= a_{0i} + a_{1i}(p_x - p_{x0i}) + a_{2i}(p_x - p_{x0i})^2 + a_{3i}(p_x - p_{x0i})^3 \\
&\quad + a_{4i}(p_x - p_{x0i})^4 + a_{5i}(p_x - p_{x0i})^5
\end{aligned}
$$

$$
s.t.\quad \begin{cases} p_y(p_{x0i}) = p_{y0i},\ p_y(p_{xei}) = p_{yei} \\ \dot{p_y}(p_{x0i}) = \dot{p_{y0i}},\ \dot{p_y}(p_{xei}) = \dot{p_{yei}} \\ \ddot{p_y}(p_{x0i}) = \ddot{p_{y0i}},\ \ddot{p_y}(p_{xei}) = \ddot{p_{yei}} \end{cases} \tag{11}
$$

Based on the above equations, the parameters can be solved as:

$$
\begin{cases} a_{0i} = p_{y0i} \\ a_{1i} = \dot{p_{y0i}} \\ a_{2i} = \frac{1}{2}\ddot{p_{y0i}} \\ a_{3i} = \frac{1}{2T^3}\left[20h - \left(8\dot{p_{yei}} + 12\dot{p_{y0i}}\right)T - \left(3\ddot{p_{y0i}} - \ddot{p_{yei}}\right)T^2\right] \\ a_{4i} = \frac{1}{2T^4}\left[-30h - \left(14\dot{p_{yei}} + 16\dot{p_{y0i}}\right)T + \left(3\ddot{p_{y0i}} - 2\ddot{p_{yei}}\right)T^2\right] \\ a_{5i} = \frac{1}{2T^5}\left[12h - 6\left(\dot{p_{yei}} + \dot{p_{y0i}}\right)T + \left(\ddot{p_{y0i}} - \ddot{p_{yei}}\right)T^2\right] \end{cases} \tag{12}
$$

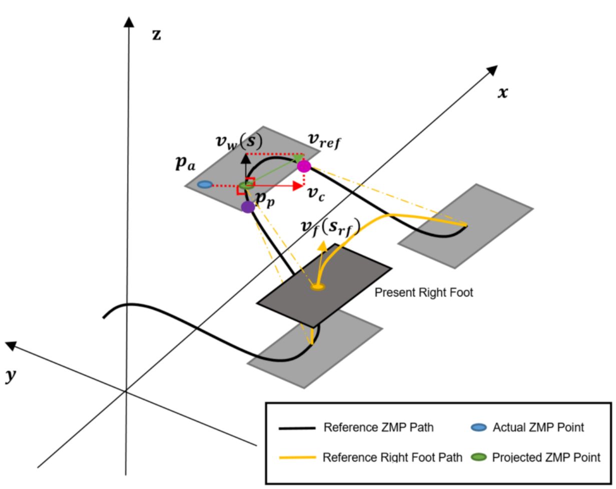


Fig. 6. **Trajectory planning of ZMP and feet.** The purple and pink points mark the positions where the reference ZMP path enters and leaves the left single-foot support polygon respectively.

i is the number of the path segment, and the path of the limb (such as the foot path) is planned according to the details of the task. The CoM path will be calculated in real time while walking so that the actual ZMP tracks the ZMP reference path, which will be discussed later in Section IV. Fig. 5 shows an example of a ZMP reference path for a walking task sequence comprising 5 steps.

After ZMP path is planned as in Fig. 5, only portions of the ZMP reference path in the footprint (grey regions in Fig.4) own mappings to the corresponding foot perceptive reference and its motion path. Such as the right foot's motion path as yellow line in Fig. 6, the right foot begins to swing when the projected ZMP - p_p enters the grey footprint on the left. The perceptive reference of right foot $s_{rf} = (s - s_{si})/(s_{ei} - s_{si})$ where s_{si} and s_{ei} correspond to the ZMP traveled distance at purple and pink points in Fig. 6 at ith step. Then, according to the fifth-order polynomial path planning in (11), (12) and trajectory planning in (16), the reference path and trajectories of feet are planned.

Then, ZMP, limb and CoM trajectory planning will be done in real time. For ZMP, its reference velocity along the path direction -v_{ref} consists of two parts as in (13) and Fig. 6. The first velocity portion is to ensure that the ZMP moves along the reference ZMP path, the value of which is also determined by the expected walking speed, which then is calculated by the step duration D_s and step length l_s as shown in Fig. 7, using a perceptive time optimal plan [21]. In fact, other optimal objectives for trajectory planning can also be used here. The second speed portion is to ensure the actual ZMP track the reference path of ZMP by approaching the corresponding projected (expected) ZMP-p_p.

$$\boldsymbol{v_{ref}} = \boldsymbol{v_w}(\mathbf{s}) + \boldsymbol{v_c} \tag{13}$$

$$\boldsymbol{v_c} = k_c * (\boldsymbol{p_p} - \boldsymbol{p_a}) \tag{14}$$

$$e_p = |\boldsymbol{v_{ref}} * T_c\,| \tag{15}$$

$$
v_w(s') = \begin{cases} (u_m {s_p}'^2 - 2u_m s_0 {s_p}' + u_m {s_0}^2)^{1/2} & s_{0i} \le {s_p}' \le s_1 \\ (2a_m {s_p}' + u_m {s_1}^2 - 2u_m s_0 s_1 + u_m {s_0}^2 - 2a_m s_1)^{1/2} & s_1 < {s_p}' \le s_2 \\ (-v_m {s_p}'^2 + 2u_m s_3 {s_p}' + {v_m}^2 - u_m {s_3}^2)^{1/2} & s_2 < {s_p}' \le s_3 \\ v_m\ (set\ as\ k_s \cdot D_s/l_s) & s_3 < {s_p}' \le s_4 \\ (-v_m {s_p}'^2 + 2u_m s_4 {s_p}' + {v_m}^2 - u_m {s_4}^2)^{1/2} & s_4 < {s_p}' \le s_5 \\ (-2a_m {s_p}' + 2a_m s_5 - u_m {s_5}^2 + 2u_m s_4 {s_5}^2 + {v_m}^2 - {v_m}^2 {s_4}^2)^{1/2} & s_5 < {s_p}' \le s_6 \\ (u_m {s_p}'^2 - 2u_m s_0 {s_p}' + u_m {s_0}^2)^{1/2} & s_6 < {s_p}' \le s_{ei} \end{cases} \tag{16}
$$

In Fig. 7, the s_{0i} and s_{ei} correspond to the start and end points of the ith segment of the ZMP reference path (i= 1,...,N, N is the number of steps in the walking task); s'= s -s_{0i}; l_s and D_s represent the expected step size and expected duration required by the user command; u_{m}, a_{m} *and* v_{m} are the maximum value of the jerk, acceleration and velocity (set as $5\ \mathrm{m}/s^3$, $0.5\ \mathrm{m}/s^2$, $k_s \cdot D_s/l_s$; k_c and k_s are constant values and can be adjustable; T_c is the control cycle of the system (0.0008s in our system); e_{ZMP} means the error of the ZMP in the present control loop; $p_p(p_{px}, p_{py})$ and $p_a(p_{ax}, p_{ay})$ stand for the projected ZMP and actual ZMP respectively. Based on (14) and ZMP reference path $p_y = f_i(p_x)$, v_w would be pointing to the tangent direction of the reference ZMP path at p_p.

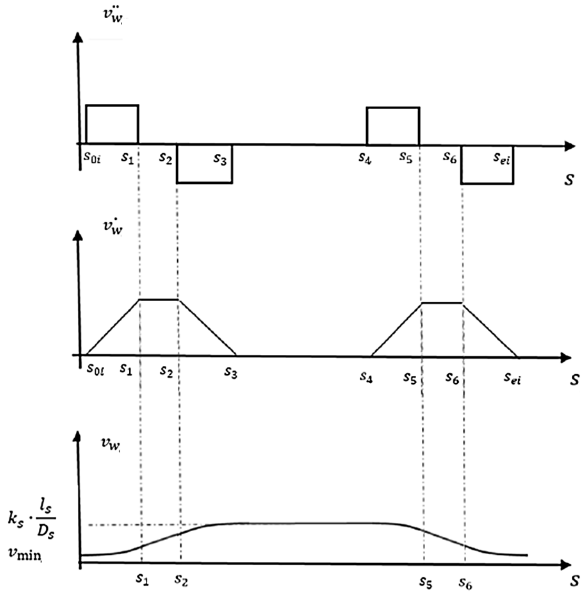


Fig. 7 Walking velocity $\boldsymbol{v_w}$ and foot velocity $\boldsymbol{v_f}$ (when $v_{\min} = 0$ and $\boldsymbol{s}$ is replaced by $\boldsymbol{s_{rf}}/\ \boldsymbol{s_{lf}}$) perceptive planning

IV. Perceptive Gait Controllers

A. CoM Controllers

In order to ensure that the actual ZMP stably and correctly tracks the reference ZMP path, two points need to be ensured: i) At any time, the ZMP position remains within the supporting polygon (SP), so that the dynamic balance of the biped robot can be ensured. ii) The actual ZMP moves at the desired speed.

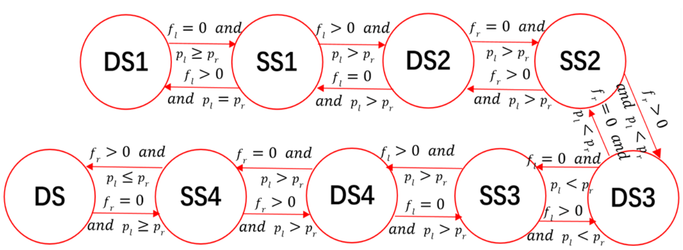
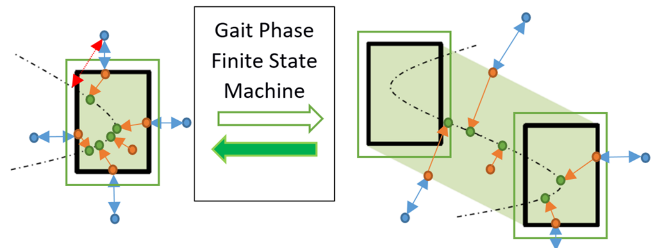


Fig. 8. Gait phase finite state machine based on sensory information

To realize the first point, the range of support polygon (SP) at any moment during a gait is a necessity. One of the vital message the time-based reference can provide is accordingly present SP area with a given time. As the time-based reference is replaced, so the real-time spatial knowledge of the SP is now provided by a gait phase finite state machine. Take four steps walking as an example, there are nine states of SP that correspond to nine gait phases: DS1 (short for "double support phase for first step"), SS1 (short for" single support phase for first step"), DS2, SS2, DS3, SS3, DS4, SS4, DS (short for "double support phase as the end"). And the feet's relative positions (p_l - position on x axis of left foot, p_r - position on x axis of right foot) and forces (f_l – force on z axis of left foot, f_r - force on z axis of right foot) would form the events as state transition triggers of the mentioned nine states as in Fig. 8.



(a) Single support foot (b) Double support foot

Fig. 9. The projection of ZMP based on current support polygon

It then instructs the real-time planner to find the appropriate projected ZMP on the planned path in current SP as the desired ZMP by the two-steps orthogonal projections with the edge of the SP and the reference path shown in Fig. 9. (The blue point is the actual ZMP, the orange point is the intermediate projected ZMP, and the green point is the projected ZMP - p_p).

Finally the desired position of CoM (x_0, y_0) is then calculated based on $p_a(p_{ax}, p_{ay})$, $v_{ref}(v_{refx}, v_{refy})$, T_c and current acceleration of CoM ($\ddot{x}_0, \ddot{y}_0, \ddot{z}_0$) by:

$$x_0 = \frac{z_c}{g+\ddot{z}_0}\ddot{x}_0 + (p_{ax} + v_{refx} * T_c) \quad (17)$$

$$y_0 = \frac{z_c}{g+\ddot{z}_0}\ddot{y}_0 + (p_{ay} + v_{refy} * T_c) \quad (18)$$

B. Feet Controllers

Since the foot plays an important role in the balance criterion as it directly creates the supporting polygon area, their trajectories are now based on their perceptive references - $s_{lf}, s_{rf} \in [0,1]$, which are mapped by design from a specific segment of the ZMP reference path to the foot perceptive reference path (yellow line in Fig. 7) which fundamentally ensures that if only the actual ZMP enters the support surface, it transitions from double support (DS) to single support (SS).

On the other hand, in order to smoothly land without any avoidable disturbances on uneven terrains. The mentioned perceptive control swing the leg to the planned footprint smoothly and stably when f_z is about zero. The contact force on the z-axis - f_z determines each foot's mode between 3 settings as Table 1. The damping control would reduce the bouncing back when the $f_z \in (0, 150\text{N}]$. $f_z > 150\text{N}$ is regarded as the landing is finished, so the foot begins supporting the body with desired supporting force based on present gait phase and using ankle PD controllers for ZMP tracking based on the ZMP error from the perceptive model as (15).

Table 1. Three modes of perceptive foot control

Foot's	Swing mode	Landing mode	Support mode
Position	Perceptive Control	Damping Control	Force Control
Orientation	Parallel to the ground	Damping Control	Perceptive Control

V. SIMULATION AND EXPERIMENT

The testing of perceptive planning and control system of humanoid robot walking task would be divided into two parts. Firstly, a 4-step locomotion test without external disturbance is conducted with 1s step duration and 0.1 m step length would be conducted in the simulation, which would validate proposed method feasibility. Then an unexpected disturbance would be added to the same locomotion test in both simulation and experiment its robustness.

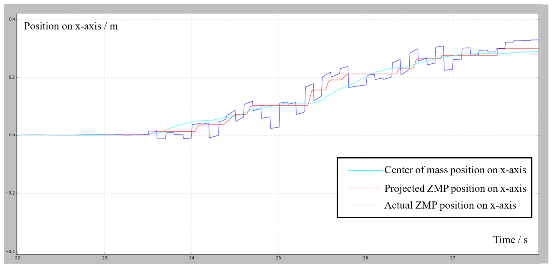


Fig. 10. Actual ZMP, projected ZMP and CoM position on x-axis with perceptive model

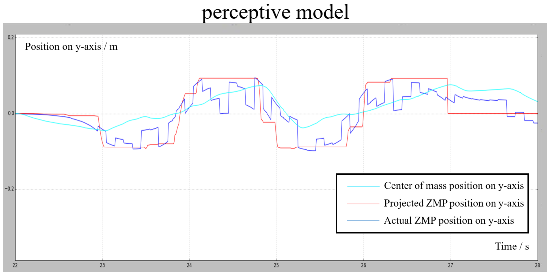
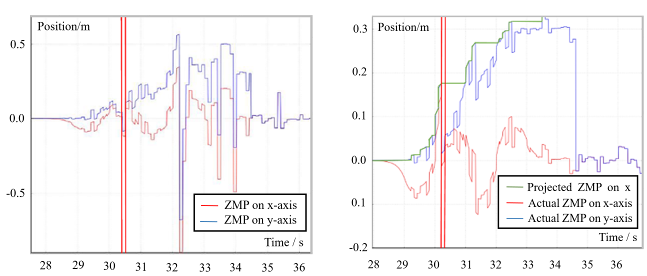


Fig. 11. Actual ZMP, projected ZMP and CoM position on y-axis with perceptive model

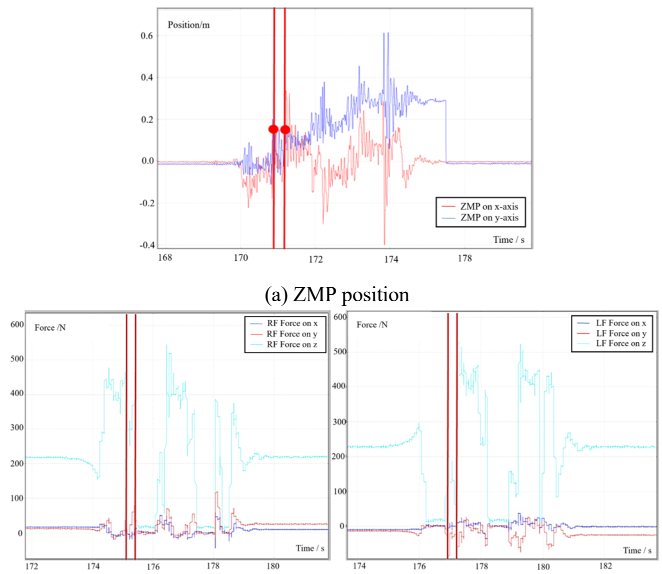
As the first test, the perceptive planning and control model is used for 4 steps locomotion. The actual ZMP, projected ZMP and CoM positions are recorded in blue, red and light blue in Fig. 10 and Fig. 11. Without any external disturbances, the average walking speed is 0.085 m/s, which is close to expected 0.1 m/s. The method successfully ensures the dynamic balance with internal accumulated errors of CoM position caused by simplified dynamic model.



(a)Time based model ZMP position (b) Perceptive model ZMP position

Fig. 12. The locomotion simulation comparison between time-based and perceptive one

Secondly, both time-based planning and control model and perceptive planning and control model would be disturbed with a temporal block at a random moment. In the simulation, a movable wall was placed to block the robot at the beginning at the second step and removed as the robot hit the wall. As the block happens between two vertical lines in Fig. 12 (a), the time based planning leg keeps pushing, which causes ZMP leaving the support polygon and the robot failing in about 1.5s at 32s in Fig. 12 (a). In contrast, the perceptive planning and control model pause about half second at 17s to 18s in Fig. 12 (b) due to the stop of perceptive reference, which doesn't cause bigger deviation of ZMP and give extra time to ankle ZMP controller to eliminate unexpected ZMP errors caused by the block. When the actual ZMP was controlled back to the planned path, the rest of the gait is successfully finished.



(a) ZMP position

(b) Right foot force (c) Left foot force

Fig. 13 The locomotion experiment on real robot with perceptive model

In the experiment, the robot is asked to walk four steps with 1s step duration and 0.1m step length with perceptive planning can control method, and was also temporally blocked by an inverse push while walking. This time, the inverse push happened in the end of the first step when the right foot was about to lift up. However, as the increase of perceptive reference, which is the ZMP traveled distance on the path, is delayed, so the right foot's lift up motion was also delayed so that the right foot could support the body longer and left foot starts supporting the body later between red lines in (b) and (c) of Fig. 13 till the ZMP recovered to the point just before the push (two red points in (a) of Fig. 13).

VI. CONCLUSION AND DISCUSSION

Both simulation and experiments on real robot indicate that perceptive locomotion model can generate stable, robust but unique gait each time, which can handle unexpected block on its way while the robot is walking. The main contribution of the paper is eliminating strong temporal constraints of humanoid gait planning and control with a perceptive locomotion model. When using this, the sensor accuracy must be ensured by other ways to provide a reliable perceptive reference for the whole gait planning and control. In the future, the arm and waist would be added into the perceptive gait planning and control to resist bigger disturbances and realize whole body perceptive control.

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