Exploiting the Redundancy for Humanoid Robots to Dynamically Step Over a Large Obstacle

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Abstract—In this paper, we resolve the issue of stepping over a large obstacle by exploiting the redundancy of pelvis rotation and the versatility of foot trajectories for the humanoids. The control framework consists of a motion pattern that exploits the redundancy of pelvis rotation to enlarge the kinematic workspace, a generic foot trajectory generation which can be modified by a parametric interface to adapt to a specific task as well as utilizing the hip abduction to avoid obstacle collision. Moreover, the compensation strategies are also presented for reducing the discrepancies to implement the dynamic stepping motion on a real robot. The effectiveness is validated by COMAN’s capability of dynamically stepping over a large obstacle in both simulation and experiment.

I. INTRODUCTION

The essential advantage and strength of the legged robots are the potential capability of negotiating rugged and unstructured terrains in contrast to the wheeled robots. However, this performance has not been widely demonstrated by real legged platforms, especially the humanoid robots. Without this critical capability, i.e. on the paved roads, legged robots would not attract potential applications compared with the wheeled machines.

Though there are many humanoid robots that cope with different types of terrains such as rough or inclined [1]–[3] surfaces, the conventional decision of encountering an obstacle was to re-plan the path in order to avoid it [4]–[6], despite the robot might have the ability to step over it. The critical merit of humanoid robots was thus not exploited. Therefore, it is significant to manifest humanoid robots’ superior mobility in overcoming uneven terrain even with large obstacles.

Very limited research on this topic has gained enough attentions in literature. ASIMO [7] could autonomous decide whether to step over an obstacle or re-planning the path using vision guided planner, however, the capability of traversing a large obstacle was not presented. In HRP-2 platform, Guan et al. [8] focused on stepping over obstacles in a quasi-static manner by keeping the Center of Mass’s (COM) projection on ground within the convex hull of support area. Also, Stasse et al. [9] used zero moment point (ZMP) criterion to maintain the dynamic stability, and demonstrated that the HRP-2 robot could dynamically cross over an obstacle of 15\text{cm} as high as 21\% of the its leg length, and improved the duration of stepping over from 40\text{s} to 4\text{s} compared to the quasi-static case.

The static and quasi-static stepping over strategies have several limitations as follows:
1) requiring powerful and stiff motors for keeping the static or quasi-static stability;
2) requiring much more time to accomplish one task;
3) requiring more control effort to implement on an intrinsically compliant humanoid robot.

Particularly, the DARPA Robotics Challenge (DRC) requires the humanoid robots to have the potential to be deployed during a disaster response. The one of the greatest hurdle is their locomotion capability, which is still poorer than humans. It is strongly demanded that humanoid robots should be capable of autonomously overcoming obstacles, which means that robots can detect the environment and determine the feasibility of stepping over the obstacle, then make a decision for their next movement. This is especially important, since in the disaster site, it is very much unlikely to have a clean path without any obstacles. Several teams have been already advancing ahead in this field [10]–[12].

The dynamic stepping over strategies without the utilization of redundancy or the versatility of foot trajectories have several obvious limitations. It restricts the humanoids to perform a longer and higher step, or easily encounter kinematic singularity while trying to do so. Moreover, without exploiting the redundancy in the trajectory planning stage could spend unnecessary computational power for doing complex optimization for a high degree of freedom (DOF) humanoid.

Therefore, to maximize the humanoid robot’s entire potential in mobility, we focus on the development of deterministic algorithms for exploiting the pelvis rotation and foot trajectories. We will demonstrate the feasibility to overcome large obstacles and achieve more human-like behavior as an alternative to the optimization approach which is more sophisticated and requires much higher computational power.

The testbed on which we study is the COmpliant Hu-
MANoid COMAN (Fig. 1). It is a full body robot developed based on the compliant leg prototype in [13], [14] capable of stable dynamic walking [15]. The pitch joints of the lower body are selected to equip the passive elastic elements to retain the capability of instantaneous shock absorption, while at the same time to shift the system resonance out of the operation frequency. To enable COMAN to step over a large barrier, we apply deterministic algorithms to explore the pelvis rotational motion to enlarge the leg’s workspace in the direction of stepping, and to make good use of the diversity of all possible swing foot trajectories to negotiate with the obstacles without violating the kinematic constraints.

The paper is organized as follows. Section II delineates the design of swing foot trajectory design, the exploitation of the redundancy of pelvis rotation, and the collision avoidance for stepping over a large obstacle. Section III introduces ankle backlash and the gravity compensation for the pelvis abduction, as well as the whole control framework for implementing the proposed theoretical algorithms on real robot. Section IV and Section V successfully demonstrate the effectiveness in simulation and experiments respectively. We summarize and conclude our study in Section VI.

II. EXPLOITING REDUNDANCY OF PELVIS ROTATION AND VERSATILITY OF SWING FOOT TRAJECTORY DESIGN

A. Generic Foot Trajectory Design

The swing foot trajectory is generated based on a non-dimension pattern as shown in Fig. 2 by the blue line. The pattern is a cubic spline curve with natural boundary conditions in the Cartesian space.

Given a set of interpolation points $\{(x_0, z_0), \cdots, (x_n, z_n)\}$ with $x_0 < x_1 < \cdots < x_n$ to constrain the profile of the trajectory. Define the piecewise cubic polynomials $f_i : [x_i, x_{i+1}] \rightarrow \mathbb{R}$ by

$$f_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + c_i(x - x_i) + z_i, \quad x \in [x_i, x_{i+1}]$$  \hspace{1cm} (1)

for the overall function to be twice continuously differentiable, it is required that

$$\begin{cases} f_i(x_{i+1}) = f_{i+1}(x_{i+1}) = z_{i+1} \\ f_i'(x_{i+1}) = f_{i+1}'(x_{i+1}) \\ f_i''(x_{i+1}) = f_{i+1}''(x_{i+1}) \end{cases}$$  \hspace{1cm} (2)

at the intermediate points. Particularly, to further gain a better clearance and smoothness at lifting and landing, we set the second order derivative to zero at both boundaries. Following the boundary constraints,

$$\begin{cases} f_0(x_0) = z_0 \\ f_0'(x_0) = 0 \\ f_n(x_n) = z_n \\ f_n'(x_n) = 0 \end{cases}$$  \hspace{1cm} (3)

by combining the continuous conditions in (2), we could obtain the trajectory pattern with sufficient lift up and touchdown angles by tuning the set of interpolation points. The sufficient foot-ground clearance and more perpendicular touchdown angles with respect to the ground surface could reduce undesired sliding at lifting and landing.

The foot trajectory pattern defines the relationship between percentage of the step length and the percentage of the lift height, $f_{\text{temp}} : p_{SL} \rightarrow p_{LH}$. Thus, we can generate the foot trajectory by scaling and tuning the pattern using the target parameters to accommodate different tasks:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} p_{SL} & 0 & 0 \\ 0 & p_{SL} & f_{\text{temp}}(p_{SL}) \end{bmatrix} \begin{bmatrix} x_{\text{targ}} \\ y_{\text{targ}} \\ z_{\text{targ}} + h_{LH} \end{bmatrix}$$  \hspace{1cm} (4)

where $x_{\text{targ}}, y_{\text{targ}}, z_{\text{targ}}$ are the target positions of the swing foot, and $h_{LH}$ represents the maximum lift height during the swing phase. The red line in Fig. 2 shows an example of the swing foot trajectory. The used parameters are: 22.5cm forward step length, 5cm side step width, 5cm of lift up height on a stair, and 4cm foot clearance.

![Fig. 2. Swing foot trajectory and template.](image)

![Fig. 3. The variation of the height and the vertical velocity.](image)

In order to use the trajectory to control the robot, we need to add the time mapping $p_{SL} = \tau(t)$ to transform these formulations from three dimensional space $\mathbb{R}^3$ to four dimensional space $[\mathbb{R}^3, t]$. To avoid high impact shock at landing and to smooth the motion pattern transition at lifting, we use the third order polynomial interpolation to formulate
the time mapping $\tau(t)$,

$$\tau(t) = at^3 + bt^2 + ct + d, \quad t \in [0, 1]$$

(5)

where $t$ is the percentage of the step time, and $\tau(0) = 0$, $\tau'(0) = 0$, $\tau''(0) = 0$, $\tau(1) = 0$, $\tau'(1) = 0$, $\tau''(1) = 0$. As shown in Fig. 3, the variation of the position and velocity on the vertical direction are all continuous, and velocity is zero at both the landing and lifting phases.

B. Exploiting Redundancy of Pelvis Rotation

Stepping over a large obstacle challenges the kinematic limitation of a humanoid robot that the kinematics singularity could easily occur. Therefore, it is essential to control the robot to the near singularity condition. Here, taking advantage of the redundancy of the pelvis rotation, the singularity dilemma can be prevented. As shown in Fig. 4, by rotating the pelvis during the walking, it is not necessary to extend the leg as much as the case of the original pelvis orientation to perform the same step length. Therefore, the knee singularity can be avoided.

Based on the geometric correlation between the pelvis yaw rotation and the alternation of support legs, the cooperative yaw rotation $\Psi_{pelvis}$ can be generated in a straightforward manner as

$$\Psi_{pelvis} = k(x_{rt} - x_{lft}),$$

(6)

where $k$ is the ratio factor between the desired rotational angle and the step length, $x_{rt}$ and $x_{lft}$ are the position of left and right foot along walking direction, respectively. The feet trajectories generated in Section II-A are second derivative continuous with the boundary conditions of zero velocity and acceleration. Therefore, the continuous conditions of $\Psi_{pelvis}$ is guaranteed.

C. Collision Check

For stepping over an obstacle, we should check the position of the edge of the foot to make sure that it would not collide with the obstacle. Thus, we set a safety margin around the obstacle, as shown in Fig. 6 by the red shadow area. Besides the trajectory generation, we also compared the trajectory of the foot with the obstacle region. If any section of the trajectory is inside the obstacle region, then $h_{t_{1H}}$ needs to be increased until no trajectory passes through the obstacle region.

Apart from the trajectory design in the Cartesian space, the physical joint limitations can also cause problems in the joint space. As shown in Fig. 5, the foot of the dashed leg cannot maintain its desired orientation, and clashes on the obstacle. Especially the ankle pitch joint limit causes the tilting limitation of the foot, and makes the toe stumble into the obstacle, as shown in Fig. 6 by red line. In this situation, we need to check the whole edges of the swing foot.

The collision detection can be performed through geometric computation based on the regular obstacle shape in the plane of travel, in our case, the sagittal plane. Given two vectors $P_iP_{i+1}$, $O_jO_{j+1}$, where $i, j = 1, 2, 3, 4$, are the perpendicular vectors on sagittal plane of the edges of the foot and the obstacle, as shown in Fig. 6. They are intersected if and only if the collision index $A_{P_iP_{i+1}O_jO_{j+1}} \leq 0$ [8]. $A_{P_iP_{i+1}O_jO_{j+1}}$ is the production of two areas of the triangle formed by points sets $\{P_i, Q_j, Q_{j+1}\}$ and $\{P_{i+1}, Q_j, Q_{j+1}\}$. The collision index can be calculated as

$$A_{P_iP_{i+1}O_jO_{j+1}} = \frac{1}{2} ||O_jP_i \times O_jO_{j+1}||_2$$

$$\cdot \frac{1}{2} ||P_iP_{i+1} \times O_jO_{j+1}||_2$$

(7)
Based on the collision check of the four corners of the foot, $P_1$, $P_2$, $P_3$, $P_4$, we can further explore the abduction DoF of the leg, $\theta_{abd}$, as shown in Fig. 5. Then, three hip joints are synchronized to generate the abduction movement. The angles of three hip joints can be calculated through virtual leg rotation:

$$R_{comp} = R_{x}(\Psi_{pelvis})^{-1}R_{x}(\Phi_{abd})R_{z}(\Psi_{pelvis})$$  \hspace{1cm} (8)

where $R_{comp}$ is the rotation matrix cause of the hip compensation, $R_{x}(\Phi_{abd})$ represents the abduction movement along heading direction, $R_{z}(\Psi_{pelvis})$ is the pelvis rotation. Fig. 6 shows that, with exploitation of the abduction redundancy strategy (blue line), the robot could step over the obstacle.

At last, by combining with the kinematics limitation, the constraint used for the trajectory generation should be as follows,

$$q_{\text{min}} \leq q_i(t) \leq q_{\text{max}}, \quad i = 1, 2, \cdots, 15$$ \hspace{1cm} (9)

$$A_{\mathbf{p}j_i}{O_j}{O_j+1} > 0, \quad \forall i, j \in \{1, 2, 3, 4\}$$ \hspace{1cm} (10)

$$y_{lf} \geq y_{rt}.$$ \hspace{1cm} (11)

where (9) is the constraint on the joint limits (6 DoF for each leg and 3 DoF for torso), (10) represents the constraints to avoid collision with an obstacle, and (11) states that the position of the left foot ($y_{lf}$) would not cross over right foot on the lateral direction to avoid the self-collision of the leg. These constraint formulas will be used as one module in the robot control.

III. COMPENSATION SCHEME FOR THE REALIZATION ON THE REAL HUMANOID

As a humanoid robot with compliant joints, the COMAN robot needs more control efforts to realize the stable and dynamic movements than its rigid peers. Therefore, a special effort needs to be made on the compensation scheme to bridge the gap between the ideal model and the real robot. It is crucial for the implementation of theoretical control algorithms to be successful on the real robot.

A. Backlash Compensation

A humanoid robot can be seen as an inverted pendulum with pivot at its support foot during walking. Hence, even a tiny backlash in the ankle joint generates significant displacement at the COM level, which will deteriorate the state of robot. Therefore, it is important to compensate for the ankle backlash to eliminate this unexpected disturbance. A nonlinear compensation is introduced as shown in Fig. 7, the ankle compensation angle $\theta_{ankle}$ is defined as a function of COP measurement in the support foot,

$$\left\{ \begin{align*}
\theta_{ankle} &= \alpha, & x_{cop} \geq x_{upper} \\
\theta_{ankle} &= 0, & x_{cop} \leq x_{lower} \\
\theta_{ankle} &= \theta_{ankle}, & x_{lower} < x_{cop} < x_{upper}
\end{align*} \right.$$ \hspace{1cm} (12)

Due to the limited stiffness, the torque generated by the weight of the upper body and swing leg will cause a deflection in the support leg’s hip joints, which will tilt the upper body then result in an early landing problem of the swing leg. The robot will gradually lose its balance influenced by the early landing impacts. Therefore, a feed-forward gravity compensation strategy is introduced. As shown in Fig. 8, since the generated walking trajectories are known, the compensation angle $\theta_{gravity}$ can be calculated accordingly using a simplified model which only has three point masses located at upper body, left and right leg’s COM respectively. The stiffness of hip joints is identified experimentally in advance.

B. Feed-forward Gravity Compensation

![Gravity Compensation](image)

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C. Control Framework

Fig. 9 shows the control framework for dynamically stepping over obstacles. The white blocks are the general modules for dynamic walking used in COMAN, due to its generic property, combining additional sub-modules such as stepping over or omnidirectional walking does not require further modification of these basic modules. The blue blocks are the strategies proposed for stepping over previously described in this paper.

The pattern generator used in this work is firstly introduced by Kajita et al. [16] which uses the preview controller to maintain dynamic stability based on the ZMP criterion. The COM reference, pelvis orientation after pelvis rotation strategy (blue line), the robot could step over the obstacle. Therefore, a feed-forward gravity compensation strategy is introduced. As shown in Fig. 8, since the generated walking trajectories are known, the compensation angle $\theta_{gravity}$ can be calculated accordingly using a simplified model which only has three point masses located at upper body, left and right leg’s COM respectively. The stiffness of hip joints is identified experimentally in advance.
obstacle collision check, are the inputs to the COM based inverse kinematics [17]. Then the desired joint angles combined with support foot ankle backlash and hip feed-forward gravity compensations will be passed to a joint limitation validation in order to keep robot within the joints’ workspace. During the whole motion, a local stabilizer [18] is enabled for COMAN to cope with unexpected impacts and disturbances.

IV. SIMULATION

In this Section, the proposed control framework is implemented on a multi-body humanoid robot simulated in the Open Dynamic Engine (ODE). This model has the same physical parameters of COMAN [14]. It has 6 DOFs in each leg, 3 DOFs in the waist, only these 15 DOFs are controlled during the following tests. The upper body joints are controlled to hold the initial position.

The obstacle is modeled as a block with dimensions of 10 cm high by 5 cm wide. Considering the foot size (14 cm × 9 cm) of COMAN and its kinematic limits, as well as the 1 cm safe margin around the obstacle, the step length to walk over the obstacle is designed as 24 cm with the lift height of 12 cm, which are 47.4% and 23.7% of the leg length respectively. The pelvis rotation angle ratio \( k \) in (6) is set to be 0.01 \(^{\circ}/\text{m} \). This means that an incremental change of 1 cm distance between two feet along walking direction corresponds to the change of 1° at the pelvis yaw rotation. Therefore, \( \psi_{\text{pelvis}} \) will reach its maximum of 24° during the double support phase while the robot is passing over the obstacle. The abduction angle \( \Phi_{\text{abd}} \) is designed with half sinusoidal shape with the maximum amplitude of 15° and applied during the swing phase.

The feet trajectories are shown in Fig. 10, the red line represents the left foot which steps over the obstacle first, and then the right foot in blue follows whose orientation is changed during swing phase due to the hip compensation using (8). As shown in Fig. 11, the pelvis rotation angle changes according to the feet distance within one step cycle, which modulates from 0° to −24° during right foot support phase, keeps the maximum rotation angle throughout double support, then reduce back to 0° during the swing phase of the right leg. Fig. 11 also shows the right hip joints’ difference with and without the exploitation of the hip abduction movement. It can be seen that the orientation modification \( R_{\text{comp}} \) is realized by both the roll and pitch joints of the right hip.

V. EXPERIMENTS

The same setting of parameters in Section IV are applied to the real robot in order to experimentally validate the proposed control framework. The gait is generated by the pattern generator: the step time is 1.5 s and the double support phase is 20% of the step time. The backlash \( \alpha \) in (12) is measured as 2.0°, and the \( x_{\text{upper}} \) and \( x_{\text{lower}} \) are 0.01 m and 0 m, respectively. The maximum feed-forward gravity compensation reaches 10° and 9° of left and right hip roll joint during single support phase, respectively.

Unlike the ideal simulation, without these necessary compensations, though COMAN is capable of walking with small steps, it loses balance immediately while trying a longer step.

Fig. 9. Control framework of proposed stepping over strategies.
or stepping over the obstacle. Thanks to the compensation scheme, COMAN is capable of stepping over an obstacle of $10 \times 5\text{cm}$ which is almost 20% of its leg length. Fig. 12 shows both the perspective and the front view of COMAN during the same experiment of stepping over this large obstacle.

VI. Conclusion

This paper presents a control framework for a humanoid robot to step over a large obstacle. It proves that it is unnecessary neither shortening the double support phase nor lowering the COM height for the purpose of stepping over. By only combining the stepping over module to the generic dynamic walking framework, the robot could accomplish the mission without any modification of the normal walking gait pattern.

The proposed strategies include a generic foot trajectory module which can be modified to a specific task, and the redundancy of pelvis rotation is used during walking in order to avoid reaching robot’s kinematic limits, as well as the validation of the margin between the foot and obstacle then adding the hip abduction to avoid collision. Additionally, ankle backlash and hip joint compensations are introduced in experiment. Both results in simulation and experiment show the strategies could successfully accomplish the challenging task of stepping over a obstacle of the height of almost 20% of the leg length.

Future work will focus on the autonomous stepping over obstacles by using the vision perception, involving recognition of the obstacle’s geometrical volume and location. The information from perception will be firstly used to check the stepping over feasibility and collision avoidance, thus the proposed strategies can be used to generate dynamically stable stepping motion.

REFERENCES


