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Dynamically Consistent Motion Design of a Humanoid Robot Even at the Limit of Kinematics

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***Abstract*— A motion design for humanoid robots to satisfy dynamical constraints on the external forces even at the kinematic exceptions such as singular configurations and joint angle limits is proposed. It enables robots to mimic natural, comfortable and lively human motions, which leverage the limit of kinematics, based on a robust numerical solver of the prioritized inverse kinematics. The idea of prioritization is to strictly constrain the least number of contact points to form the supporting region which contains the desired ZMP and to unconstrain the other points rather than to keep foot-flat. It increases available degrees-of-freedom instead of degenerate components. Motion continuity in spite of the discontinuous change of a set of constraints is also taken into account. Knee-stretched walks are demonstrated as an application with the inverse dynamics analyses.**

I. INTRODUCTION

The similar morphology of humanoid robots to humans helps to design motions to do complex tasks which require human's high skills. People might be able to project their knowledge and skill to the robot rather intuitively and straightforwardly. In this sense, humanoid robots potentially work as if they were alternative bodies of humans. Many humanoid robots at present, however, move in different manners from those of humans, typically bending their knees deeply, which sometimes looks unnatural for us. It is mainly due to the mathematical difficulty in motion synthesis.

The motion design of a humanoid robot is formalized as a two-point boundary-value problem in which a time series of a high-dimensional variable representing the whole-body configuration of the robot should be found under many kinematic and dynamical constraints. The kinematic constraints include the limit of motion range and collisions between links, while the dynamical constraints do the limit of joint torques and contact forces which have to be within the friction cones. Several methods which iteratively correct the trajectory so as to satisfy the constraints have been proposed so far [1], [2], [3]. They assume that the trajectory does never pass the singular point even during the iteration. Once the motion falls into the singular point, the robot cannot yield local movements in certain directions. From the viewpoint of computation, it causes numerical ill-posedness and the iteration often fails to converge. The same things also happen at the joint angle limits. Hence, motions have had to be carefully designed with a sufficient margin from the limit of motion range and the singular points, so that they tend to be conservative and seem unnatural. On the other hand, humans positively take limits of knees and elbows, for instance, which gives a human-like lively but comfortable impression to their motions. It is more important than impression to free motion designers from a burden that they have to keep being conservative, caring about the limit of motion range and the distribution of the singular points, and to allow them to project natural behaviors which humans usually take onto the robot intuitively. A technique to edit motions and to satisfy the dynamical constraint even at the limit of kinematics is required.

Sugihara [4] proposed an inverse kinematics solver which is not concerned with whether the required position and attitude is within the motion range. If the required position and attitude of hands and feet of the robot are within the motion range, it provides the whole-body configuration which satisfies them as Fig. 1(a) shows. If the required values are out of range, it robustly finds a solution in the least square sense as depicted in Fig. 1(b). The solution in Fig. 1(b), however, does not work when considering the dynamical constraint since it loses contacts with the environment and cannot produce necessary supporting forces; the contact to the ground should be enforced as illustrated in Fig. 1(c) in reality, which is enabled by a robust prioritized inverse kinematics solver [5].

Now, there still remains the following two problems.

(i) It is not trivial which requirement should be prioritized in order to satisfy the dynamical constraint. Excess number of high-priority constraints intensify the error of low-priority constraint.

(ii) Discontinuous change of constraints and passing by the limit of motion range including the singular point may cause large deviation of velocity, which possibly makes the robot motion unstable, or even in better cases, requires large torques at motors.

This paper proposes the following techniques to resolve the above problems. An answer to problem (i) is to strictly constrain the least number of contact points forming the supporting region, which is determined by the desired reaction force, or more simply, the desired zero-moment point (ZMP) [6] with respect to the desired motion, and also to unconstrain the other points on the sole rather than to keep foot-flat. The other required movements such as the center of mass (COM) and hands are treated as the low-

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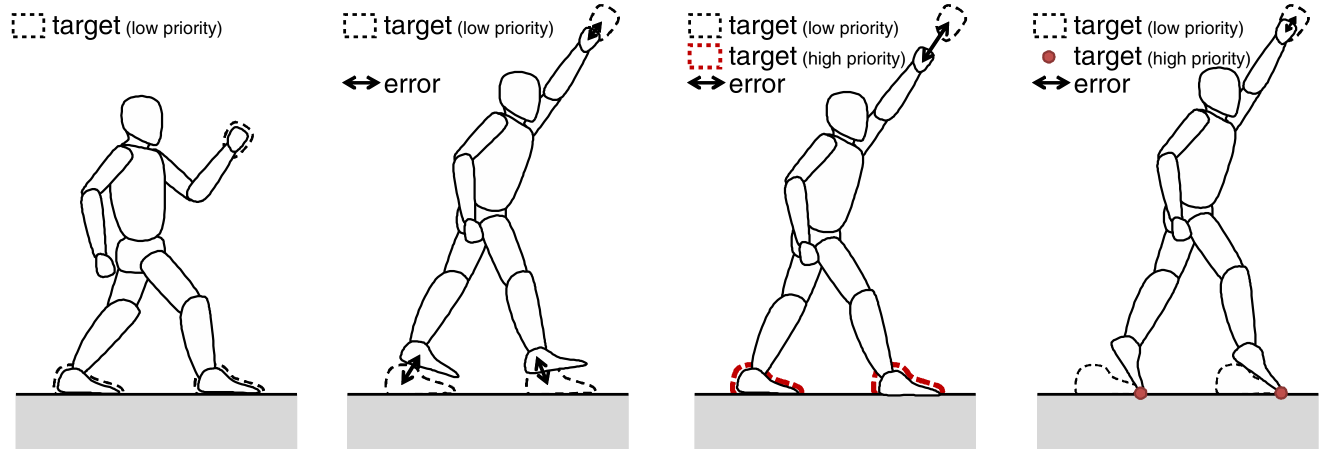
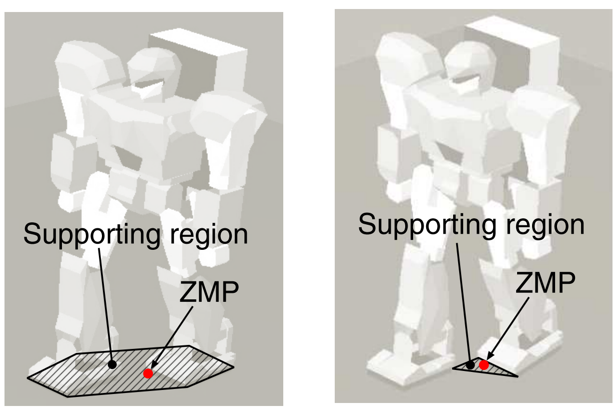


(a) solvable case i.e. all targets in workspace (b) unsolvable case without priority (c) unsolvable case with contact prioritized (d) unsolvable case with minimal supporting region

Fig. 1. Solvability of inverse kinematics and priority of constraints



(a) maximal supporting region with foot-flat (b) minimal supporting region with point/edge contact

Fig. 2. Minimal supporting region with respect to the desired ZMP

priority constraints. It increases available degrees-of-freedom to compensate degenerated local movements and reduces the error as depicted in Fig.1(d). Problem (ii) is suppressed by mitigating the velocity of required motions with low-priority for smooth movements in spite of the discontinuous change of priority and constraints. Dynamically consistent motion design can be achieved by combining the above techniques with the dynamics filter [1]. Knee-stretched walks with heel-strike and toe-off are demonstrated as an application with the inverse dynamics analyses.

II. Prioritization of Constraints based on Dynamical Consistency

Humanoid robots move in the inertial frame by pushing the environment via contact points and being pushed back as the reaction. The reaction force is constrained to be within the friction cone, namely, the normal force can act only in the direction to push the environment, and the tangential force cannot exceed the maximum static friction force. The former constraint is more severe in general, and whether the desired motion is dynamically consistent depends on the distribution of contact points. If all the contact points are on the same horizontal plane, it is equivalent with the condition in which ZMP lies within the supporting region, namely, the convex region of the contact points. Even if they are ranged three-dimensionally, ZMP approximately respresents the dynamical condition on the motion in many cases [7].

Many conventional methods [8], [9] took a strategy that ensures sufficiently wide supporting region by contacting to the ground on the sole and manipulates ZMP around the center of the region. Although there have been some studies that enabled walking with toe-off [10], [11], [12], they are not different from the above at a point that they keep sufficient supporting region at any moment with respect to the supposed ZMP locus. The proposed method rather chooses the minimal set of contact points which contain the desired ZMP within at every moment, poses the high-priority constraint on them, and unconstrains the other points on the sole as described in Fig. 2. It also treats the movements of non-contacting body parts such as COM and the hands as the low-priority constraints.

The minimal supporting region is determined as follows. Suppose the ground level is $z = 0$ and the position of ZMP is $\boldsymbol{p}_Z = [x_Z \quad y_Z \quad 0]^{\mathrm{T}}$. First, the desired ZMP trajectory ${}^d\boldsymbol{p}_Z(t) = [{}^d x_Z(t) \quad {}^d y_Z(t) \quad 0]^{\mathrm{T}}$ is designed in advance by Terada et al.'s method [13] (one may find the early versions in English in Terada et al. [14] and Sugihara et al. [15]) as

$$\begin{bmatrix} {}^d x_Z(t) \\ {}^d y_Z(t) \end{bmatrix} = \begin{bmatrix} x_S \\ y_S \end{bmatrix} - \begin{bmatrix} x_S - x_K \\ y_S - y_K \end{bmatrix} \left(\frac{t}{T} - 1 \right)^N , \qquad (1)$$

where t is the time, T is the total duration of a step, $\boldsymbol{p}_S = [x_S \quad y_S \quad 0]^{\mathrm{T}}$ and $\boldsymbol{p}_K = [x_K \quad y_K \quad 0]^{\mathrm{T}}$ are the center positions of the pivot foot (the foot which works as the stance foot in the single-support phase) and the stepping foot (the foot which performs as the swing foot in the single-support phase), respectively, and N is a positive even number to indicate the pace of change of ZMP i.e. the larger N is chosen, the faster ZMP travels. This function has a property with which the stepping foot kicks the ground at $t = 0$ and

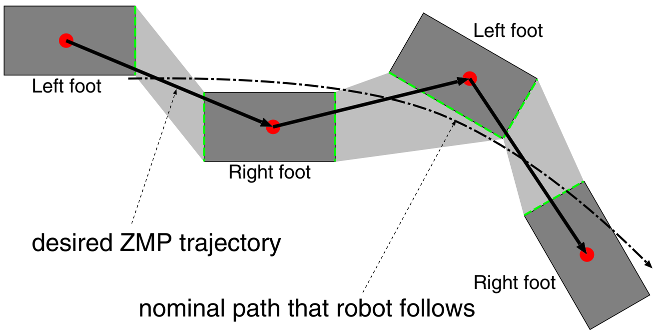


Fig. 3. Desired ZMP trajectory and transition of supporting region

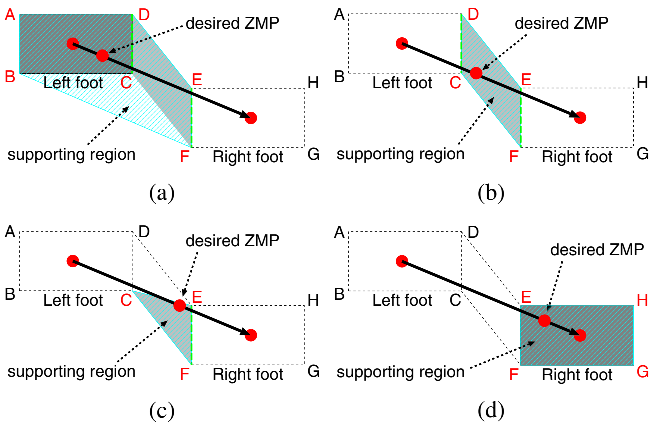


Fig. 4. Automatic constraining/unconstraining of contact points

the point of action of the reaction force moves onto the pivot sole by $t = T$. Since the function is monotone in $0 \le t \le T$, it guarantees that a convex region which contains both $\boldsymbol{p}_S$ and $\boldsymbol{p}_K$ also contains ${}^{d}\boldsymbol{p}_Z(t)$ at $\forall t \in [0, T]$. Having this desired ZMP trajectory, one can predict across which edge ZMP enters and goes out of the region at which moment in advance as Fig. 3 shows.

Suppose a process illustrated by Fig. 4, where ZMP travels from the left sole to the right sole. (Fig. 4(a)) In the early stage, ZMP lies in the left foot, so that the points A, B, C and D are constrained. The points E and F on the right sole are also constrained since it is known that ZMP eventually enters the right sole across the edge EF. (Fig. 4(b)) In the middle stage, ZMP goes out of the left foot and then the points A and B are unconstrained. (Fig. 4(c)) ZMP moves further toward the right foot, and when the triangle CEF can confine the ZMP, the point D is unconstrained. (Fig. 4(d)) In the final stage, ZMP enters the right foot and the point G and H are additionally constrained. The point C is unconstrained in turn. This process runs automatically. By unconstraining points which are unnecessary to compose the minimal supporting region, the degree-of-freedom of the whole-body motion increases and it works to reduce the error of the motion.

III. Velocity Mitigation for the Low-Priority Constraint

Discontinuous change of the constrained points, passing by and reaching at the limit of kinematics including the singular point, may cause degeneracy of movable directions and recovery from degenerate condition, and accordingly, abrupt change of velocity. It leads to fluctuation of robot motion particularly at contact points and possibly makes the robot unstable, or even in better cases, requires large torques at motors. This problem is resolved by mitigating the velocity of required movement with the low-priority.

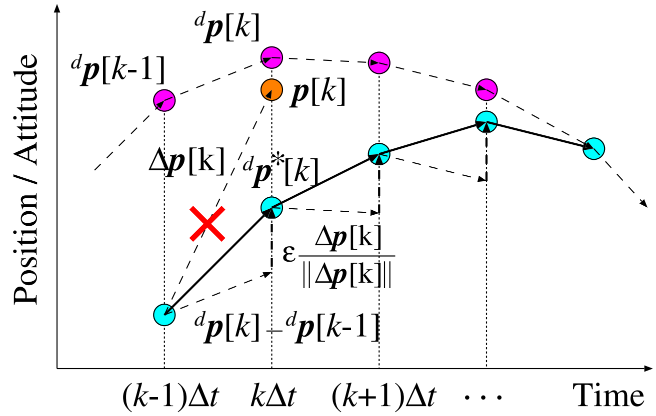


Fig. 5. Velocity constraint

Let us consider a discrete series of $\boldsymbol{p}[i]$, which can be either position or attitude of any body part, where i is the discrete time, and a situation where a certain error remains from the desired movement ${}^{d}\boldsymbol{p}[k-1]$ at a discrete time $k-1$ as Fig. 5. If the motion tracks the desired value ${}^{d}\boldsymbol{p}[k]$ in spite of the error, it largely changes the velocity. Let us admit an over deviation up to the norm ε. A tentative movement $\boldsymbol{p}[k]$ with respect to ${}^{d}\boldsymbol{p}[k]$ is obtained through the inverse kinematics. If

$$\|(\boldsymbol{p}[k] - \boldsymbol{p}[k-1]) - ({}^{d}\boldsymbol{p}[k] - {}^{d}\boldsymbol{p}[k-1])\| > \varepsilon, \quad (2)$$

then, the required movement is mitigated according to the following equation:

$${}^{d}\boldsymbol{p}^{*}[k] = \boldsymbol{p}[k-1] + ({}^{d}\boldsymbol{p}[k] - {}^{d}\boldsymbol{p}[k-1]) + \varepsilon \frac{\Delta\boldsymbol{p}[k]}{\|\Delta\boldsymbol{p}[k]\|}, \quad (3)$$

where $\Delta\boldsymbol{p}[k] \equiv {}^{d}\boldsymbol{p}[k] - \boldsymbol{p}[k-1]$. The inverse kinematics is solved again with this modified requirement. It is expected that the actual motion gradually approaches to the originally required movement.

IV. Example of Motion Design and Evaluation

A. Fast ZMP compensation by Dynamics Filter

The proposed method was applied to a design of a walking motion of a miniature humanoid robot developed by Sugihara et al. [16] by combining it with the dynamics filter for fast ZMP compensation proposed by Nagasaka [1], which is summarized as follows.

The equilibrium between the torque about the desired ZMP and the net six-axis force working at COM is represented as

$$\boldsymbol{n}_Z = m(\boldsymbol{p}_G - {}^{d}\boldsymbol{p}_Z) \times (\ddot{\boldsymbol{p}}_G + \boldsymbol{g}) + \boldsymbol{n}, \quad (4)$$

where $\boldsymbol{n}_Z$ is the torque about the desired ZMP, m is the total mass of the robot, $\boldsymbol{p}_G = [x \;\; y \;\; z]^{\mathrm{T}}$ is the position of COM, $\boldsymbol{g} = [0 \;\; 0 \;\; g]^{\mathrm{T}}$ is the acceleration due to the gravity with $g = 9.8$[m/s^2], and $\boldsymbol{n}$ is the torque about COM. Let us consider to compensate the horizontal component of $\boldsymbol{n}_Z$ by modifying x and y to $x + \Delta x$ and $y + \Delta y$, respectively, which derives

$$ {}^d\boldsymbol{n}_Z = m(\boldsymbol{p}_G + \Delta\boldsymbol{p}_G - {}^d\boldsymbol{p}_Z) \times (\ddot{\boldsymbol{p}}_G + \Delta\ddot{\boldsymbol{p}}_G + \boldsymbol{g}) + \boldsymbol{n}, \quad (5) $$

where ${}^d\boldsymbol{n}_Z$ is the desired torque about the desired ZMP, and $\Delta\boldsymbol{p}_G = [\Delta x \quad \Delta y \quad 0]^{\mathrm{T}}$. Note that ${}^d\boldsymbol{n}_Z = [0 \quad 0 \quad *]^{\mathrm{T}}$, where $*$ can be any value. Then, from Eq. (5), we get

$$ (\ddot{x} + \Delta\ddot{x})z - (x + \Delta x - {}^d x_Z)(\ddot{z} + g) = 0 \quad (6) $$

$$ (\ddot{y} + \Delta\ddot{y})z - (y + \Delta y - {}^d y_Z)(\ddot{z} + g) = 0, \quad (7) $$

where $\boldsymbol{n}$ is ignored to be zero.

The above Eqs. (6) and (7) can be discretized with respect to Δx and Δy by some techniques. The 3rd-order spline interpolation is available, for example, to turn Eqs. (6) and (7) to simultaneous linear equations about $4S$ variables, $\Delta x[1] \cdots \Delta x[S]$, $\Delta y[1] \cdots \Delta y[S]$, $\Delta\dot{x}[1] \cdots \Delta\dot{x}[S]$ and $\Delta\dot{y}[1] \cdots \Delta\dot{y}[S]$, where S is the number of discrete steps. The number of equations is $4S$ in total with the boundary condition $\Delta x[1] = \Delta y[1] = \Delta x[S] = \Delta y[S] = \mathbf{0}$, so that all the variables can be found. One should notice that the boundary condition of the velocity cannot be posed, and hence, this method is not suitable to an on-line trajectory planning. By adding each $\Delta x[i]$ and $\Delta y[i]$ to values at the discrete time i, the horizontal components of $\boldsymbol{n}_Z = [n_x \quad n_y \quad n_z]^{\mathrm{T}}$ are expected to approach to zero. In order to deal with the error due to the approximation $\boldsymbol{n} \approx \mathbf{0}$, the above computation is repeated until

$$ \int_0^T \left(n_x^2 + n_y^2\right) \mathrm{d}t < \delta \quad (8) $$

is satisfied, where δ is a sufficiently small threshold. n_x and n_y are obtained via the inverse dynamics.

B. Design of Knee-streched walking motions

The followings are examples of walking motions designed by the proposed method.

(I) The robot walks with bent-knee and does neither pass by the singular point nor the limit of motion range during the walk. The inverse kinematics is always solvable (Fig. 6).

(II) The robot walks with stretched-knee. The inverse kinematics is solved based on the least square method without the proposed prioritization technique (Fig. 7).

(III) The robot walks with stretched-knee. The desired motion is the same with the above case (II). The proposed prioritization for the inverse kinematics is conducted, but all the vertices of the sole are constrained with the high-priority, so that the robot keeps foot-flat contact during stance (Fig. 8).

(IV) The robot walks with stretched-knee. The desired motion is the same with the above case (II). The proposed prioritization for the inverse kinematics and the minimal supporting region determination are conducted, while the velocity mitigation is not applied (Fig. 9).

(V) The robot walks with stretched-knee. The desired motion is the same with the above case (II). The proposed prioritization for the inverse kinematics, the minimal supporting region determination, the velocity mitigation are conducted (Fig. 10).

Resulted motions of all the above cases were analyzed and the ZMP locus was evaluated based on the inverse dynamics. Note that the contact forces were not explicitly estimated.

In case (I), the inverse kinematics was always solvable, so that the motion can be designed without any problems. Fig. 11 shows snapshots of the motion. In case (II), the inverse kinematics often became unsolvable and the feet often detached off the ground, so that the resulted motion was dynamically inconsistent. In case (III), the feet were certainly grounded thanks to the prioritization and the ZMP locus was always confined within the supporting region. As a trade-off, the error of the trunk position increased. In case (IV), the proposed technique to form the minimal supporting region worked and the error was reduced. Also, the ZMP locus always existed within the supporting region. However, some discontinuous jumps were found on the trajectory of the trunk at the switching moments from the single-support phase to the double-support phase. In case (V), the velocity mitigation worked to smooth the trunk motion, so that all the above problems were resolved. Fig. 12 shows snapshots of the motion, in which it is seen that a natural toe-off motion is emerged.

A sideward walk was also designed by the proposed method. Fig. 13 shows snapshots of the motion. It should also be remarked that natural transition sequence of foot contact not only from front-heel-strike to rear-toe-off but also from the inner-edge-strike to the outer-edge-off in this case was automatically emerged. It is different from the conventional methods to design human-like knee-stretched motions in which the contact state transition is carefully decided in detail [17], [18] or the trajectory of knee joint is designed in advance and a special joint is used when the knee joint is intentionally locked [19], [20], [11].

V. Conclusion

A novel method to design dynamically consistent motions in which the robot passes by the limit of kinematics was proposed based on the robust prioritized inverse kinematics solver. An idea to constrain the minimal number of contact points with respect to the desired ZMP and unconstrain the other points works to emerge natural contact state transition. Also the velocity mitigation succeeds to suppress the effect of discontinuous change of constraints. It is expect to enable motion designers to more intuitively synthesize human-like motions. An enhancement to on-line motion planning is the future work.

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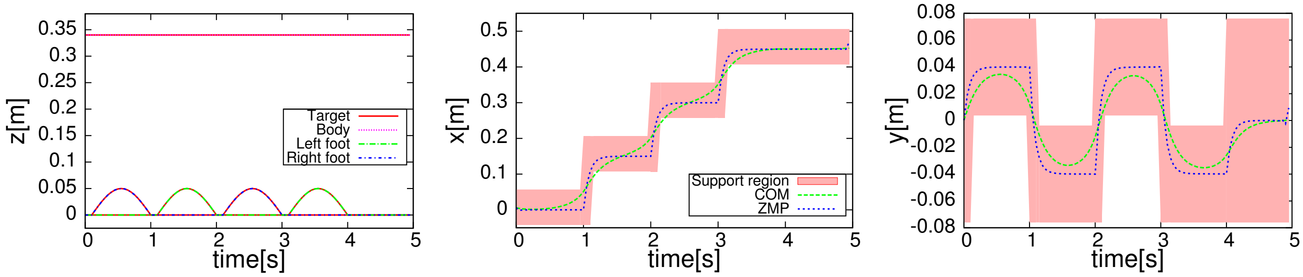
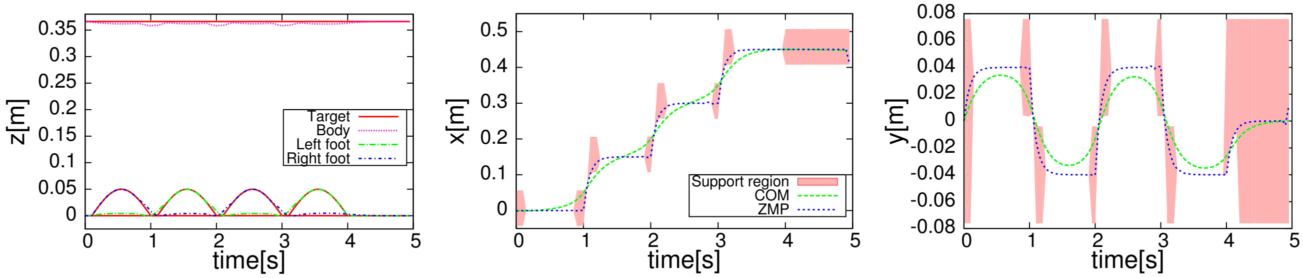


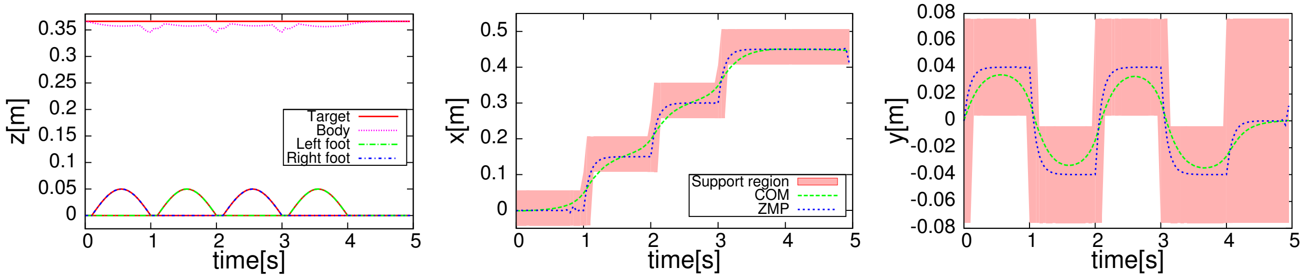
(a) trunk and feet (b) supporting region and ZMP (c) supporting region and ZMP

Fig. 6. Trajectories of trunk, feet and ZMP in case I



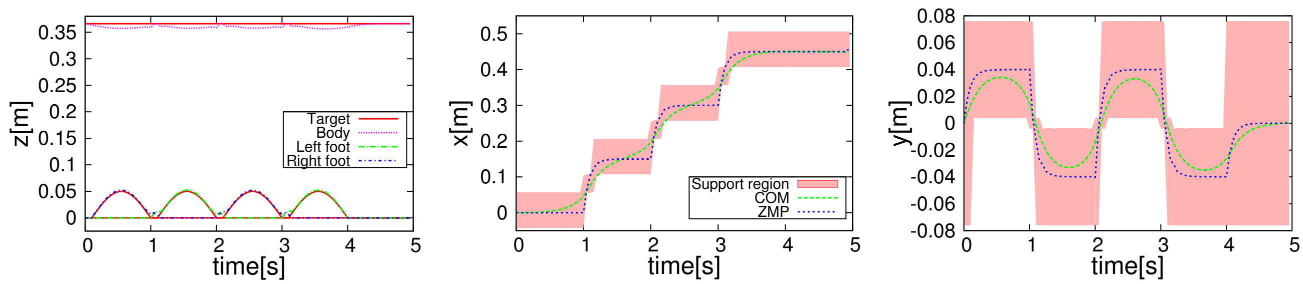
(a) trunk and feet (b) supporting region and ZMP (c) supporting region and ZMP

Fig. 7. Trajectories of trunk, feet and ZMP in case II



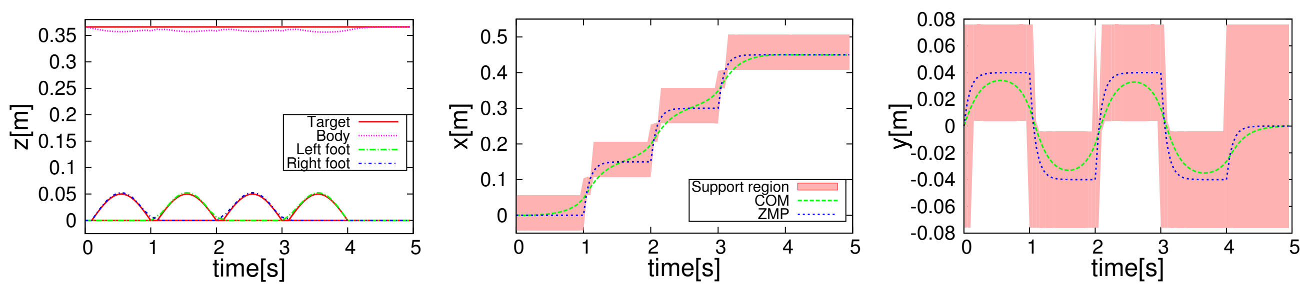
(a) trunk and feet (b) supporting region and ZMP (c) supporting region and ZMP

Fig. 8. Trajectories of trunk, feet and ZMP in case III



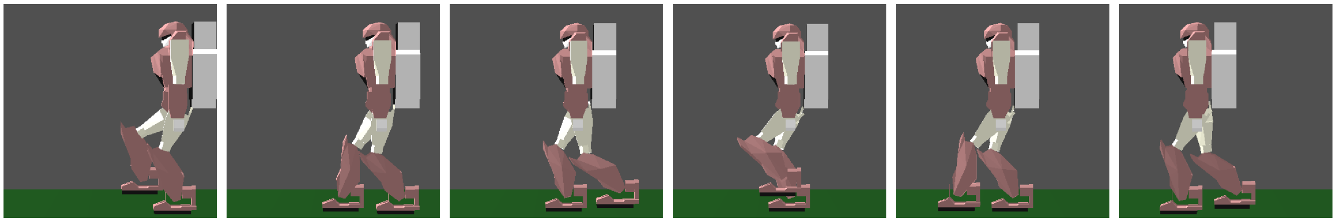
(a) trunk and feet (b) supporting region and ZMP (c) supporting region and ZMP

Fig. 9. Trajectories of trunk, feet and ZMP in case IV



(a) trunk and feet (b) supporting region and ZMP (c) supporting region and ZMP

Fig. 10. Trajectories of trunk, feet and ZMP in case V



0.6[s] 1.0[s] 1.2[s] 1.6[s] 2.0[s] 2.2[s]

Fig. 11. Snapshots of a designed walking motion in case I

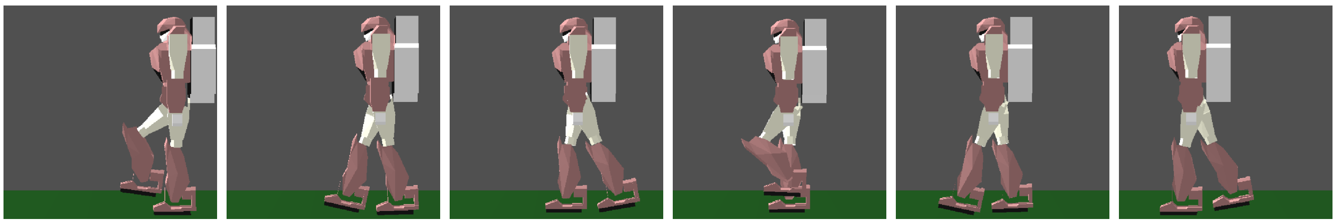


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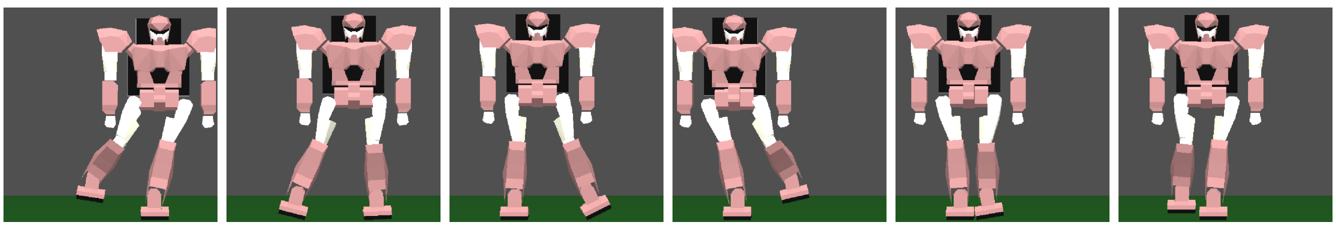
Fig. 12. Snapshots of a designed walking motion in case V



0.6[s] 1.0[s] 1.2[s] 1.6[s] 2.0[s] 2.2[s]

Fig. 13. Snapshots of a sideward walking designed by the proposed method

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