

On the Backwards Hopping Problem of Legged Robots

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Abstract—When realizing jumping locomotion on legged robots, trajectories that are generated without assessing angular momentum information are found to be prone to backwards hopping motions, due to the undesired body rotations developed during the support phase, prior to lift-off. In this letter, we succinctly discuss the underlying characteristics of such an undesired motion and propose a possible solution that is based on our previous work. In order to validate our claims, we conducted vertical jumping experiments on the actual bipedal robot MARI-3. As the result, the robot is able to exhibit dynamically-balanced jumping motions without any backwards hopping motion.

Index Terms—jumping robot, humanoid, legged locomotion, angular momentum, backwards hopping.

I. INTRODUCTION

Starting with Kato's first walking biped robot, we have witnessed quite an impressive humanoid evolution throughout the last couple of decades. Several technologies have been developed for humanoids [1]–[5]. The so-called long term goal in humanoid research is to create anthropomorphic mechanisms which can potentially duplicate humans' motion capabilities. Therefore, a well-developed humanoid should be able to run and jump, in addition to walking function. Moreover, sufficient jumping ability also enables robots to stabilize their motion when they are subject to external forces. Based on these factors, jumping motion appears to be an essential characteristic in humanoid robotics technology.

In order to explore jumping dynamics on legged mechanisms, various jumping motion generation and control methods are proposed. A thorough literature review regarding this issue can be examined in [3]. In this letter, we specifically focus on the backward hopping problem, which may occur during jumping motion, caused by the undesired rotations developed in the support phase, prior to lift-off.

Most conventional pattern generation methods, such as linear inverted pendulum mode, cannot characterize the rotational inertia and the associated angular momentum, which are of importance in representing legged robots dynamics. Oftentimes, angular momentum is omitted to simplify the motion generation task. However, this action is interpreted by the system as if the angular momentum is deliberately forced to be zero [6]. That being the case, the upper body rotates in a way to cancel the angular momentum that is inevitably induced due to angular velocity and rotational inertia [7]. This issue further leads it to the backwards hopping problem, as we thoroughly discuss later in section II.

In [3], the authors primarily proposed a forward jumping trajectory generation method for a one-legged planar robot, in which angular momentum is characterized. However, this method is not applicable to 3-D bipedal humanoid robots. In particular, the planar robot used in [3] has its motion constrained in x-z plane. Therefore, only pitch axis angular momentum is considered. On the other hand, if the angular momentum characterization is aimed for a 3-D biped trajectory

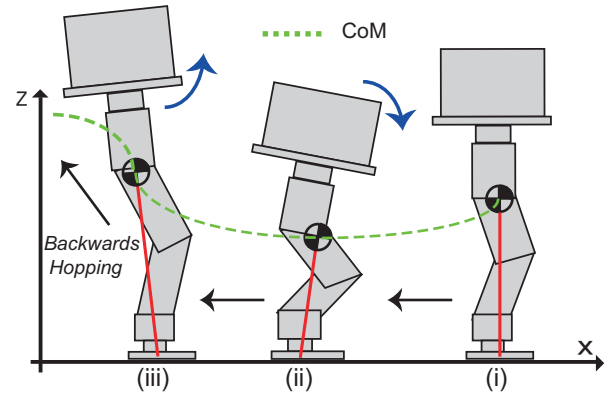


Fig. 1. Illustration of a support phase, realized with a trajectory which is generated for zero-referenced (omitted) angular momentum information. The upper body inevitably rotates in a way to cancel the induced angular momentum, causing an undesired backwards hopping. Note that the robot foot is in the same position in x-axis; the offset is left for illustrative purposes.

generation task, all three elements (not just only pitch) should be considered. Furthermore, simple duplication of planar motion equation for 3-D does not reveal a dynamically consistent methodology due to motion interference between the planes. Moreover, pitch axis angular momentum expression gets more complex in 3-D case, comparing to the planar case. Because of these reasons, direct implementation of the method proposed in [3] could not solve backwards (and even sideways) hopping problem for the actual 3-D biped robot MARI-3.

Correlative to this issue, the authors recently proposed a thorough expansion of their method for 3-D bipedal trajectory planning, in which angular momentum information is considered in a concrete manner [8]. They demonstrated the superiority of this method over off-the-shelf methods via 3-D walking experiments. In the light of this result, it is anticipated that the method presented in [8] may appear to be a feasible solution for jumping motion generation of 3-D bipedal robots in which backwards hopping problem is remedied.

Considering the facts stated above, this letter provides a succinct treatment on the backwards hopping problem of biped robots, with a special emphasis on the vertical jumping motion. That being said, we discuss the underlying characteristics of such an undesired motion. Having diagnosed the main factor related to the issue, we provide a possible solution that is based on our previously proposed pattern generation technique [8] to handle the backwards hopping problem. In order to demonstrate our claims, a comparative analysis is also presented, including results from vertical jumping experiments, conducted on the actual bipedal robot MARI-3.

This letter is organized as follows. Initially, backwards hopping problem is discussed in section II. The pattern generator which characterizes angular momentum is briefly explained in section III. Experimental results are presented in section IV and finally the letter is concluded in section V.

II. PROBLEM STATEMENT

In Fig. 1, three main events from a support phase are illustrated, respectively from right hand side (RHS) to left hand side (LHS). The first event stands for the beginning of a given support phase. Before reaching to lift-off, the CoM (Center of Mass) follows a trajectory. When its acceleration vertically exceeds the gravitational acceleration, it jumps if the vertical velocity is non-zero. During this trajectory, the rotational inertia inevitably changes as it is joint configuration-dependent. In other words, the rotational inertia vary with respect to joint angles [8]. Naturally, angular velocity also varies

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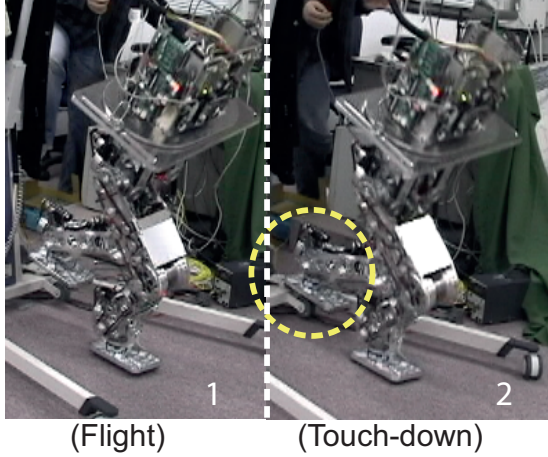


Fig. 2. A couple of snapshots from a jumping experiment, in which the robot suffered backwards hopping [9]. Even though the upper body is initially bent forward, the robot still performs an undesired backwards hopping. In this case, the experiment is concluded somewhat catastrophic; the robot hopped backwards and its swing leg harshly struck the safety crane (see yellow circle).

when the robot is in motion. As a result, these facts cause a certain amount of change in angular momentum, induced at the composite CoM. If angular momentum is zero-referenced or simply omitted, the upper torso unavoidably rotates in a way to cancel the angular momentum that is caused by the rotational inertia variance.

One may think that this problem could be handled by initially presetting the upper body orientation to a non-zero value. Fig. 2 displays a couple of snapshots from an experiment, in which such a strategy is implemented [9]. The result turns about to be somewhat catastrophic; the robot performs an undesired backwards hopping and harshly strikes its swing foot to the safety crane, causing a mechanical failure that requires a further maintenance. Regardless of the preset upper body angle, the body still needs to rotate because the angular momentum is related with angular velocity. Therefore, it is obvious that we are in need of a pattern generator which is able to characterize angular momentum rather than zero-referencing it.

III. A BRIEF OVERVIEW ON THE PATTERN GENERATOR

In generating dynamically-consistent CoM trajectories with angular momentum information, we previously proposed a method [8]. In this letter, the main purpose is to demonstrate the influence of angular momentum during legged jumping. Keeping this in mind, we introduce a simplified technique which utilizes the method proposed in [8], within a practical manner. Therefore, let us begin with analyzing the ZMP (Zero Moment Point) equation in x-axis [8].

$$mX_{zmp}(\ddot{z} + g) = mx(\ddot{z} + g) - m\ddot{x} - \dot{L}_y \quad (1)$$

In (1), (x, z) are CoM position in Cartesian frame, X_{zmp} is x-axis ZMP input, $\dot{L}_y$ is pitch axis Angular Momentum Rate change associated with the rotational inertia, m and g are the total mass and gravitational acceleration. Considering jumping conditions, z -axis trajectory can be obtained via polynomials [3], and therefore $(z, \ddot{z})$ couple is known for all times. $\dot{L}_y$ is associated with composite rigid body inertia [8] and joint motions. We recursively compute its value for each cycle using the method reported in [8]. Under these conditions, (1) can be discretized if we express $\ddot{x}$ as in the following.

$$\ddot{x}_{[k]} = \frac{x_{[k-1]} - 2x_{[k]} + x_{[k+1]}}{h^2}, \quad (2)$$

in which k is the discrete event and h is sampling time. Inserting (2) to (1), x-axis ZMP equation can be written in a tridiagonal form.

$$d_{[k]} = x_{[k-1]} + x_{[k]}b_{[k]} + x_{[k+1]} \quad (3)$$

$b_{[k]}$ and $d_{[k]}$ terms in (3) are obtained as follows.

$$d_{[k]} = -h^2 \frac{\dot{L}_{y_{[k]}} + mX_{zmp_{[k]}}(\ddot{z}_{[k]} + g)}{mz_{[k]}} \quad (4)$$

$$b_{[k]} = -2 - h^2 \frac{\ddot{z}_{[k]} + g}{z_{[k]}} \quad (5)$$

The tridiagonal equation given above can be efficiently solved using Thomas algorithm [10] which enables us to perform Gaussian elimination without partial pivoting. For this purpose, (3) should be reformulated in the following manner,

$$x_{[k]} = p_{[k+1]}x_{[k+1]} + q_{[k+1]}, \quad (6)$$

where $p_{[k+1]}$ and $q_{[k+1]}$ are recursively derived as below.

$$p_{[k+1]} = \frac{1}{p_{[k]} + b_{[k]}}; \quad q_{[k+1]} = \frac{d_{[k]} - q_{[k]}}{p_{[k]} + b_{[k]}} \quad (7)$$

This process is carried out over the whole support phase period; $k = 1, 2, 3, \dots, n-1$, where $n = \frac{T_s}{h}$ with appropriate rounding. T_s is support phase period. In Thomas algorithm, we need to supply initial and terminal x positions, namely, $x_{[0]} = x_0$ and $x_{[n]} = x_n$. Note that initial position also reveal $p_{[1]}$ and $q_{[1]}$; $p_{[1]} = 0$ and $q_{[1]} = x_0$. Assessing these conditions, Thomas algorithm provides a solution for the tridiagonal equation, which reveals x-axis CoM trajectory (x). Conducting a similar approach for the y-axis ZMP equation, y-axis CoM can be yielded. While performing this operation, it should be noted that motion equations cannot be duplicated as the associated angular momentum terms for x-axis and y-axis are different [8].

IV. EXPERIMENTAL RESULTS

In order to validate the proposed application, we conducted single leg jumping experiments on the actual bipedal robot MARI-3. In these experiments, the robot initially sways to RHS in lateral plane, so as to lift the left foot for single leg jumping. Afterwards, it vertically jumps and lands on the supporting right foot. Flight and support time periods are designated as 0.12 [s] and 0.5 [s]. Fig. 3 displays six significant moments from an experiment, in which the robot exhibited dynamically-equilibrated vertical jumping without any backwards hopping problem.

Fig. 4(a)-(b)-(c) display 3-D CoM trajectories. As it may be observed, flight and support phase trajectories are connected seamlessly. Moreover, x-axis and y-axis CoM trajectories are non-zero; they vary before the jumping. We hypothesize that the pattern generator produces non-zero sagittal and lateral motions in a way to comply with the angular momentum condition. On the other hand, they automatically become zero at the moment of lift-off, so that the robot can perform a vertical jump.

Vertical GRF (Ground Reaction Force) response may be examined in Fig. 4(d). In this plot, zero GRF response indicates the successful flight phase period. Moreover, touch-impact is also indicated. After the landing, it becomes equals to the total weight as the robot keeps its balance successfully.

ZMP measurements before take-off (solid purple) and after landing (solid green) are disclosed in Fig. 4(e). Examining the figures, ZMP slightly shifts towards toe and right bound before the take-off. After the flight phase, the robot lands and ZMP appears in a

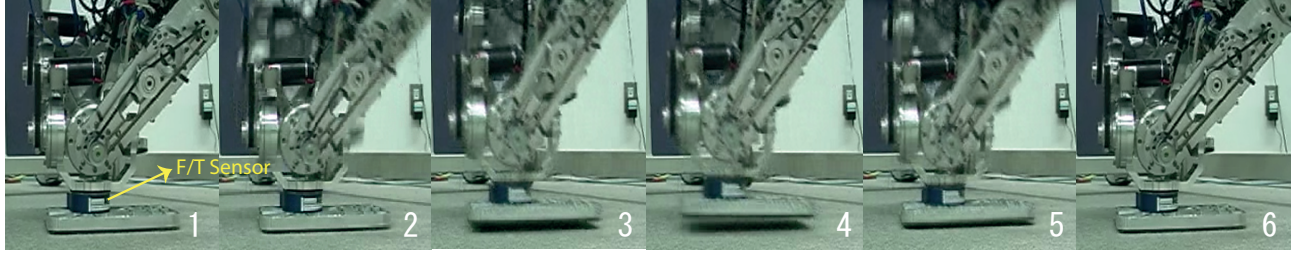


Fig. 3. Significant moments from a jumping experiment. 1) Initial position, 2) lift-off, 3) just after the lift-off, 4) apex, 5) landing, 6) after landing.

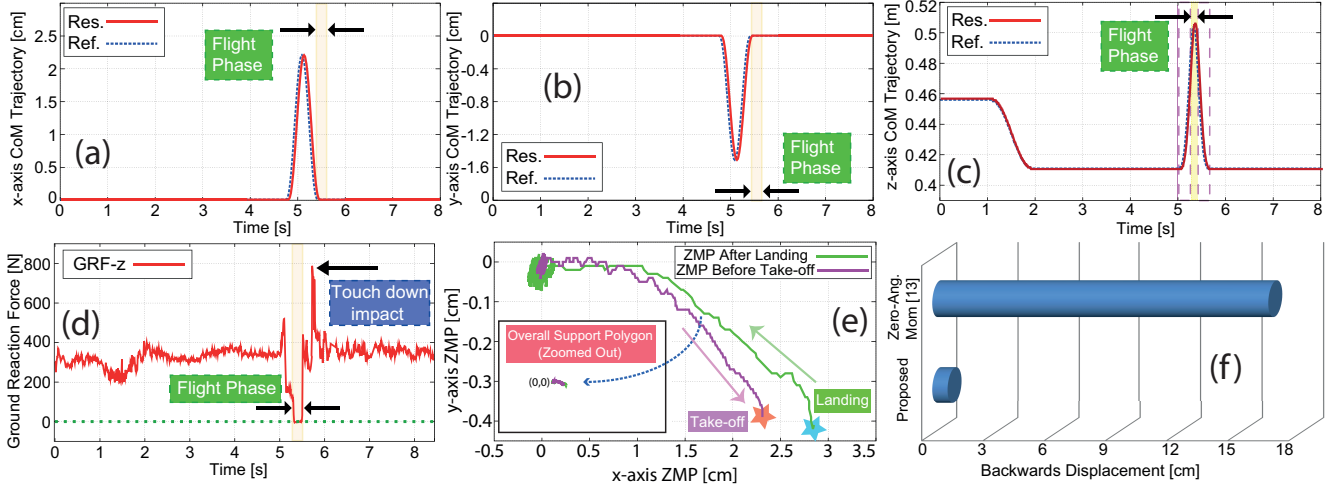


Fig. 4. a) x-axis CoM trajectory, b) y-axis CoM trajectory, c) z-axis CoM trajectory, d) vertical GRF response, e) ZMP response, f) comparison chart.

close proximity. Subsequently, ZMP returns back to the origin. In addition, the box at the left-bottom side depicts ZMP variation in the overall support polygon. As may be observed, ZMP travels only a small amount; so that the robot performs a dynamically balanced jump without any undesired backwards or sideways hopping motion.

In order to stress the importance of angular momentum in handling backwards hopping issue, a comparative analysis is given in Fig. 4(f). Firstly, we conducted 5 vertical jumping experiments using the method provided in section III. In these experiments, the average backwards hopping displacement is measured to be around 1 [cm]. Subsequently, the same procedure is applied via another jumping motion generator which cannot characterize angular momentum [11]. In this case, the average backwards hopping displacement is calculated as 15.25 [cm]. Judging by the result of this comparison, it is obvious that the method proposed is superior in suppressing backwards hopping tendency; indicating the close relationship between angular momentum and backward hopping issue.

V. CONCLUSIONS

In this letter, we succinctly discussed the underlying characteristics of backwards hopping problem which might occur when legged robots perform jumping motions. Based on our experimental observations, the pattern generation methods that can characterize angular momentum are efficient in handling this issue, such as the algorithm proposed in [8].

REFERENCES

[1] K. Erbatur, and O. Kurt, "Natural ZMP trajectories for biped robot reference generation", in *IEEE Trans. on Industrial Electronics*, vol. 56, no. 3, 2009, pp. 835-845.

[2] I. A. Smadi, H. Omori, and Y. Fujimoto, "Development, analysis, and experimental realization of direct-drive helical motor", in *IEEE Trans. on Industrial Electronics*, vol. 59, no. 5, 2012, pp. 2208-2216.

[3] B. Ugurlu, and A. Kawamura, "ZMP-based online jumping pattern generation for a one-legged robot", in *IEEE Trans. on Industrial Electronics*, vol. 57, no. 5, 2010, pp. 1701-1709.

[4] Y. Kang, H. Kim, S.-H. Ryu, N. L. Doh, Y. Oh, and B.-J. You, "Dependable humanoid navigation system based on bipedal locomotion", in *IEEE Trans. on Industrial Electronics*, vol. 59, no. 2, 2012, pp. 1050-1060.

[5] N. Motoi, T. Shimono, R. Kubo, and A. Kawamura, "Task realization by a force-based variable compliance controller for flexible motion control systems", in *IEEE Trans. on Industrial Electronics*, Forthcoming article.

[6] S.-H. Lee, and A. Goswami, "A momentum-based balance controller for humanoid robots on non-level and non-stationary ground", in *Autonomous Robots*, vol. 33, no. 4, 2012, pp. 399-414.

[7] S. Kajita, K. Kaneko, M. Morisawa, S. Nakaoka, and H. Hirukawa, "ZMP-based running enhanced by toe springs", in *Proc. IEEE Conf. on Robotics and Automation*, Rome, Italy, 2007, pp. 3963-3969.

[8] B. Ugurlu, and A. Kawamura, "Bipedal trajectory generation based on combining inertial forces and intrinsic angular momentum rate changes: Eulerian ZMP resolution", in *IEEE Trans. on Robotics*, vol. 28, no. 6, 2012, pp. 1406-1415.

[9] K. Suzuki, "Basic Study on Realizing Biped Running", Master's Thesis Dissertation, Yokohama National University, Japan, 2006, in Japanese.

[10] J. C. Strikwerda *Finite Difference Schemes and Partial Differential Equations*, Wadsworth&Brooks/Cole Adv. B. & Soft. pp. 74-80, 1989.

[11] T. Maeda, "Research on Stable Jumping Control of Biped Robots: Towards Realizing Running Motion", Master's Thesis Dissertation, Yokohama National University, Japan, 2009, in Japanese.