Biologically Motivated Push Recovery Strategies for a 3D Bipedal Robot Walking in Complex Environments*

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Abstract—Though balancing is a fundamental part of human walking, it has been a challenging topic for bipedal robot. Compared to the versatile strategies for handling disturbances of humans, current bipedal robots possess limited skills of managing external disturbances. Among them the capabilities of push recovery and maintaining balance are obviously of prior importance for a bipedal robot to walk in an unknown environment. Existing solutions, such as, capture point, walking phase modification, foot placement estimator and etc, are mostly based on simplifying a bipedal robot as a linear inverted pendulum, which result in omitting the effects of knee and ankle joints, natural dynamics, ground reaction forces and interaction between joints in sagittal and frontal planes in a 3D bipedal robot. To overcome those drawbacks, this paper presents a work that classifies push types, presents a push detector, and proposes control strategies for managing continuous strong pushes occurring during walking. Based on biological and biomechanical research, more efficient strategies, e.g., hip and ankle strategy and a bent-knee strategy, can be transferred to control methods for bipeds. Through generating required torques and/or regulating joint positions in order to stabilize bipedal robot, a push recovery controller is proposed in this paper. Simulation results demonstrate that a 3D physically simulated anthropomorphic biped with 21 degrees of freedom can succeed in recovering from a strong push of up to 200 N during walking in different walking scenarios.

I. INTRODUCTION AND RELATED WORK

Much research has focused on the problem of push recovery while the robot is standing [1]–[3]. However, the problem of push recovery during walking is more intriguing and has not been explicitly explored. The motivation of this paper is to find human-like strategies of push recovery for bipedal walking.

The contribution of this paper is a way to detect and classify a push and design various strategies for balancing the robot when pushes occur in different situations. According to the strength of the external push, it can be categorized into light push and strong push. A push detector can detect the push when the robot is both standing and walking by computing the Center of Mass (CoM), the extrapolated Center of Mass (XcoM) [4], as well as the Center of Pressure (CoP). Afterwards, a strategy that is called hip and ankle strategy generates more forward momentum at hip and ankle joint if a push is detected before the foot clearance. A second one that is called knee strategy bends the knee joint and then holds the joint position if a push is detected after the

foot clearance. Finally, the proposed strategies are verified with a 3D physically simulated bipedal robot in scenarios of walking on level ground and rough terrain.

A brief literature survey concerning push recovery strategies for bipedal robots will first be deliberated. Hofmann [5] has presented three push recovery strategies. The first one is to shift the CoP for light push. The second one is to generate torque around the CoM if the first one failed. Finally if both of them failed, a step must be taken in order to maintain stability.

Kajita et al. [6] point out the importance of the angular torque control in postural balance analysis for bipedal robots by using Linear Inverted Pendulum Model (LIPM). Pratt et al. [2] introduce the concept of Capture Point (CP) and extend the model of LIPM with a flywheel body.

Besides the LIPM model, multi-body models describing dynamics of bipedal robots for high accuracy recently receive more interests. Zutven et al. [7] introduce the Foot Placement Indicator (FPI) by using a multi-body model in which the masses of all links are taken into account. A 3D multi-body model offers higher accurate description of the dynamics, however, greater computational cost and less consideration of inherent dynamics can be observed.

Therefore, towards a more competitive push recovery strategy, researchers have tried to compound various approaches. Zhao et al. [3] integrate the CP into a biologically motivated controlled biped [8], [9] when it is standing still. The proposed strategies are that the hip joint provides maximum torque if a push is detected while the ankle joint offers braking torque when the swing leg contacts the ground in order to come to a safe stop.

Yet all of those aforementioned methods solve the problem of push recovery when the biped is standing still.

Komura et al. [10], [11] propose a theoretical feedback controller scheme for push recovery when walking in sagittal plane. It states that the hip strategy is employed and the stepping location is adjusted to compensate the unexpected angular momentum operating on the LIPM model. Unfortunately the experimental verification upon a biped is yet missing. Adiwahono et al. use the LIPM to adjust the step duration and length [12] of the robot against disturbances during walking. However, the effect of ground contact has been neglected. Assman et al. [13] study the side stepping through a simplified model and then validate assumptions by testing it on a 3D bipedal robot in reality and simulation. Nevertheless, the strategies of push recovery for sagittal walking are not yet proposed theoretically and verified experimentally. Therefore, investigating strategies of push

*This work has been funded by the European Commission 7th Framework Program under the project H2R (no.60069).

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recovery for 3D biped during walking in a thorough and systematical way is still required.

II. DYNAMIC SIMULATION OF A BIPEDAL ROBOT

A. Introduction of Simulation Environment

The control system and simulation of this work is achieved through utilizing the framework mca2 (modular controller architecture). Its elemental control units characterizes an interface of control and sensor inputs and outputs as modules. Modules are connected by edges transferring processed data between interfaces. For rigid body dynamics calculations, the Newton Game Dynamics library\(^1\) is applied.

B. Robot Setup

A bipedal robot model, which is based on human gait analysis associating with the most relevant joints for walking, is developed as the simulation subject (as shown in Fig. 1). The overall system amounts to 21 degrees of freedom, and the robot’s height adds up to 1.8 m. Weight distribution is based on average human data, with a total weight of 76 kg. Furthermore, the sensory system includes a sense of balance, load perception, and cutaneous sensor information of the foot soles. At each joint, the current angular position and the acting torque can be captured as sensory data. In addition, four one-dimensional force sensors are mounted in the corners of each foot, and referred to as inner toe, outer toe, inner heel, and outer heel sensor.

C. Control Structure

A biologically motivated control method emerges as a transfer of key features in biomechanics and biology of human walking control to biomimetic robotics [8]. The control architecture is developed as a hierarchical system with the combination of feed-forward and feedback control units. Fig. 2 illustrates the hierarchical layout defined by the flow of stimulation, inhibition, and modulation between six classes of control units.

\(^1\)http://www.newtondynamics.com

![Fig. 1: (a) Simulated biped in the simulation framework. (b) Joint layout of the biped model. It has three DoFs at hip and spine joints, with the shoulder and ankle joints as two subsequent revolute joints and one for the knee joint.](image)

![Fig. 2: Hierarchical organization of control units and interaction of control system, stimulation and modulation paths, and connection to the mechatronics and environment [8].](image)

III. CLASSIFICATION OF PUSHES

Although extensive investigation has been given to developing feedback controllers for handling disturbances, clear categories of disturbances are still missing. Among all kinds of disturbances, the push is the favorable research object. For facilitating the experiments in this paper, we will define and categorize them as follows:

**Light Push**

A push is called a light push if the induced angular momentum is less than that of the biped at the moment just before impact. Eq. (1) describes the relation between push force and the biped, in which \(F\) is the external push, while \(m_{com}\), \(\dot{\theta}\), and \(l\) represent respectively the mass, angular acceleration about the ankle joint and the leg length of the biped.

\[
F < m_{com} \cdot \dot{\theta} \cdot l.
\] (1)

**Strong Push**

A push is called a strong push if the induced angular momentum is larger than that of biped at the moment just before impact. Eq. (2) expresses this relation

\[
F > m_{com} \cdot \dot{\theta} \cdot l.
\] (2)

Considering the impulse impact on the biped, the duration of push introduces two terms: one is the instantaneous push, while another is the continuous push.

- **Instantaneous Push**
  
  A push is called an instantaneous push if the contact time is less than a constant time \(T\).

- **Continuous Push**
  
  A push is called a continuous push if the contact time is greater than or equal to a constant time \(T\).

According the natural frequency of the system, we choose \(T = 0.1\) s as a decent time limit of push for such a bipedal system in the simulation.

IV. PUSH DETECTION

A. CoM and XcoM

Two main concepts in the study of balance control are the CoM and CoP; while the force of gravity acts on the CoM
and the ground reaction force on the CoP. To control the balance of biped, Hof [4] introduces the XcoM to predict balance. When the projection of the CoM position on the ground is denoted as $d$ and linear CoM velocity as $\dot{d}$, XcoM position $x_{com}$ is defined as:

$$x_{com} = d + \frac{\dot{d}}{\omega_0}, \quad \text{with} \quad \omega_0 = \sqrt{\frac{g}{l^3}},$$  \hspace{1cm} (3)

where $\omega_0$ denotes the natural frequency with the pendulum length $l_3$ of the CoM above the foot. The XcoM reflects both the integration of the CoM’s velocity and the oscillation of the upper body. Therefore, to control the forward velocity of a simulated biped, Luksch [8] developed a postural controller Forward Velocity that calculates a correction value for the forward velocity, which is used to generate a suitable ankle torque. Given the fact that a deviation from the XcoM trajectory stems from external or self-induced disturbances, the correction portion is based on this deviation. Hence, $x_{comi}$, the trajectory of XcoM in sagittal plane over the time interval, during which the corresponding leg has ground contact, is approximated by the first quarter of a sinusoidal function in [8].

Furthermore, Hof et al. [14] state that in order to keep the biped in stable state, the following condition has to be fulfilled:

$$x_{cop} \geq x_{com},$$  \hspace{1cm} (4)

with $x_{cop}$ defining the sagittal position of the CoP. In the scope of this work, four force sensors, which are mounted in the foot corners as mentioned in Sec. II-B, allow to estimate the position of the CoP. The $x_{cop}$ expresses a relative position with respect to the foot, where 1 denotes the anterior end of the foot and 0 the posterior end.

**B. Push Detection**

To detect the push, we employ the two critical terms mentioned above to estimate the stability. The first is to calculate the actual $x_{com}$ and then compare with the target $x_{comi}$. In case the absolute difference is larger than a threshold value (expressed in Eq. (5)), we assume that a push is detected.

$$|x_{com} - x_{comi}| > x_{com\text{threshold}} \hspace{1cm} (5)$$

In accordance with Eq. (4), a second way is to compare the CoP with XcoM as a means of detecting pushes. Fig. 3 explains how a biped detects and responds to a push during walking.

**V. STRATEGIES OF PUSH RECOVERY**

Much research has been conducted to the postural control of human in presence of disturbances. For instance, Pijnappels et al. [15] show that a large ankle plantar-flexion movement, a knee and a hip extension can be observed in case of trimming obstacles or preventing a fall. Chen [16] shows through simulation studies that if a fall is starting, a maximum torque development in lower extremity joints, which leads to take a step in order to prevent a fall, is a significant determinant of regaining stability. Thelen et al. [17] also state that a rapid development of ankle joint torque determines a successful stepping for push recovery.

Inspired by the aforementioned research, the hip and ankle strategy is applied to the push recovery during walking in this work. The first inspiration, which is motivated by human walking, is to generate a torque at the hip joint to compensate the angular acceleration induced by external forces. The second one is to propel the leg by creating large torques at ankle joint, which can be introduced by quick plantar-flexion of the foot.

Given the fact that a push is detected instantaneously and the hip and ankle joints can produce extensive torques, a successful larger stepping will appear and stability can be regained. Obviously the hip and ankle strategy works only if a push has been detected before foot clearance. Once a push is detected after the foot left the ground and the leg is already in the process of leg swing, an alternative strategy is required.

Observing competitions in sports, many athletes try to catch a ball or run to a position by means of bending the knee and then hold the knee position to maintain stability as shown in Fig. 4. This control strategy is called knee strategy which functions in a way of holding and adjusting the stiffness at knee joint. As a result, it can support the upper trunk and decelerate the body to prevent over-swinging of the upper trunk. Inspired by the behavior of the bending knee of athletes, a knee strategy for push recovery can be reconstructed. In this section, we will elaborate both push recovery strategies respectively.

**A. Hip and Ankle Strategy**

Known from biomechanical studies, the hip and ankle joints play an important role in rapid stepping to prevent falling during walking. It is stated that the hip joint should generate a torque to swing the lower limb while the ankle joint should plantar-flex as quickly as possible to get a reaction force from the ground. To design a postural controller through hip and ankle strategy, existing controllers for hip swing and leg propel will be introduced respectively.
To walk in such situations, a new control strategy is introduced. Before investigating how the Hold Knee controller influences the biped, we have to first look into the joint setup and control. Each joint of the biped consists of a parallel elasticity and a damper that make the joint compliant. Given the constant equilibrium position \( \theta_0 \) and velocity \( \dot{\theta}_0 \) of the joint and the actual joint angle \( \theta \) and velocity \( \dot{\theta} \), the resulting torque is computed as

\[
\tau = \text{sgn}(\theta_0 - \theta) \cdot K_e \cdot (\theta_0 - \theta)^2 - K_d \cdot (\dot{\theta}_0 - \dot{\theta}),
\]

where all \( K_e \) and \( K_d \) indicate a non-linear spring and damper constant at each joint. Based on this compliant joint setup, we developed a stiffness controller to control the position of joint during push recovery. The stiffness controller receives the actual position and the strength of joint activation and then computes the target joint position and the strength of activation. Those outputs from the stiffness controllers enter into the low-level joint setup where the resulting torque for the joint is calculated.

Based on the introduced stiffness controller, the Hold Knee controller is designed. Algorithm 1 summarizes the behavior of the Hold Knee. The initial strength of stiffness \( \text{stiff}_{\text{init}} \) is set at first stimulation and when there is no ground contact. The minimal and maximal stiffness \( \text{stiff}_{\text{min}} \) and \( \text{stiff}_{\text{max}} \) define an interval of stiffness used during ground contact. Once ground contact is fulfilled, the target angle \( \phi_{\text{knee}} \) follows the current joint angle \( \phi_{\text{knee current}} \) in each cycle. Accumulating an small increment, \( \Delta \text{stiff} \), to the previous one in each cycle, it brings forth an increasing activation of this controller that makes the joint more stiff. As the result of the stiffness control, the knee joint absorbs kinetic energy by holding its position, which leads to a deceleration for the movement of the upper body. Once the knee holds the position for a while after ground contact, the next problem is to control the gesture so that a regular walking gait is reestablished. To regain the normal walking gesture, following behaviors can be observed. First, the leg which bends its knee has to move its knee angle to be upright again. At the same time, the other leg should generate more torque during \( \text{Leg Propel} \) to contribute to erecting the bent-knee and to compensate the XcoM.

VI. SIMULATION OF A BIPED AND RESULTS

To verify the control approaches proposed in Section V, experiments in different scenarios were conducted. A simu-
2) Knee Strategy: As mentioned before, if a push is detected after foot clearance, the ankle and/or hip joint cannot produce extra torques instantaneously. It results in a request for the emergence of a knee strategy. A push with 200 N lasting 100 ms is applied to the biped. The biped can not detect this push before the left foot touches the ground. A bent knee at the left leg can be observed just after foot contact with the ground and it holds the position to provide more support than during normal gait to prevent falling forward. The controller Hold Knee, as mentioned in Algorithm 1, is triggered if the knee angle is larger than that in normal gait when the foot touches the ground. It modulates gradually the target angle and the strength of activation in the course of the extension of knee joint until it reaches the equilibrium position. The angle of left knee joint during bent-

Fig. 5: Snapshots of the biped walking in hip and ankle strategy against an external force 200 N lasting 100 ms at the torso. The red arrow pointing forwards on the torso denotes an external push from backwards.

lated biped shown in Fig. 1 is used as the plant for the push recovery experiments to investigate and verify the suggested approaches.

A. Push Recovery on Level Ground

1) Hip and Ankle Strategy: It is studied how the biped reacts to an external force during walking on level ground. A force of 200 N was applied on the torso of the biped from the back with a duration of 100 ms, corresponding to a continuous Strong Push mentioned in Section. III. The first row in Fig. 5 shows the biped being pushed by an external force where the red arrow illustrates the external force acting on the torso of the biped. The motor patterns Leg Swing and Leg Propel are adjusted according to the measurement of the push detector and the estimation of XcoM. The resulting larger step can be observed in the second row in Fig. 5. The torques generated at hip and ankle joint are shown in Fig. 6. It can be seen that the torques increase suddenly when a push is detected. The added torques result in a larger step length than normal so that stability is regained. Compared to the torques before the push, the peak torque at hip and ankle joint shows nearly a increase of 25% in accordance with the computation in (6), (7) and (8). This experiment has shown

that the hip and ankle strategy can cope with the situation in which a push is detected before foot clearance.

Fig. 6: Hip and ankle torques in Hip and Ankle Strategy for push recovery. The torque profiles show in the form of a sinusoidal wave. After a push is detected, one can observe an abrupt increasing of 15% and 20% at left hip and ankle joint respectively.

Fig. 7: Snapshots of the biped walking in knee strategy against an external force 200 N during 100 ms.

Fig. 8: Angle and generated torques of knee joint in Knee Strategy for push recovery.
B. Push Recovery on Rough Terrain

To enhance the applicability of the proposed strategies for push recovery, a more challenging experiment, e.g. a push while walking on a rough terrain is performed consequently. A simulated terrain is constructed with roughness up to 3.3 cm, which is equivalent to randomly spacing rocks or similar obstacles with this maximum height throughout the terrain. One can observe that after the push the foot lands on the ground with a tilted angle of the ankle joint, the existing controllers attempt to handle the unaccustomed situation and the push recovery controllers regulate the hip, knee and ankle joint to create the required torques, joint stiffness and positions that allow the emergence of a stable state again.

Fig. 9: Hip and ankle torques in Hip and Ankle Strategy for push recovery on rough terrain.

Fig. 10: Snapshots of the biped walking on rough terrain with an external force 200 N during 100 ms.

VII. CONCLUSION AND FUTURE WORK

In this paper, we have presented the state-of-the-art in push recovery control for bipeds. Most of the current proposals for push recovery can only be applied to a very specific experiment setup or a special configuration of the biped. Few researchers have attempted to transfer the contributions from biological and biomechanical researches into the control for bipedal robots. Thus, the authors have developed a biologically inspired mechanism for push recovery on level ground and even rough terrain. The proposed approaches have not only simplified the analysis of the bipedal dynamics, but also considered the influences from the environment. Experimental results prove that if a push can be detected instantaneously, the hip and ankle strategy leads to a larger step of the biped and stable walking can be restored. However, if a push cannot be detected instantly, the knee joint of the landing leg has to hold its position to decelerate the movement of the upper trunk. This is solved by controlling the stiffness of the knee joint. Experimental results verify its applicability. To verify the adaptability of the controllers, experiments of a push acting on the biped when it is walking on rough terrain have been performed. For the future work, a further development of push recovery for lateral pushes on the biped will be investigated. We aim at developing a more reliable controller for the biped that can handle various external disturbances and walk in unknown environments.

REFERENCES