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Trajectory-free dynamic locomotion using key trend states for biped robots with point feet

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Dear editor,

Biped robots can not only cross complex environment such as ravines and rocks [1], but can also interact in more diverse activities with people. A biped robot with point feet is called an underactuated biped robot (UBR) because there is no driving device at the contact point between the foot and the ground. The dynamic walking of a UBR usually requires gait planning and its trajectory generation methods often use simplified models [2]. However, the joint coupling effect caused by dynamic attributes is prominent in the dynamic motion of the robot. To solve this problem, full model optimization was studied [3]. Optimization of the whole body dynamic (WBD) model consumes more computing resources with an increase in the degrees of freedom (DoFs). In addition to the above problems, the uncontrollability of the DoFs of UBR requires the motion trajectory adjusted online. In the dynamic walking control of a UBR, it was found that the influence of the joint trajectory tracking error on walking stability is not serious [4]. Yin et al. [5] proposed a robot control framework based on a trajectory-free and realized computer animation design. Because the dynamic constraints of the actual robot were not considered, it could not be directly used in an experiment. Besides, upper-body attitude control and foothold adjustment are key to making the robot balanced [6]. The traditional method makes it difficult to achieve stable attitude control for robots with little difference in mass distribution among parts. The foothold adjustment is limited by the state of the previous step and the kinematic singularity.

Based on these considerations, this study proposes a trajectory-free dynamic locomotion method via state key points. This method can realize real-time motion planning at each control period point. These state key points are defined as key trend states (KTSs) because they only provide the current motion trend for the robot, and these KTSs divide the biped robot's motion into finite states of joints. An improved torso attitude control based on WBD compensation (WBD-c) and a real-time foothold adjustment algorithm for the angle of joint are used to stabilize the dynamic motion of the robot. Finally, the proposed method is implemented on the planar UBR BR-S1 in a 1 kHz control loop.

KTS. Through the study of human walking motion, the supporting leg mainly supports the torso in walking with a few joint angle changes, while the swinging leg realizes the processes of lifting and stepping down from the back to the front. As shown in Figure 1(a), the KTS can be set for two phases of the supporting leg, $\varepsilon \in \{\mathrm{r}, \mathrm{l}\}$, which means the right or left leg, respectively. $\varsigma \in \{\mathrm{st}, \mathrm{sw}\}$ denotes the standing and swinging legs, respectively. Two sub-phases $\mathrm{subp} \in \{\mathrm{u}, \mathrm{d}\}$ represent lifting-up and stepping-down leg states. Therefore, the set representation of KTS $\Phi_{\varepsilon}^{\varsigma}$ is defined as

$$\Phi_{\varepsilon}^{\varsigma} = \begin{cases} \text{lifting up: } ({}^{\mathrm{u}}_{\varsigma}\theta_{\mathrm{h}}^{\mathrm{ref}},\ {}^{\mathrm{u}}_{\varsigma}\theta_{\mathrm{k}}^{\mathrm{ref}}), \\ \text{stepping down: } ({}^{\mathrm{d}}_{\varsigma}\theta_{\mathrm{h}}^{\mathrm{ref}},\ {}^{\mathrm{d}}_{\varsigma}\theta_{\mathrm{k}}^{\mathrm{ref}}), \end{cases} \tag{1}$$

where the KTS $\theta_{\mathrm{h}}^{\mathrm{ref}}, \theta_{\mathrm{k}}^{\mathrm{ref}}$ are the angle reference values of the hip joint and knee joint of the ς leg in two sub-phases subp, respectively. The KTS of the supporting leg over the entire supporting state duration has an almost constant value: ${}^{\mathrm{u}}_{\mathrm{st}}\theta_{\mathrm{h}}^{\mathrm{ref}} \approx {}^{\mathrm{d}}_{\mathrm{st}}\theta_{\mathrm{h}}^{\mathrm{ref}}, {}^{\mathrm{u}}_{\mathrm{st}}\theta_{\mathrm{k}}^{\mathrm{ref}} \approx {}^{\mathrm{d}}_{\mathrm{st}}\theta_{\mathrm{k}}^{\mathrm{ref}}$. When setting the KTS, we hope that the movement trend of the robot is a speed-free standing state which indicates the center of mass (CoM) of the robot is directly above the support point with zero speed. Therefore, the relationship between the hip joint and the knee joint should be $\theta_{\mathrm{h}}^{\mathrm{ref}} = \mathrm{asin}(\frac{L_{\mathrm{tib}} \sin(\pi + \theta_{\mathrm{k}}^{\mathrm{ref}})}{\sqrt{L_{\mathrm{fem}}^2 + L_{\mathrm{tib}}^2 - 2L_{\mathrm{tib}} L_{\mathrm{fem}} \cos(\pi + \theta_{\mathrm{k}}^{\mathrm{ref}})}})$, where $\mathrm{asin}(\cdot)$ is the antitrigonometric function of sin, and L_{fem} and L_{tib} are the lengths of the robot's femur and tibia, respectively. The switching conditions between KTSs are defined

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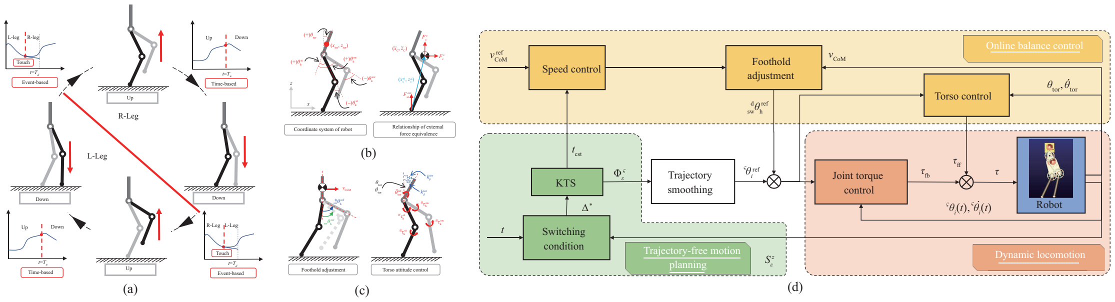

Figure 1 (a) Block diagram of KTS design method; (b) coordinate system of dynamic model; (c) foothold adjustment and torso attitude control; (d) real-time dynamic locomotion control diagram.

below.

Event-based and time-based switching. We set the lifting stage to go through the specified time T_u. A change in the contact signal S^z_{ε} that is between the swinging leg and ground is defined, and we define the switching condition mapping Δ^* of KTS as

$$\Delta^*(\Phi^{\varsigma}_{\varepsilon}, t, S^z_{\varepsilon}) = \begin{cases} \Phi^{\varsigma}_{\varepsilon}(\mathrm{u} \to \mathrm{d}), & t = T_u, \\ \Phi^{\varsigma}_{\varepsilon(\mathrm{r}\to\mathrm{l},\mathrm{l}\to\mathrm{r})}, & S^z_{\mathrm{l}} = 1 \ \&\ S^z_{\mathrm{r}} = 1, \end{cases} \tag{2}$$

where $S^z_{\varepsilon} = 1$ means a connection with the ground and 0 means disconnection. t represents the current running time of each sub-phase. $\Phi_{\varepsilon(\mathrm{r}\to\mathrm{l},\mathrm{l}\to\mathrm{r})}$ means that the supporting leg changes from the right leg to the left leg or from the left leg to the right leg, and it also means the change of the swinging state.

Motion trajectory smoothing. As shown in Figure 1(a), to ensure the continuity of robot motion, we need to carry out an interpolation between the KTSs: ${}^{\varsigma}\theta^{\mathrm{ref}}_i(t) = \gamma(\Phi^{\varsigma}_{\varepsilon}, \Delta^*, T_{\mathrm{subp}}, t)$, where $i \in \{\mathrm{h}, \mathrm{k}\}$ stands for the hip or knee joint, $\Phi^{\varsigma}_{\varepsilon}$ is the KTS before triggering the switching condition, and Δ^* is the KTS after triggering switching conditions. $\gamma(\cdot)$ is quintic spline interpolation function. The joint angular velocity and acceleration at the driving point are set to zero. We set a time interval T_d of sub-phase d for interpolation.

Dynamic balance control strategy. Because of the instability of the gait itself and external random disturbance, the balance algorithm needs to control the robot online (Figure 1(d)). Firstly, we design the following foothold adjustment algorithm: ${}^{\mathrm{fp}}_{\mathrm{sw}}\theta^{\mathrm{ref}}_{\mathrm{h}} = {}_{\mathrm{sw}}\theta^{\mathrm{ref}}_{\mathrm{h}} + k^{\mathrm{sw}}_d \frac{1}{2} t_{\mathrm{cst}} \cdot v_{\mathrm{CoM}} + k^{\mathrm{sw}}_v (v_{\mathrm{CoM}} - v^{\mathrm{ref}}_{\mathrm{CoM}})$, where ${}^{\mathrm{fp}}_{\mathrm{sw}}\theta^{\mathrm{ref}}_{\mathrm{h}}$ is the reference angle adjusted according to the real-time state based on the track ${}_{\mathrm{sw}}\theta^{\mathrm{ref}}_{\mathrm{h}}$ of the hip joint of the swinging leg. $k^{\mathrm{sw}}_d, k^{\mathrm{sw}}_v > 0$ are the coefficients manually to match the real robot. t_{cst} is the time of current support stage. The forward speed at the CoM of the torso $\dot{x}_{\mathrm{tor}}$ defaults to the CoM speed v_{CoM} (Figure 1(c)).

To control the robot to realize the above motion, it is necessary to establish a dynamic model (Figure 1(b)) which is provided in Appendix A. Then, we designed the attitude control algorithm based on WBD-c: $\tau_{\mathrm{ff}} = B(D(q^{\mathrm{ref}}_w)\ddot{q}^{\mathrm{ref}}_w + N(q^{\mathrm{ref}}_w, \dot{q}^{\mathrm{ref}}_w) - J^{\mathrm{T}}_{\mathrm{st}} F_{\mathrm{ext}})$ with $\ddot{\theta}^{\mathrm{ref}}_{\mathrm{tor}} = k^{\mathrm{tor}}_p(\theta^{\mathrm{ref}}_{\mathrm{tor}} - \theta_{\mathrm{tor}}) + k^{\mathrm{tor}}_d(\dot{\theta}^{\mathrm{ref}}_{\mathrm{tor}} - \dot{\theta}_{\mathrm{tor}})$, where $\tau_{\mathrm{ff}} = [\,{}^{\mathrm{ff}}\tau^{\mathrm{st}}_{\mathrm{h}}\ \ {}^{\mathrm{ff}}\tau^{\mathrm{st}}_{\mathrm{k}}\ \ {}^{\mathrm{ff}}\tau^{\mathrm{sw}}_{\mathrm{h}}\ \ {}^{\mathrm{ff}}\tau^{\mathrm{sw}}_{\mathrm{k}}\,]^{\mathrm{T}}$ is WBD-c torque values which is obtained by inverse dynamics. $\ddot{\theta}^{\mathrm{ref}}_{\mathrm{tor}}$ is the reference angular acceleration of the torso pitch angle, which is related to the error of angle and velocity (Figure 1(c)). $\theta^{\mathrm{ref}}_{\mathrm{tor}}$ and $\dot{\theta}^{\mathrm{ref}}_{\mathrm{tor}}$ are the reference angle and angular velocity of the torso, respectively. $k^{\mathrm{tor}}_p, k^{\mathrm{tor}}_d$ are the stiffness of the spring and damping coefficient, respectively. $q^{\mathrm{ref}}_w, \dot{q}^{\mathrm{ref}}_w, \ddot{q}^{\mathrm{ref}}_w \in \mathbb{R}^{7\times 1}$ are the reference position, velocity, and acceleration vector of the dynamic model, respectively. In addition, closed-loop control of position at the joint is also needed. A detailed description of WBD-c is provided in Appendix B.

The simulation and experimental results are illustrated in Appendix C in detail.

Conclusion. This study proposed a human-inspired-based KTS design method and control framework for UBRs. A trajectory-free motion planning method was directly applied to joint angles, and it is simple and convenient to design KTSs according to human motion. We put forward several parts of the balance control method to achieve real-time dynamic and stable movement. This method can support large joint trajectory errors and avoid optimization of a complex model. Our methods can run and control the robot at 1 kHz. Based on this motion generation and control framework, we realized a walking experiment of the biped robot. This planning method has being used to generate a running motion.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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