Responsive Biped Control Based on COM-ZMP that is Available Even at the Limit of Kinematics

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1. Introduction

The use of biped robots is a preferable choice for tasks in environments where navigation over many different types of terrains is required as robots could move through it in a similar way as humans without any modification of the environment. However, as biped robots are highly complex systems with a large number of degrees-of-freedom, redundancy and under-actuation, their locomotion is still a challenge. One widely used strategy is to simplify the complex robot model to an inverted pendulum model where the robot dynamics is reduced to the motion of its center of mass (COM) and the point of interaction with the ground where the horizontal moment around it is zero, also known as Zero Moment Point or ZMP[1] in short. Many works based on COM-ZMP model showed its use for locomotion[2][3][4].

Due to the simplified model, kinematics constraints are not considered in the calculation of COM reference which may be located outside the robot workspace and the system may reach a singular point, which may create indeterminacy in terms of computation. A conservative approach differs from the human natural motion as it restricts the robot motion to avoid singular points and limits of motion range. An example is walking, where humans use the kinematics limits such as stretched knee while robots with this approach keeps their knees bended to avoid singularities (Fig. 1). Consequently, there is great care to design motion restraints and a detailed knowledge of the robot structure is required which is a great burden for its design. Herdt et al.[5] considered the problem of motion range limits to obtain a more efficient and natural walk for a Linear Model Predictive Control. However, it did not take into account the whole workspace and only considered the upper part of workspace which was convex and approximated it by a convex polyhedron, thus this approach was not general enough to consider the lower limits of workspace. Due to these facts, the present work aims to fill the gap between control based on reduced models and kinematics constraints.

Tanaka et al.[6] proposed a novel dynamically consistent motion design method in which the robot passes by the limit kinematics based on a robust prioritized inverse kinematics[7] which automatically mitigates velocity to deal with the discontinuous change of priorities. When this method is applied to a controller, there are the following problems:

1. The controller output may diverge when the robot reaches the limit of kinematics as this kind of configuration usually makes leads to loss of controllability.
2. Velocity mitigation depends on a recalculation of the inverse kinematics which may not be practical to real-time control.
3. Discontinuous change of constraints may still leads to non-smooth motion, particularly in the case they reduce the workspace.

This work proposes the following techniques to solve the above issues: for 1, the idea is to bound the controller output by use of the robot bounded states when it reaches the limit to solve the loss of controllability. To solve the issue 2 a criterion to mitigate velocity is based on the gap between desired and actual position of COM. Lastly, to solve 3 manipulation of low-priority weights to decrease continuously the error between desired and actual value of COM is proposed. Walking motion with stretched knees demonstrates the applicability of this work for the kinematics limit problem where the conventional approach is not successful.

2. Bounding desired motion

The equations of motion of the COM-ZMP model can be defined as

\[ \ddot{x}_G = \zeta^2 (x_G - x_Z) \]  
\[ \ddot{y}_G = \zeta^2 (y_G - y_Z) \]  
\[ \ddot{z}_G = \frac{f_z}{m} - g \]  
\[ \zeta^2 = \frac{\dot{z}_G + a}{z_G - z_Z} = \frac{f_z}{m(z_G - z_Z)} \] 

Fig.1 Comparison of walking motion between human which uses kinematics limits (stretched knees) and robot with restrained motion due to conservative approach (bended knees).
where \( \mathbf{p}_G = [x_G \ y_G \ z_G]^T \) is the COM position coordinates, \( m \) is its whole mass, \( g = 9.8\text{m/s}^2 \) is the gravitational acceleration, \( f_z \) is the vertical force, \( \mathbf{p}_Z = [x_Z \ y_Z \ z_Z]^T \) is the ZMP coordinates. As vertical force is the reaction force from the ground and ZMP must lie within the support region \( S \), the dynamical constraints are given by

\[
\mathbf{p}_Z \in S, \quad f_z \geq 0. \tag{5}
\]

To satisfy the dynamical constraint, ZMP and vertical force are chosen as system inputs and designed to ensure Eqs.\( (5) \) and \( (6) \).

From these equations, the referential COM is obtained by integrating Eqs. \( (1) \) \( (2) \) and \( (3) \) and applied to the prioritized IK solver, which gives the desired joint angles to be used in the joint servo control for the robot motion. If the joints can track the desired angles such that the error of angles are zero, inverse kinematics and joint control are equivalent to a buffer with desired and actual task as input and output, respectively. When the robot reaches the limit of kinematics there might be a non-negligible gap between the actual and desired positions, and the controller loses controllability. Such behavior can be characterized as a saturation with varying value as workspace boundary changes and the complete system becomes as Fig. 2(a) with the saturation

\[
\mathbf{p} = \begin{cases} \bar{p}, & \text{if } \delta\mathbf{p} \notin \mathcal{W} \\ \delta\mathbf{p}, & \text{if } \delta\mathbf{p} \in \mathcal{W} \end{cases}, \tag{7}
\]

where \( \mathcal{W} \) is the reachable workspace, \( \mathbf{p} \) is the limit of the workspace, \( \delta\mathbf{p} \) and \( \bar{p} \) are the desired and actual positions, respectively. In saturation, the feedback loop is broken and the controller works in open-loop with wind up of the output. The error of low-priority may become large enough to overcome the effects of high-priorities as demonstrated by the stand motion in Fig. 3(a) and 3(c), where the referential height diverged from the actual COM. As the problem of wind-up comes from integrator and break of feedback loop, the proposed technique is to bound the integrator output by using the values of actual position and velocity as its initial values to avoid excessive increase of the desired value. If the robot reaches the limit at a discrete time \( k_0 \) and stays there for \( n \) time steps, the actual position and velocity become \( \mathbf{p} = \bar{\mathbf{p}} \) and \( \dot{\mathbf{p}} = \mathbf{0} \), respectively, and the controller output is constant to \( a_{lim} \). The desired position \( \mathbf{p}^*[k] \) (for \( k_0 < k \leq n \)) given by the integrator is demonstrated below

\[
\begin{align*}
\dot{\mathbf{p}}^*[k] &= \dot{\mathbf{p}}[k-1] + a_{lim} \Delta t = a_{lim} \Delta t \quad \tag{8} \\
\mathbf{p}^*[k] &= \mathbf{p}[k-1] + \dot{\mathbf{p}}^*[k] \Delta t \tag{9} \\
&= \bar{\mathbf{p}} + a_{lim} \Delta t^2
\end{align*}
\]

The stand motion behavior with bounding method is illustrated in Fig. 3(b) and 3(d). Even though the robot still could not successfully stand still, it can be observed that the referential height did not diverged enough to influence the high-priority constraints (Fig. 3(d)).

3. Limiting low-priority velocity

To solve the problem of abrupt changes of velocities due to discontinuous change of high-priority constraints and limit of kinematics a velocity mitigation[6] using the information of referential gap
4. Satisfaction of contact condition

It could be noticed after the inverse kinematics that while the feet position satisfied the constrained reference, feet attitude did not satisfy its referential value when the robot reached the limit of kinematics even though both were given high priority. This yields an irregular support region shape which makes the robot fall. Therefore feet corner points were given high priority to indirectly constrain both, attitude and position, and to yield a suitable support region.

5. Simulation

A forward motion of a walking controller[3] was simulated for a miniature humanoid robot[8] with total height of 58cm and COM height of 29.41cm when it stands upright. The desired velocity and referential height were set as \( v_x = 0.1 \text{m/s} \) and \( z_{ref} = 0.3 \text{m} \), respectively. For the case with only the feet attitude constraints, it can be seen in Fig. 5(a) a falling motion and a turn of the robot after it lands on the ground. The fall is due to rotation of right foot when it touches the ground which reduces the support region and it makes the robot move backwards (Fig. 6(a), for \( 2 < t < 3 \text{s} \)). On the other hand, with the corner points constrained, it can realize the motion with stretched knees (Fig.5(b)) even when the reference is outside the workspace (Fig.8(b)). The case when the reference height is below the minimum feasible height \( z_{ref} = 0.2 \text{m} \) was also simulated (Fig.9). The crouched walking could be accomplished even though the COM could not reach the reference. The COM height oscillation is due to feet lifting as all corners were given high priority and they have their maximum height set with the same value as the forward case (Fig.9(c)). Simulations for backward, sideward and turn motion were done and similar results were obtained, which demonstrate the accomplishment of the method.

6. Conclusion

This work addressed the problem of mobility due to kinematics constraints and proposed a trajectory-free walking controller which is available even at the limit of kinematics based on the COM-ZMP model and a robust prioritized inverse kinematics. It proposed the following techniques: 1) bounding of desired motion; 2) velocity mitigation and 3) weight manipulation of contact points. Even though the automatic constrain/unconstrain idea[6] were not implemented, the walking controller with techniques 1) and 2) applied demonstrated a higher performance than the conventional method without them. As the method was validated in a simplified dynamics environment, the issues of self-collision and constrained torques were not considered in the present work. Also, to achieve a smoother transition of the support region another approach to be investigated is the distribution of forces on the contact points instead of the geometrical approach of minimum support region.

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Fig. 5 Comparative snapshots with method implemented

Fig. 6 Support region, COM, ZMP and feet (x-axis direction)

Fig. 7 Support region, COM, ZMP and feet (y-axis direction)

Fig. 8 Support region, COM, ZMP and feet (z-axis direction)

Fig. 9 Walk with feet corners constrained and flat-foot ($\frac{d v_x}{d t} = 0.1 \text{ m/s}$, $\frac{d z}{d t} = 0.2 \text{ m}$)

References


