Fast Walking Planning using Extended Linear Inverted Pendulum Model on a Force-Controlled Biped Robot

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Motivation

Force-Controlled biped robots have some inherent abilities that they can be both compliant and stiff. These characteristics are useful for walking and safety of human-robot interaction. Robots are expected to walk as fast as human beings, or even faster. Since a biped is a non-linear complicated system, we need a simplified model to plan its online walking pattern. Linear Inverted Pendulum Model (LIPM) is widely used in walking planning of biped robots, however, when a robot walks fast, its fixed ZMP is harmful to control velocity, and heel touch-down and toe lift-off walking like human beings. ZMP moving from heel to toe can solve this issue well.

State of art

Kajita et al. [1] used LIPM to realize stable biped walking on a position-controlled robot. Stephens et al. achieved dynamic walking on a force-controlled humanoid robot using LIPM. Unfortunately, it's hard to realize heel touch-down and toe lift-off walking using a fixed ZMP model, because ZMP is at rear or front of the sole then.

Our approach

We use LIPM but let ZMP move continuously on the sole. We call it Extended Linear Inverted Pendulum Model (ELIPM). Compared with traditional LIPM covering dynamics of Single Support Phase (SSP) only, it covers both SSP and Double Support Phase (DSP). We re-deduced its dynamic equations and got an analytic equation which could be used online easily.

$$\begin{bmatrix} y_c(t) \\ T_c v_{cy}(t) \end{bmatrix} = \begin{bmatrix} C_t & S_t \\ S_t & C_t \end{bmatrix} \begin{bmatrix} y_c(0) \\ T_c v_{cy}(0) \end{bmatrix} - \frac{1}{T_c} \begin{bmatrix} \int_0^t S_t \bar{p}_y(\tau) d\tau \\ \int_0^t C_t \bar{p}_y(\tau) d\tau \end{bmatrix}$$

where $\overline{p_y}(\tau) = p_y(t-\tau)$, which represents a ZMP trajectory, $S_t \coloneqq \sinh(t/T_c)$, $C_t \coloneqq \cosh(t/T_c)$, $T_c := sqrt(z_c/g)$, z_c is the height of Center of Mass (CoM) of the robot, g is gravity acceleration. Assuming that ZMP moves from b to b+D during $[T_1, T_2]$, $\overline{p_y}(\tau) = a\tau + b$, where $a = D/(T_2 - T_1)$, then

$$\begin{bmatrix} y_c(t) \\ T_c v_{cy}(t) \end{bmatrix} = \begin{bmatrix} C_t & S_t \\ S_t & C_t \end{bmatrix} \begin{bmatrix} y_c(0) \\ T_c v_{cy}(0) \end{bmatrix} - \frac{1}{T_c} \begin{bmatrix} T_c^2 S_t - T_c t & T_c(C_t - 1) \\ T_c^2 (C_t - 1) & T_c S_t \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix}$$

As shown in Fig. 1, three layers are used to realize fast walking.

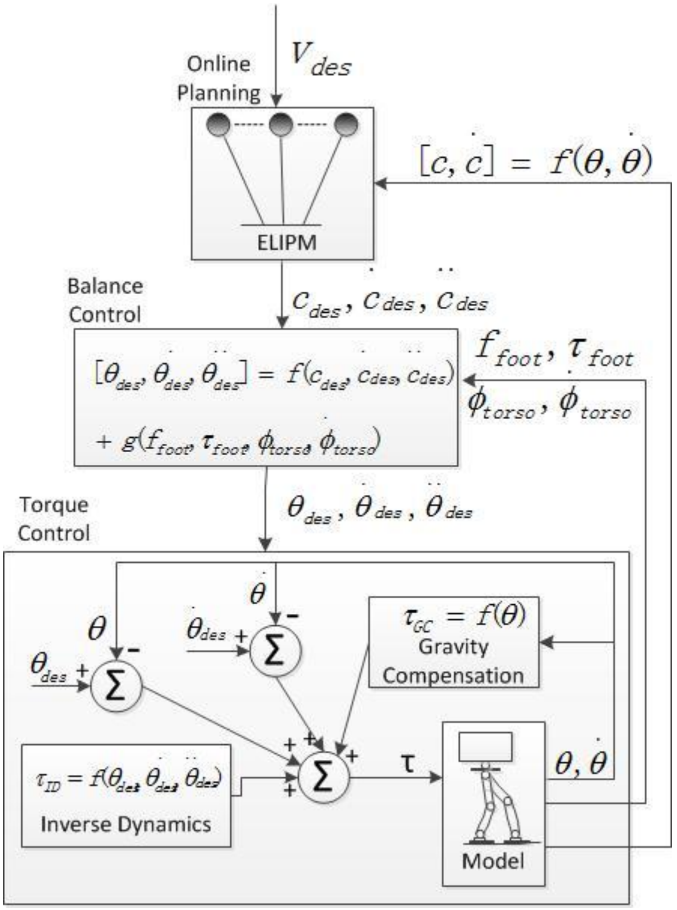

Fig. 1 Control algorithm frame

Layer 1: according to the desired and actual velocity of the robot, desired states of CoM can be obtained using ELIPM. Robots use it to recover from big disturbances.

Layer 2: stability control is applied. According to sensor information, a bias will be added. It contains ZMP control, posture control and landing time control. It is used to recover from small disturbances.

Layer 3: in order to get a precise trajectory trace, gravity compensation and inverse dynamics are used as forward input and angle and angular velocity are used as feedback input for torque control.

[1] S. Kajita, F. Kanehiro, K. Kaneko, K. Yokoi, and H. Hirukawa, ``The 3D linear inverted pendulum mode: A simple modeling for a biped walking pattern generation," in Proc. IEEE/RSJ IROS, 2001, pp. 239-246

[2] Benjamin Stephens, Christopher Atkeson, "Dynamic Balance Force Control for Compliant Humanoid Robots," in Proc. 2010 IROS, Taipei, Taiwan, pp. 1248 – 1255