Online Biped Walking Pattern Generation for Humanoid Robot KHR-3(KAIST Humanoid Robot – 3: HUBO)

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Abstract - **This paper describes an algorithm about online walking pattern generation method, sensory feedback controllers for walking of humanoid robot platform KHR-3 (KAIST Humanoid Robot – 3: HUBO) and experimental results. The walking pattern trajectories have continuity, smoothness in varying walking period and stride, and it has simple mathematical form which can be implemented easily.**

The gait trajectory algorithm is composed of two kinds of function trajectory. The first one is cycloid function which is used for ankle position in Cartesian coordinate space. Because this profile is made by superposition of linear and sinusoidal function, which has a property of slow start, fast moving, and slow stop. This characteristics can reduce the over drive at high speed motion of the actuator. The second one is 3rd order polynomial function. It is continuous in the defined time interval, easy to use when the boundary condition is well defined, and has standard values of coefficients when the time scale is normalized. Position and velocity values are used for its boundary condition. F/T (Force and Torque) sensors at the ankles of the robot and accelerometers at soles are used to compensate the input position profiles (in joint angle space and Cartesian coordinate space) for keeping its dynamic balance. They are to reduce unexpected external forces such as landing shock, and vibration induced by compliances of the F/T sensor structures, link frames and reduction gears, because they can affect seriously on the walking stability. We use real-time controllers such as ZMP (Zero Moment Point), vibration reduction, landing orientation, damping, landing timing and landing position controller according to its objectives. This trajectory and control algorithm is implemented for the free-walking of KHR-3.

Index Terms - HUBO, Humanoid, Biped walking, Walking pattern generation

I. INTRODUCTION

There are three kinds of approaches in realization of biped walking, which are offline pattern generation, offline pattern generation with online feedback compensation, and online pattern generation with online feedback control.[1][2] The first one is to generate the walking patterns after designing ZMP trajectories based on the precise knowledge of the system such as the moment of inertia, masses of each part. This approach can get the stable walking patterns, but it can make the robot to fall down easily, because it is sensitive to the unmodeled or unknown factors of the system such as reaction and friction forces with the ground. The walking pattern itself is stable, but we should calculate complicated ZMP dynamics to get the walking pattern. The second one is to overcome the stability and the robustness problems. This approach uses ZMP based walking patterns and compensates them to keep the balance by feedback. It can increase, using feedback controller, the walking stability of the robot by reducing the instability factors induced by unmodeled dynamics, ground conditions and etc., but the complexity of stable walking pattern generation still remains. We used the third approach in this paper. The online walking pattern is generated by the kinematical approach by generating the position commands of the joint. It is made by observing the human's behaviour, and modified by sensory feedback controllers to keep the walking stability. This means we divided the walking patterns into kinematic reference generation and dynamic controller.[3][4]

We used sine, cosine, linear functions, 3rd order polynomial and their superposition as the basic trajectories of the robot. The functions of the trajectories are 3rd order polynomial interpolation for the pelvis centre, cosine function for the height and left–right position of the foot, and cycloid function for the forward-backward position of the foot. We are now upgrading the walking pattern, which can make the robot change its step time and stride without stopping. The position curves of the pelvis centre are calculated with respect to the boundary conditions(position and velocity) at the start and at the end of the step, because they use 3rd order polynomial interpolation. We can adjust the shape of the curve by selecting the proper boundary condition values by considering the walking modes (forward, backward and side walk), frequency and stride, which can be the inputs from the operator or from the navigation algorithm.[4]

The feedback controllers used in this paper are named to ZMP, landing orientation, landing position, landing timing, damping and vibration reduction controller on the point of their objectives and functions. They used the F/T sensor on the ankle and the accelerometer on the sole, and they were well implemented on KHR-1, KHR-2, KHR-3(HUBO) [5][6][7] to keep the robot's stability in the fixed step time and stride walking condition. We are using the controller switching method with respect to the timing, and the phase of the walk. This means that we are applying the different controllers with different situation. This method can be a good approach in the condition of fixed step time and stride. We expanded this approach to the variable step time and stride condition during walking in this paper.

II. Overview of the Platform: KHR-3(HUBO)

KHR-3(HUBO) is a biped humanoid robot which has 41 DOF (12-DOF in leg, 8-DOF in arm, 6-DOF in head, 14-DOF in hand and 1-DOF in trunk), 125cm height, 55Kg weight. Pentium III-933MHz embedded PC is equipped as a main controller and its OS (Operating system) is Windows XP and RTX (Real Time Extension). We developed servo controller which has 400W power capacity, for each joint motor position control. There are two CCD cameras in the head, F/T sensors on the ankles and wrists, accelerometers on the soles, and inertial sensor system on the torso. We use distributed controller architecture, which is connected by CAN (Controller Area Network) communication between servo controllers, sensors, and main controller. This made us to maintain and expand the system easily. DC motor and harmonic drive reduction gear mechanism is attached as an actuator for the joint. We optimized the reduction ratio and motor specification for the joints.

Fig. 1 KAIST Humanoid robot 3 (KHR-3: HUBO)

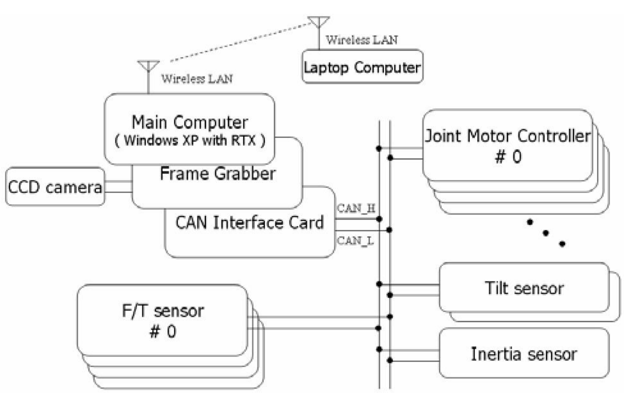


Fig. 2 Hardware system architecture

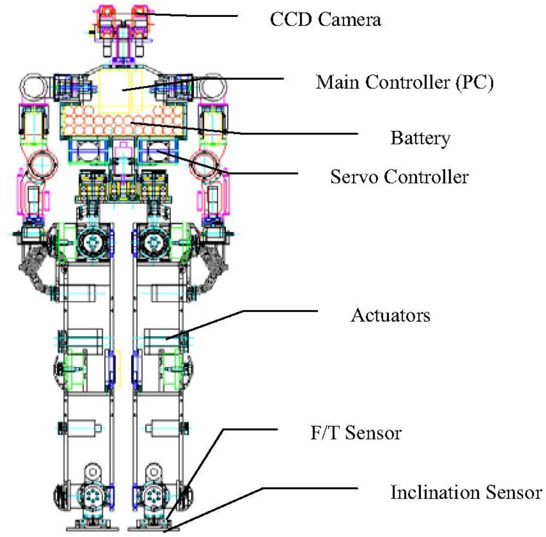


Fig. 3 Component placement

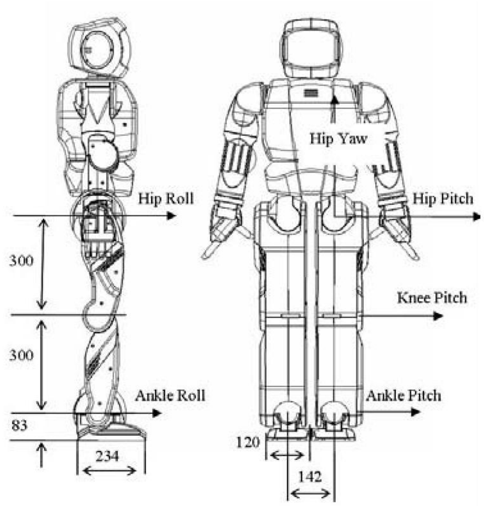


Fig. 4 Dimension(mm) and joint axis

III. Walking Pattern Generation

We have the following requirements of the pattern generation.

1) Easy to operate the robot

The operator's input should be minimized such as step time, stride, and mode (forward/backward, left/right, and etc.) and commands such as go and stop should be also minimum.

2) Simple form and smooth property

The curve of the pattern has the simple analytic form and it is differentiable because of the velocity curve continuity. We first formulate the curves of the walking pattern and update the parameters for every step. We want the curves to be clear and simple.

3) Easy to implement to the real system

The calculation burden and memory occupation should be small and the pattern modification should be flexible.

4) Small number of factors which are needed to be tuned

Walking pattern is needed to be tuned to increase its performance, because the acceptability of the pattern itself can be validated by experiment. We want to tune the robot easily.

We describe the position of the pelvis centre and the ankle in the view point of sagittal and coronal plane in this paper.

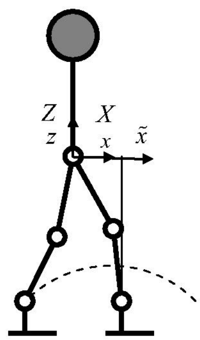


Fig. 4 Coordinate description

A. *Sagittal view (X-Direction)*

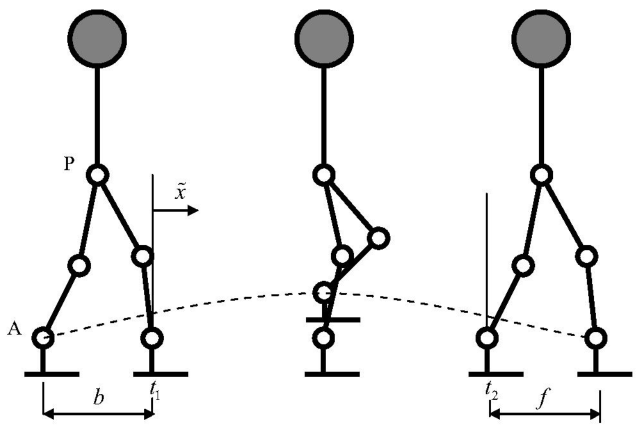


Fig. 5 Coordinate description in X-direction (Forward)

$\tilde{x}$ is located on the front supporting foot during the other leg swings in x direction. t_1 is the start time of swing from DSP (Double Support Phase) and t_2 is the end time of swing to the other DSP. We assumed that the pelvis center position is on the center of two ankles at t_1 and t_2. First, we generated the pelvis and the swing leg trajectory in this local coordinate frame - $\tilde{x}$, and implemented to the robot on the basis of x frame by translating the coordinate frame.

Equation (1) shows the ankle position and (2) shows the pelvis centre position in the local coordinate frame.

$$\tilde{x}_A(t) = (b+f)\left(\frac{t-t_1}{t_2-t_1} - \frac{1}{2\pi}\sin\left(2\pi\frac{t-t_1}{t_2-t_1}\right)\right) - b \quad (1)$$

$$\tilde{x}_P(t) = \sum_{i=0}^{3} a_i\left(\frac{t-t_1}{t_2-t_1}\right)^i \quad (2)$$

Equation (2) is a 3rd order polynomial interpolation curve. We need to have flexibility of the curve shape change by α shown in (3), because it directly affects the shape of ZMP trajectory. The curve is generated by defining its boundary values at start and end of the single step as shown in (3). We normalized the time scale of (2) from 0 ($=t_1$) to 1 ($=t_2$) and we assumed that the speed of the pelvis centre is in proportion with its initial and final position of the swing ankle position. We can get the values of a_i by the time scale normalization as shown (4).

$$\begin{bmatrix} \tilde{x}_P(0) \\ \dot{\tilde{x}}_P(0) \\ \tilde{x}_P(1) \\ \dot{\tilde{x}}_P(1) \end{bmatrix} = \begin{bmatrix} -b/2 \\ \alpha b \\ f/2 \\ \alpha f \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 \\ 3 & 2 & 1 & 0 \end{bmatrix} \begin{bmatrix} a_3 \\ a_2 \\ a_1 \\ a_0 \end{bmatrix} = \begin{bmatrix} \tilde{x}_P(0) \\ \dot{\tilde{x}}_P(0) \\ \tilde{x}_P(1) \\ \dot{\tilde{x}}_P(1) \end{bmatrix} \quad (4)$$

B. *Coronal view (Y-Direction)*

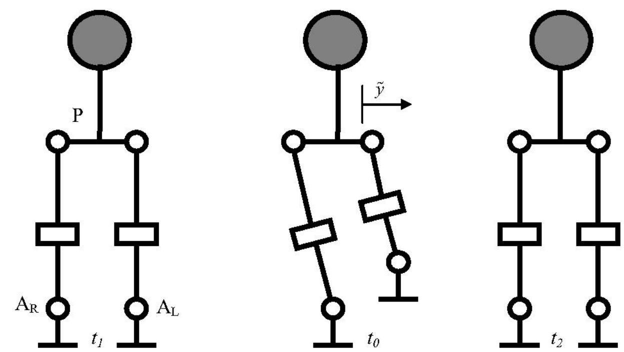


Fig. 6 Coordinate description in Y-direction (Side)

The ankle position trajectories for the side walk are generated in two steps. The first step is for the open stance, and the second step is for recovering to its original stance. We write the step number in the superscript as shown in (5), (6), (7), and (8). Equation (5), (6), (7), and (8) show the left side walk ankle trajectory as an example.

$$y_{A_L} = \frac{A}{4}(1-\eta)\left(1-\cos\left(\pi\frac{t-t_1^1}{t_2^1-t_1^1}\right)\right) \quad (5)$$

$$y_{A_R} = \frac{-A}{4}(1+\eta)\left(1-\cos\left(\pi\frac{t-t_0^1}{t_2^1-t_0^1}\right)\right) \quad (6)$$

$$y_{A_L} = \frac{A}{4}(1-\eta)\left(1+\cos\left(\pi\frac{t-t_1^2}{t_0^2-t_1^2}\right)\right) \quad (7)$$

$$y_{A_R} = \frac{-A}{4}(1+\eta)\left(1+\cos\left(\pi\frac{t-t_1^2}{t_2^2-t_1^2}\right)\right) \quad (8)$$

where, A: Stride, η : Side stride ratio(left/right), and $t_0=(t_1+t_2)/2$

3rd order polynomial interpolation is used for the pelvis centre position trajectory. The different thing from that of the X-direction case is that we divided the single step time into $t_1 \le t \le t_0$ and $t_0 \le t \le t_2$. Equation (9) and (10) shows it. The velocity at the start and end of the step can be tuned by adjusting value α_1.

$$\tilde{y}_P(t) = \sum_{i=0}^{3} \tilde{a}_i \left(\frac{t-t_1}{t_0-t_1}\right)^i \quad (9)$$

Where, $\tilde{y}_P(t_1) = 0$, $\dot{\tilde{y}}_P(t_1) = -\alpha_1$, $\tilde{y}_P(t_0) = -S_y$, $\dot{\tilde{y}}_P(t_0) = 0$

$$\tilde{y}_P(t) = \sum_{i=0}^{3} \tilde{a}_i \left(\frac{t-t_0}{t_2-t_0}\right)^i \quad (10)$$

Where, $\tilde{y}_P(t_0) = -S_y$, $\dot{\tilde{y}}_P(t_0) = 0$, $\tilde{y}_P(t_2) = 0$, $\dot{\tilde{y}}_P(t_2) = \alpha_1$

IV. CONTROLLER

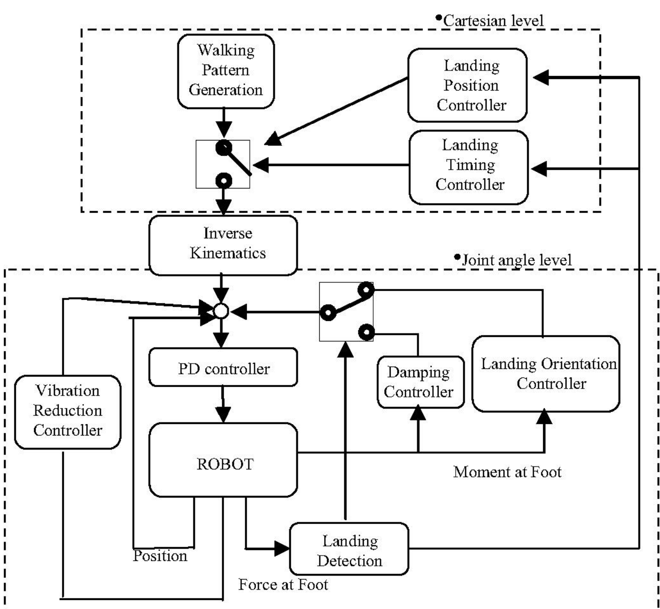


Fig. 7 Controller block diagram for trajectory implementation

Fig. 7 shows overall control architecture for experiment. All joints of the robot are controlled by PD servo controller. After we generate the walking patterns and joint angles described in previous section, we compensate them with controllers by sensory feedback. We control the ankle joint angles by using F/T sensors which can detect the ground reaction forces and moments. Those controllers can reduce the oscillations and shocks induced by abnormal contact of the foot by compensating the prescribed angle trajectory. Those are enabled and disabled by switching (as shown in Fig. 7 and 12) on the base of walking pattern and F/T sensor data.

A. Controllers for walking

We use following controllers for walking experiment.

1) Damping (DP): The vibration of whole body in SSP (Single Support Phase) is mainly caused by the compliance of F/T sensor and harmonic drive reduction gear at ankle. We modeled the robot in SSP as the inverted pendulum with compliant joint as shown in Fig. 8.

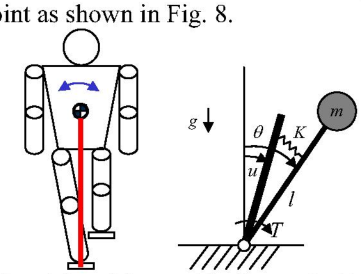
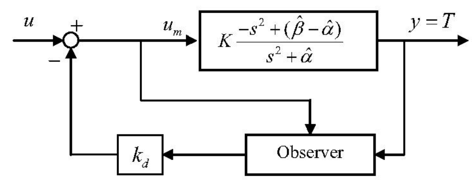


Fig. 8 Inverted pendulum model with compliant joint in SSP

$$T = mgl\theta - ml^2\ddot{\theta} = K(\theta - u) \quad (11)$$

$$u_m = u - k_d\hat{\dot{\theta}} \quad (12)$$



where, T: measured torque, $\hat{\alpha}$: $K/ml^2 - g/l$, $\hat{\beta}$: K/ml^2, k_d: damping control gain, and u_m : ankle joint angle controller input.

Fig. 9 Damping controller block diagram

2) Landing orientation (LO): This controller integrates the measured torque over time to achieve soft landing and stable contact by adapting the ankle joints to the ground surfaces (Fig. 10) inclination. It makes the ankle joint to be compliant during short period at landing. The control law of the landing orientation control is (13).

$$u_m = u + \frac{T(s)}{C_L s + K_L} \quad (13)$$

where, C_L : damping coefficient, K_L : the stiffness, u : the reference ankle joint angle, and u_m : the compensated reference ankle joint angle.

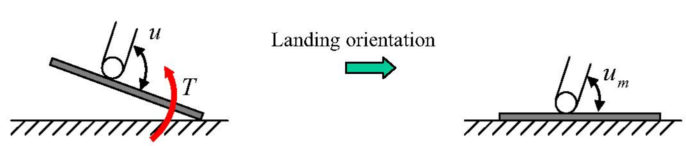


Fig. 10 The landing orientation control

3) Landing timing (LT): The landing timing controller prevents the robot from being unstable during landing by the modification of walking pattern schedule. That is, if the foot does not land on the ground at the end of stretch at the prescribed schedule, the time scheduler of the main computer will halt the motion flow until the foot contacts the ground.

Therefore, the real walking motion can follow the prescribed walking pattern despite anomalies emerging during walking.

4) Landing position (LP): The landing position controller is activated if the actual landing occurs before the prescribed landing time. The controller makes the swing leg to stop stretching on the ground and hold its position until the other leg starts swing as shown in Fig. 11.

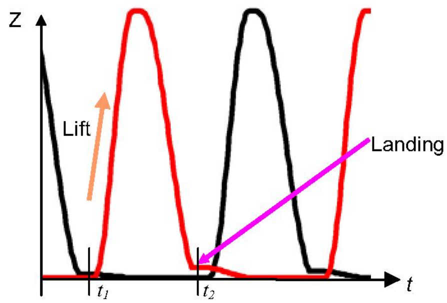


Fig. 11 The landing position control

Fig. 12 shows controller activation timing diagram. This shows when the controller is activated, disabled, and recovered in the switching controller method. ZMP and vibration reduction controller is activated in SSP.

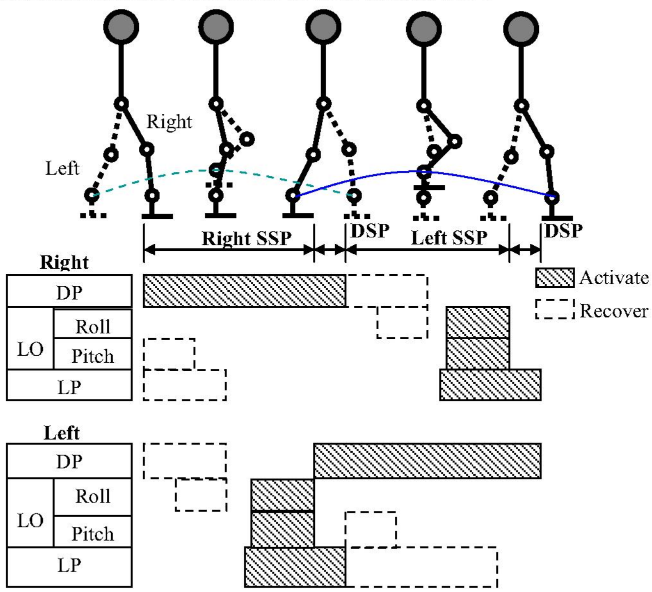


Fig. 12 Controller activation timing diagram

5) Vibration reduction (VR): This controller is for reducing vibration of the swing leg by controlling the hip joint roll and pitch joints, and it uses the accelerometer on the sole. Its equation of motion is shown in (14). We used simple lead compensator as a controller.

$$ml^2\ddot{\theta} = -k(\theta - u) \tag{14}$$

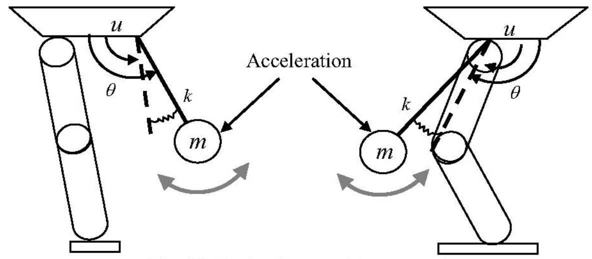


Fig. 13 The landing position control

V. Experimental Result

Fig. 14, 15, 16 shows the experimental result of forward walking, and the position data are relative the pelvis center. The step time and the stride of the experiment is changed from start → 0.8s-0cm → 0.8-20cm → 0.8s-40cm → 0.7s-20cm → 0.8-20cm to stop.

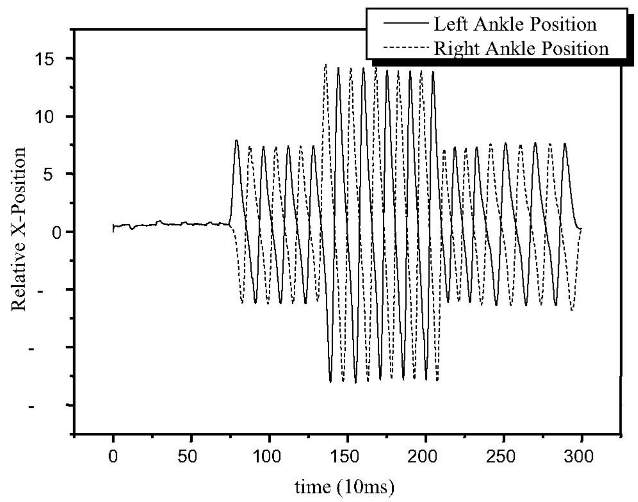


Fig. 14 Relative ankle X – position in forward walking

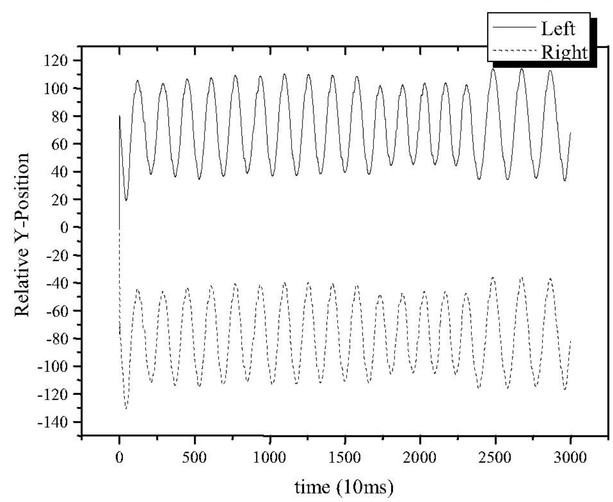


Fig. 15 Relative ankle Y – position in forward walking

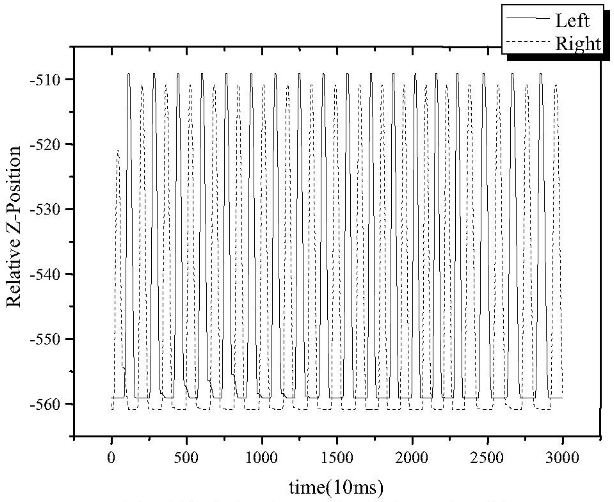


Fig. 16 Relative Z – position in forward walking

Fig. 17 shows the experimental result of side (left and right) walking, and the position data are also relative the pelvis center. The step time and the stride of the experiment varies (start → 0.8s-0cm → left 0.8-5cm → 0.8s-0cm → 0.7s-0cm → right 0.7-5cm → 0.7s-0cm → left 0.7s-0cm → stop).

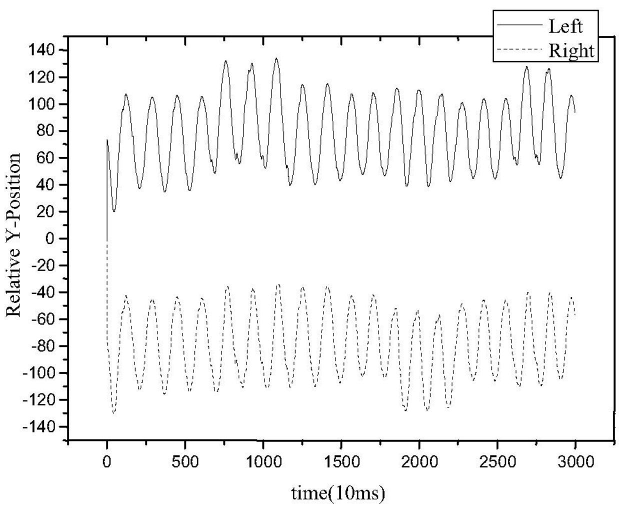


Fig. 17 Relative Y-position in side walking

VI. Conclusion

We proposed a simple online walking pattern generation method which has the continuity in variable step time and stride to realize the various bipedal walking gaits for free walking. In this paper, we implemented the gait generation and stabilization control algorithm on the robot. The method was basically proved by forward/side walking experiment.

We implemented the controllers for walking stabilization in step time and stride varying situation. The performance of the feedback controllers are also proved in that condition.

We can get the proper walking pattern simply by tuning the curve shape factors (α , α_1 , η) for each walking conditions and modes.

VII. Future work

We will realize the more general walking pattern such as turning and curve walking with variable step time and stride.

Acknowledgement

This research was mainly supported by MOCIE (Ministry of Commerce, Industry and Energy) and partly supported by HWRS (Human Welfare Robotic System) and BK-21 (Brain Korea - 21) project.

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