Reactive Bipedal Walking Method for Torque Controlled Robot *

Yisoo Lee\textsuperscript{1} and Jaeheung Park\textsuperscript{1,2}

Abstract—Reactivity to unexpected situations is one of the most important characteristics of walking for real world applications. In this study, we introduce a reactive biped robot walking method that reflects only the current state of the robot. Therefore, time plan and trajectory tracking control are not required for robot walking, and this enables reactive behavior to unexpected contact or disturbance. The walking algorithm is realized through a whole-body control algorithm based on the operational space control framework, that possesses the capability to command the required force for tasks and also implement compliant task behavior by adjusting corresponding task gains. The performance of the proposed method is verified by experiments with a 12-DoF torque controlled biped robot. Robust walking is demonstrated when the foot is stopped by an unexpected obstacle or when the lateral motion is unexpectedly blocked and released by a human.

I. INTRODUCTION

Humanoid robots have the potential to walk freely in human environments. The use of the linear inverted pendulum model (LIPM) \cite{1} enabled the expression of the dynamic relationship between the center of mass (CoM) and the center of pressure (CoP), and thus, it approximates the behavior of the CoM for stable bipedal walking. CoM trajectory generation methods were developed based on the LIPM for robust walking in complex environments by allowing a robot to walk along planned footsteps \cite{2, 3}. With the development of the capture point (CP) \cite{4} and divergent component of motion \cite{5}, footstep adjustment and footstep timing change are accomplished by reflecting the state of the robot in real time, and thus more robust walking can be performed \cite{6}.

Although the trajectory generation method enabled successful robot walking, the stability of the robot is significantly affected by trajectory tracking performance of the robot. If the trajectory tracking performance is low, the robot is unable to perform foot stepping and CoM motion based on the planned time and potentially lose its balance. This is because the trajectory generation method is based on the assumption that the humanoid robots exhibit high trajectory tracking performance. The assumption is mostly suitable for humanoid robots with accurate joint position controller \cite{7, 8, 9, 10}. However, there are robots that exhibit relatively poor position control performance, and it is difficult for these robots to walk by relying on trajectory tracking.

In order to provide compliant behavior with respect to humanoid robots for safe interaction between a robot and the environment, several humanoid robots with joint torque controller were developed recently \cite{11, 12, 13, 14}. Compliant behavior is advantageous in coping with disturbances from unexpected contacts. A torque solution for compliant control at the contact space and task space is obtained by utilizing a whole-body control framework for floating-base robots \cite{15, 16, 17, 18}. However, torque-controlled humanoid robots exhibit relatively lower trajectory tracking performance in task space when compared with position-controlled robots due to the elasticity of the joint and delay between a high-level controller and a low-level controller \cite{19}. Furthermore, good trajectory tracking performance requires high feedback gains, and this is contrary to the compliant behavior pursued by torque-controlled humanoid robots. Therefore, to use the advantages of the compliant behavior, a method of walking in a manner reactive to the state of the robot is more suitable.

Dynamic walking of the robot without high precision control is already possible by utilizing the CP. The experiment results of torque controlled biped robot M2V2 \cite{20} and Roboray \cite{21} indicate that walking is possible by reflecting only the current state of robot. These methods generate the CoM motion based on the force control and preserve the advantages of the robot’s compliance characteristics. They are relatively easy to implement since they are independent of time plan, and the desired tasks are determined according to the current state of the robot.

We developed a reactive walking method in the study utilizing the concept of CP, similar to the walking methods of M2V2 and Roboray. The previous methods assume that the robot’s foot always reaches its destination. However, the robot foot may not arrive to the desired position, not satisfying the aforementioned assumption. This is because of some reasons including unrecognized ground slope and obstacles, low performance of a foot position controller, and joint speed limit. The proposed method in the study involves a reactive and time independent walking pattern that allows walking without losing balance even when the foot does not reach the planned location, thereby enabling more robust

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\textsuperscript{1} The author is also with Advanced Institutes of Convergence Technology, 864-1, Iui-dong, Yeongtong-gu, Suwon-si, Gyeonggi-do, South Korea. He is a corresponding author.

\textsuperscript{2} The authors are with Department of Transdisciplinary Studies, Graduate School of Convergence Science and Technology, Seoul National University, 145, Gwanggyo-ro, Yeoungtong-gu, Suwon-si, Gyeonggi-do, South Korea. \{howcanii, park73\}@snu.ac.kr
walking.

The background theories of the LIPM and the CP are introduced in Section II. Section III proposes a new reactive walking pattern. The control strategy of the robot for walking with the proposed reactive pattern is described in Section IV. The experimental results obtained by using the 12-DoF biped robot with whole-body control framework are shown in Section V. Finally, the discussion and conclusions are presented in Section VI.

II. BACKGROUND

The LIPM is useful to predict the behavior of the CoM and the CoP of the biped robot. The LIPM assumes that the robot is a point mass and the height from the ground is constant. According to the LIPM that is expressed via Cartesian coordinates, the relationship between the CoM and the CoP.

The CoP is described as follows [1].

\[ \ddot{\mathbf{x}}_c = \frac{g}{z_{c,0}} (\mathbf{x}_c - \mathbf{x}_p), \]  

where \( \mathbf{x}_c = [x_c \ y_c]^T \) denotes the position of the CoM in horizontal plane, \( \mathbf{x}_p = [x_p \ y_p]^T \) denotes the position of the CoP in horizontal plane, \( g \) denotes the gravitational acceleration, and \( z_{c,0} \) denotes the height of the CoM that is assumed as constant. As shown in (1), the direction of the CoM acceleration is opposite to the direction from the CoM to the CoP and the magnitude is proportional to the distance between the CoM and the CoP.

A CoP location that decelerates the moving CoM to stop at a specific location is derived from the LIPM. The \( \mathbf{x}_p \) where the \( \mathbf{x}_c \) will stop at the same position is termed as the CP (\( \mathbf{x}_{CP} = [x_{CP} \ y_{CP}]^T \)). The CP equation derived from the LIPM is as follows [20].

\[ \mathbf{x}_{CP} = \frac{z_{c,0}}{g} \ddot{\mathbf{x}}_c + \mathbf{x}_c. \]  

The \( \mathbf{x}_{CP} \) is utilized in the proposed walking pattern because it is a time-independent variable.

Two characteristics are obtained from the LIPM. One is that the CoM accelerates in the opposite direction from the CoM to the CoP, and the other is that when the CoP is located in the CP, the CoM will also stop at the CP. We use these two characteristics to construct a time independent and reactive walking pattern in the next section.

III. TIME INDEPENDENT WALKING PATTERN

In this section, we introduce the concept of the time independent walking pattern based on the LIPM, and subsequently propose a modified pattern that is practically utilized for an actual robot. We only explain the walking pattern in the horizontal plane (\( x-y \) plane) because the LIPM does not include a vertical height change.

A. Concept of Walking Pattern with LIPM

Robot walking is possible if the moving CoM heading to the supporting foot is stopped before it goes beyond the supporting foot polygon and then the stopped CoM is accelerated towards the next supporting foot. Thus, a single footstep period during walking is composed of a single support deceleration phase (SSDP), that decelerates the CoM to stop, and a single support acceleration phase (SSAP), that accelerates the CoM to move toward the next supporting foot (Fig. 1 and Fig. 2). The SSDP and the SSAP are repeated to perform walking.
1) Single support deceleration phase: The SSDP commences with an initial condition in which the CP is located at the center of the supporting foot. This initial condition is the same as the condition for terminating the SSAP as shown in Fig. 1 (a) and (d). The CoM stops at the CP location if the CoP is placed at the center of the supporting foot (Fig. 1 (b)). If the velocity of the CoM toward the supporting foot direction is zero, then the SSDP is terminated and the SSAP is initiated. It is assumed that the massless swinging foot during the SSDP takes off from the ground and immediately moves to the planned footstep location. If the swinging foot is unable to reach the destination due to an external disturbance, it stops within its reach.

2) Single support acceleration phase: The SSAP commences when the CoM velocity in the direction toward the supporting foot is zero. The CoM is accelerated in any direction by locating the CoP inside the supporting foot in a direction opposite to the direction of acceleration, because the position of the CoM is at the center of the supporting foot. The CoP location set to accelerate the CoM remains constant during the SSAP as shown in Fig. 1 (c), and (d). During the SSAP, the CP is always calculated in real-time. The SSAP will be terminated (Fig. 1 (d)) if the CP reaches the reference CP that is located at the center of the landing foot, . The swinging foot lands on the ground at the position reached at the end of the SSDP.

Stable walking is performed with a repetitive walking pattern even when the swinging foot does not reach the planned location because the CoM is accelerated toward the landing foot and not the planned footstep.

B. Modified Walking Pattern for Real Robot

The behavior of the actual robot differs from that of the LIPM, which is a simplified model. Therefore, the walking pattern in Section III-A is modified by considering the following three practical issues caused by the difference between the real robot and the LIPM. The first issue that the CoP cannot immediately move from one foot to the other in the real robot. The second issue is that the swinging foot is unable to move sufficiently fast to reach the desired position at all times during the SSDP. The last issue is that the actual robot is unable to perfectly stop at the CP even if the CoP is located at the CP.

1) Double support phase: The first modification is the insertion of the Double Support Phase (DSP) between the SSAP and SSDP as shown in Fig. 3. Therefore, repetitive cyclic pattern consists of SSAP, DSP, and SSDP sequences. We add a DSP to allow the CoP to move continuously from the present supporting foot to the next supporting foot. When the CoP completes moving to the center of the supporting foot, the DSP is terminated and the SSDP commences.

2) SSAP - Modification of reference CP: Quite often, the swinging foot fails to arrive at the planned footstep location as previously mentioned when the SSDP is terminated. In order to extend the time that the swinging foot moves, we allow the swinging foot to move in the horizontal plane (x-y plane) not only in the SSDP and in the SSAP. The direction of CoM acceleration also changes according to the swinging foot motion during SSAP because the CoM is always accelerated toward the center of the swinging foot in this phase. For control convenience, the x-direction of the frame O is defined to exhibit a direction toward the center of the swinging foot with respect to the center of the supporting foot as shown in Fig. 4. With respect to the frame O, accelerating the CoM in the x-direction initiates the CoM motion toward the swinging foot. However, as mentioned, the acceleration direction of the CoM also changes when the swinging foot moves. The change in the acceleration direction causes a drift motion in the normal direction (y-direction in Fig. 4). The position and the velocity in the y-direction are controlled to be zero such that the CoM moves towards the center of the swinging foot without drifting in the y-direction. Details related to the control are given in Section IV.

3) SSAP - Modification of reference CP: The behavior of the robot differs from that of the LIPM, and the DSP causes a delay in the transition of the CoP. Due to these reasons,
the CoM often stops after the expected location. It usually stops after exceeding the expected location. The robot loses its balance if the CoM moves beyond the supporting foot area as shown in Fig. 5 (a), and this situation should be avoided. Therefore, it must stop before the CoM crosses the supporting foot during the SSDP. Thus, the reference CP is located at a distance \( r \) from the center of the landing foot to the center of the supporting foot. In Fig. 4, \( x_p \) and \( y_p \) represent the reference CP. It is expressed as \( x_p = x_f - r \) and \( y_p = 0 \) with the frame \( O \). The distance \( r \) is empirically determined. If the estimated CP is more accurate and the control response of the robot is faster, then the robot walks even if \( r \) is low. At the next SSDP, the CoP is located at the center of the supporting foot and not where the reference CP is located such that the CoM stops near the CoP.

4) SSAP - Determination of desired CoP: Based on the position of the swing foot, the range of feasible CoP also changes as shown in Fig. 4. While using frame \( O \) in Fig. 4, in order to accelerate the CoM in the \( x \)-direction, the desired CoP in the same direction \( (x_{p,d}) \) should be located behind the CoM. Additionally, the CoP should be placed inside of the supporting foot polygon. Therefore, the CoP in the \( x \)-direction must lie between the CoM within the foot boundary. The range of feasible boundary in \( x \)-direction is expressed as \( \Delta P_r \) in Fig. 4 (b). The \( x_{p,d} \) is the center of the foot when the CoM locates in front of the center of the foot. But when the CoM locates behind the center of the foot, \( x_{p,d} \) should be located behind the CoM. In that case, as shown in Fig. 5 (b), the desired CoP is set as \( x_{p,d} = x_c - \zeta \), where \( \zeta \) is an empirically determined value. Then, the CoM is accelerated because the desired CoP, \( x_{p,d} \), is located behind the CoM by \( \zeta \).

IV. CONTROL STRATEGY

The adoption of the whole-body control framework [15], [16], [17], [18] allows force control in the task space. When the walking pattern provides desired acceleration of the CoM (\( \ddot{x}_c = [\ddot{x}_r, \ddot{y}_c, \ddot{z}_c]^T \)) and the swing foot (\( \ddot{x}_f = [\ddot{x}_f, \ddot{y}_f, \ddot{z}_f]^T \)), the whole-body controller calculates joint torque (\( \Gamma \)) for the task space control to generate the required acceleration (Fig. 6).

Each walking phase is described based on the frame \( O \) in Fig. 7. Frame \( O \) in SSAP is equivalent to that in Fig. 4. The frame in DSP is the same as the frame at the end of the SSAP. At the SSDP, the origin is located at the center of the new supporting foot, although, the direction matches that of the DSP. The origin of frame \( O \) that is located at the center of the supporting foot, the \( x \)-axis is parallel to the straight line connecting the centers of the two feet, and the \( z \)-axis is perpendicular to the ground. Thus, the direction of the \( x \)-axis is always toward the direction in which the CoM is required to accelerate or decelerate.

Frame \( O \) is used to control the \( x \)-direction of the CoM to produce the desired acceleration. The \( x \)-direction acceleration (\( \dot{x}_c \)) is determined by the desired CoP in the same direction \( (x_{p,d}) \). During the SSAP, \( x_{p,d} \) is determined as described in Section. III-B.4. During the DSP, the \( x_{p,d} \) moves to the center of the next supporting foot from the final value of \( x_{p,d} \) at the SSAP. The straight line between the two points is expressed by using a linear interpolation equation divided by an arbitrary interval \( (d_{p,d}) \), and subsequently \( p_{x,d} \) increases by the interval \( d_{p,x,d} \) for each sampling time of the controller with \( x_{p,d} = 0 \) during the SSDP. Acceleration \( \dot{x}_c \) generated by \( x_{p,d} \) can be calculated with the LIPM equation (1) or can be calculated using multi-body dynamics for more accurate calculations. In the study, the method employing multi-body dynamics in [22] that we previously developed is utilized.

The \( y \) and \( z \)-directions of the CoM are controlled to maintain a constant position with PD-control scheme. The accelerations of each direction of the CoM is expressed as follows.

\[
\begin{align*}
\ddot{y}_c &= k_p(y_{c,d} - y_c) - k_v\dot{y}_c, \\
\ddot{z}_c &= k_p(z_{c,d} - z_c) - k_v\dot{z}_c,
\end{align*}
\]

where \( y_c \) and \( z_c \) are the position of the CoM in each direction, \( y_{c,d} \) and \( z_{c,d} \) are the desired position of the CoM in each direction, \( k_p \) is the proportional gain, and \( k_v \) is the derivative gain. As previously mentioned, \( y_{c,d} = 0 \) and \( z_{c,d} = 0 \).

The swinging foot position is controlled during the SSDP and the SSAP to move towards the planned footstep with PD-control. Therefore, the linear acceleration of the foot is expressed as follows.

\[
\begin{align*}
\ddot{x}_f &= k_p(x_{f,d} - x_f) - k_v\dot{x}_f, \\
\ddot{y}_f &= k_p(y_{f,d} - y_f) - k_v\dot{y}_f, \\
\ddot{z}_f &= k_p(z_{f,d} - z_f) - k_v\dot{z}_f.
\end{align*}
\]

The desired height of the swinging foot (\( z_{f,d} \)) depends on the phase. During the SSAP, the desired height is zero because the foot must land on the ground. The desired height of the swinging foot during the SSDP is a constant value \( z_0 \) that exceeds zero because the swing foot is taken off and should be in the air for swinging motion. The desired foot location...
The balance controller [25] is additionally used since the proposed method does not consider the effect of the tasks with the exception of the x-direction CoM force on the balance. The balance controller controls the contact moment in the null-space of the high-priority task. Therefore, tasks set as high-priority are always executed, and low-priority tasks are modified for balance control. In the experiment, all tasks with the exception of the trunk orientation are set as high-priority, and thus the balance is controlled by rotating the body orientation. For all the experiments, $k_p$ is 100 and $k_e$ is 20 for all the tasks. These control gains were selected to allow the task to behave in a manner similar to a critically damped system, and a relatively low value was selected for compliant control. The desired footstep positions for the experiments were arbitrarily determined. In order to express the results of walking experiments, we defined the frame $O_g$, in which the origin is located at the CoM position projected on the ground when the robot commences walking. The $X_g$-direction of $O_g$ is equal to the heading direction of the torso at the beginning of the walking, while $Z_g$ is parallel to gravity direction albeit opposite in direction.

### A. Case 1. Walking experiment

As shown in Fig. 8, the robot performed a continuous walking experiment. The CoM motion and footstep results during walking are shown in Fig. 9. The desired step length is 0.1 m and the step width is ±0.24 m from the supporting foot. To prevent landing from unexpected early contact with the ground, the vertical landing position of the foot was set to a position that is 0.005 m higher than that of the supporting foot. To prevent landing from unexpected early contact with the ground, the vertical landing position of the foot was set to a position that is 0.005 m higher than that of the supporting foot. The swinging foot height may be reduced to a negative value as shown in Fig. 9 (c) because the ground is not perfectly flat. The position where the swing foot arrives differs from the desired position by several centimeters, because the ground is slightly inclined and the control feedback gains of the robot are relatively low (Fig. 9). The robot walks even without accurate position control...
Fig. 8. Snapshots during walking experiments. (a) to (f) show states during continuous walking.

Fig. 9. Actual CoM motion, desired swing foot position and actual foot position during the walking experimental (Case 1). (a) \(X_g\)-direction. (b) \(Y_g\)-direction. (c) \(Z_g\)-direction.

Fig. 10. Results of the experiment Case 1. (a) Phase of walking pattern. Double foot support when phase value is 0 in the plot, right foot support when phase value is 1 in the plot, and left foot support when value is -1 in the plot. (b) Reference capture point and capture point \((x_{CP})\) calculated by measured CoM state in \(x\)-direction. (c) Desired CoP \((x_{p,d})\) in \(x\)-direction.

The phase changes according to the state are shown in Fig. 10 (a). The walk commences from the DSP since the CoM is stationary and the robot is in the DSP at the beginning. During the DSP, the desired CoP moves to the supporting foot at approximately 1.3 s as shown in Fig 10 (b). When the desired CoP arrives at the center of the supporting foot, the SSAP subsequently commences. The CP is calculated during the SSAP to determine when to terminate the SSAP. As shown in Fig. 10 (a), SSDP commences after the CP and reference CP intersect. Following this, the pattern is repeated and the walking progresses.

The CP is significantly influenced by the accuracy of the estimated CoM. If the CP is inaccurate, it affects the stability of the developed walking method. Therefore, the value of \(r\) corresponding to the safety margin of the CP is relatively as high as 0.09 m in the experiment. The same value of \(r\) as in Case 1 is used in the all experiments. If the value of \(r\) is high, the single step time is shortened and the time to perform the swing foot motion is potentially insufficient. If the value of \(r\) is low, the CoM may move beyond the supporting foot boundary and loses balance. In the experiment, the average time taken for single step was 0.68 s, and the step length was 0.1 m. Thus, the robot moved at a velocity of approximately 0.147 m/sec.

B. Case 2. Unexpected collision at the swing foot

As shown in Fig. 11, the experiment is conducted in the case where the obstacle is present in front of the right foot of the robot. Walking is performed under the same conditions as those in Case 1. Due to the compliant behavior of the torque-controlled robot, the foot is safely controlled when it collides with the obstacle. However, the swing foot is unable to move to the planned footstep. The experiment shows that walking is continues even when the swinging foot is unable to move to the target place due to obstacles on the ground. Therefore, it is advantageous to use both the compliant control scheme and the reactive walking method developed in the study.

As shown in Fig. 12 (a), the obstacle is located approximately 0.34 m ahead of the right foot. Changes in the position of the feet and the desired position of the swing foot are shown in Fig. 12 (b). At the first step of the right foot (1.25 \(\sim\) 1.94 s), it collides with the obstacle and is unable
to move to the destination. The second step motion of the right foot (2.77 ~ 3.63 s) is also disturbed by the obstacle. Therefore, it only moves a short distance of approximately 0.016 m. During the experiment, the desired position of each step of the swinging foot is controlled to move forward by 0.1 m relative to the position of the supporting foot (Fig. 12 (b)). The robot is unable to escape from its current location.

Fig. 12. Experimental results of Case 2. (a) CoM and supporting foot position plotted on a horizontal plane. Obstacle is described by green square. $X_g$ and $Y_g$ are describing direction of horizontal plane. (b) Motion of right and left foot in $X_g$-direction.

Fig. 13. Snapshots of the experiment Case 3. When the robot is walking, the person stops the movement of the robot from the side. Red arrow is the direction of movement of the human hand.

Fig. 14. Results of the experiment Case 3. (a) Side motion of CoM and swinging foot during walking in place. $Y_g$ is side direction in lateral plane. The CoM is disturbed from person during 7.8 to 8 seconds and 14.6 to 16 seconds as seen in Fig. 13. (b) Reference capture point and measured capture point in $x$-direction. (c) Phase of walking pattern. Double support phase when phase value is 0 in the plot, right foot support when phase value is 1 in the plot, and left foot support when value is -1 in the plot.

However, it does not fall and continues the walking motion in the same position due to the walking pattern.

C. Case 3. Disturbance at upper body in lateral plane

In the experiment, an external force is applied to the upper body of the walking robot to disturb movement. As shown in Fig. 13, an individual blocks the upper body of the robot. The CoM is quasi-stationary between approximately 7.8 and 9 s as shown in Fig. 14 (a) because the individual completely blocks the robot. Therefore, the CP did not exhibit a significant change during this time as shown in Fig. 14 (b). At approximately 9 s, an individual releases the hand that blocks the robot. Following this, the CoM of the
robot accelerates again toward the swinging foot to continue walking.

From approximately 14.6 to 16 s, an individual again blocks the robot with a low amount of force such that the robot moves slowly but does not stop. These experimental results indicate that the developed walking method reacts to unexpected contact or disturbance and adjusts its motion very robustly. If the robot is unable to move, it stops walking and subsequently continues when it is possible and moves slowly if a disturbance interferes with the movement. Therefore, reactive walking is performed.

VI. CONCLUSIONS

In the study, a reactive walking algorithm for bipedal robots is proposed. The method uses only the current state of the robot to compute the control force for tasks during walking. Therefore, it provides the robot with reactive behavior with respect to an unexpected contact or disturbance. The main part of the proposed walking algorithm involves the creation of a control force on the COM of the robot. The force is always computed in the line from the supporting foot position to the current swing foot position. This enables the reactive behavior of the COM when the swing foot is unable to move forward due to an unexpected obstacle or force. In addition, the instantaneous capture point is used to determine when to accelerate, decelerate, and stop the COM. The compliant behavior of the COM for the disturbance at the trunk of the robot was realized by this part of the algorithm. The experimental results demonstrated the reactive walking behavior of the robot especially when an unexpected contact or disturbance was applied to the robot. A future study will additionally use a force-torque sensor feedback control for more reactive and stable walking. This type of reactive walking algorithm is further utilized for more complex and stable walking in combination with a higher level of planning for the robot.

REFERENCES


