

BIPED LOCOMOTION: STABILITY, ANALYSIS AND CONTROL

Prahlad Vadakkepat and Dip Goswami
Electrical And Computer Engineering
National University of Singapore,
Singapore

Emails: <mailto:prahlad@ieee.org>, <mailto:dip.goswami@nus.edu.sg>

Abstract- In this paper, researches and advances in biped locomotion are reviewed. A detailed survey is presented describing the various research problems and the approaches reported in the literature to analyze and control biped locomotion. A method of Zero-Moment-Point (ZMP) compensation is discussed to improve the stability of locomotion of a biped which is subjected to disturbances. A compensating torque, computed from the force sensor reading, is injected into the ankle-joint of the foot of the robot to improve stability. The effectiveness of the method is demonstrated on a humanoid robot, MaNUS-I, to reject disturbances of various form.

Index terms: Zero-Moment-Point, Foot-Rotation-Indicator, Periodicity in Biped Locomotion, online ZMP compensation.

I. INTRODUCTION

In the field of humanoid robotics, particular area of research interest currently being pursued actively is the control of biped locomotion. The motivation in the research on bipedal locomotion is its much-needed mobility required for maneuvering in environments meant for humans or in rugged terrains. Wheeled vehicles can only move efficiently on relatively flat terrains whereas a legged robot can make use of suitable footholds to traverse in a rugged terrain. Bipedal walking is a much less stable activity than say four-legged walking, as multi-legged robots have more footholds for support. Bipedal walking allows instead greater maneuverability especially in smaller areas.

and control is designed based on the simplified dynamical equations [9, 10, 11]. Sometimes the dynamical effect of robot-dynamics is taken care of by intelligent techniques such as neural network or CMAC. In [24, 25, 26], the neural network is used to predict the dynamical effect of the robot-dynamics to design actuator-level control input.

Id. VISION-BASED CONTROL

The basic purpose of vision or visual servoing is to control a robot using visual information. Visual servo can directly compute joint inputs or the inputs can be in terms of image features: Position-based Visual servoing [27] and Image-based Visual servoing [28, 29].

In position-based approaches the first task is to estimate the 3D pose parameters from 2D images using pose estimation algorithms. These pose estimations are then applied to solve inverse kinematics and to design control laws for tracking desired target and linear control algorithms like PID or PD controller. In this approach, even if a closed loop control is used, which makes the convergence of the system possible in presence of calibration errors, it is very difficult to analyze the stability of the system. In contrast, image-based visual servoing eliminates the robot controller entirely, replacing it with a visual servo controller that directly computes joint inputs, using vision information alone to stabilize the mechanism.

In image-based control, control inputs are computed on the basis of image features directly. The image-based approach may reduce computational delay eliminating the necessity for image interpretation and errors due to sensor modeling and camera calibration. Its convergence is theoretically ensured only in a region (quite difficult to determine analytically) around the desired position. The analysis of the stability with respect to calibration errors is very difficult, since the system is coupled and nonlinear.

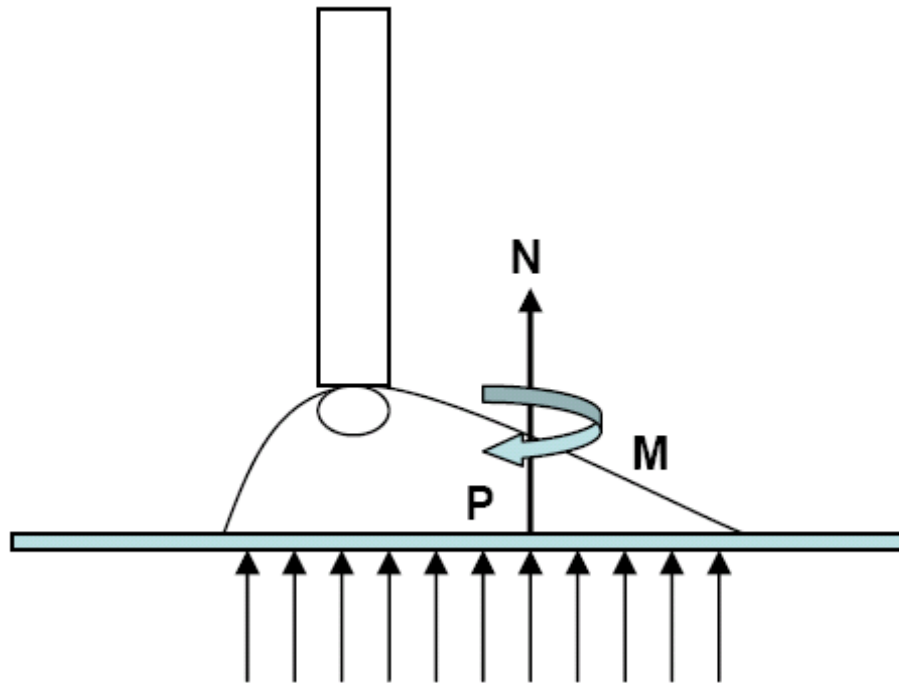


Figure 2: Zero-Moment-Point

Another well-known concept for analyzing postural stability of the biped systems with feet is Centre-of-Pressure (CP). CP is defined as the point on the ground where the resultant of the ground-reaction-force acts. When ZMP is within the support polygon of the feet of the robot, CP coincides with the ZMP [2]. If ZMP goes outside the support polygon, the biped becomes unstable. However, degree of instability is not indicated by ZMP criterion.

IIiii. FOOT ROTATION INDICATOR POINT

During biped locomotion, rotational equilibrium of the foot is an important criterion for the evaluation and control of gait and postural stability. For stationary robot, the rotational equilibrium of the feet is determined by the location of the ground projection of the center-of-mass (GCM). However, when the robot is in motion, the rotational properties of the foot are decided by the position of the Foot-Rotation-Indicator (FRI) point [2].

IIa.iii. BIPED MODEL WITH POINT FOOT-GROUND CONTACT

From recent literature [3, 4, 5] it can be noticed several researcher are investigating the stability of biped systems without foot or point foot. Due to absence of foot (and support polygon), stability concepts such as ZMP, FRI are not applicable to such systems and there is no statically stable posture for these systems while they are in single-support phase. The motivation of these biped models comes from the fact that an anthropomorphic walking gait should have a fully actuated phase where the stance foot is flat on the ground, followed by an under-actuated phase where the stance heel lifts from the ground and stance foot rotates about toe. The point foot model is simpler than a more complete anthropomorphic gait model.

The success of Raibert's control law for a one-legged hopper [4] motivated others to analytically characterize the stability of point foot biped systems. Due to absence of statically stable posture in single-support phase, the locomotion studies of point foot biped systems are mainly performed for periodic or repeated movements like walking, running, hopping or jogging (not standing or jumping) (figure 4). Absence of active actuation at the joint between point-foot and the ground makes these systems under-actuated. The stability of the *under-actuated* systems is essentially governed by its *zero-dynamic* [6]. The zero-dynamics of these systems does not have any stable equilibrium. However, the zero-dynamics can move from one bounded unstable solution to another periodically leading to bounded zero-dynamics. The concept of orbital stability and periodicity is applied to establish the periodicity of zero-dynamics by Raibert [3] and Koditchek [5]. In [5], Poincare return map is used to show periodicity of motion of a simplified spring-damped hopping robot. Similar concept is used by Grizzle et al. in [3] to establish the conditions of periodicity for stable walking/running of a planar robot without foot.

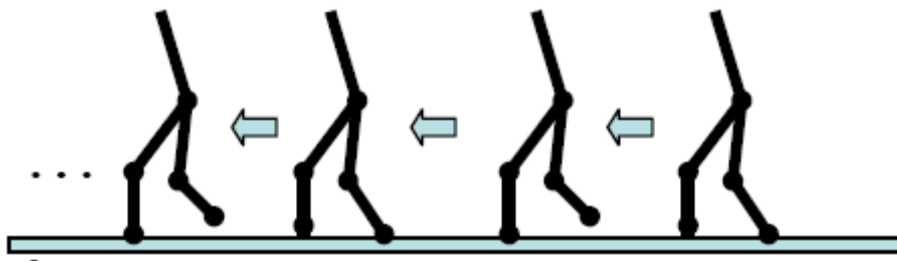


Figure 4: Periodic Motion

where g is the gravitational acceleration, τ_x, τ_y , are the torque applied around x-axis and y-axis respectively. Let (x_{zmp}, y_{zmp}) be the position of the ZMP. It is clear from (1) that the value of ZMP is,

$$\begin{aligned} x_{zmp} &= -\frac{\tau_y}{mg}, \\ y_{zmp} &= \frac{\tau_x}{mg}. \end{aligned} \quad (2)$$

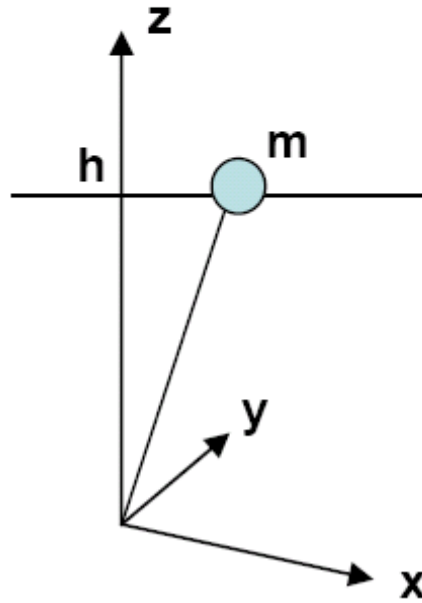


Figure 5: Inverted Pendulum Model.

Using (2) in (1) the expression of ZMP become,

$$\begin{aligned} x_{zmp} &= x - \frac{h}{g} \ddot{y}, \\ y_{zmp} &= y - \frac{h}{g} \ddot{x}. \end{aligned} \quad (3)$$

Digital Signal Processor (DSP) (Motorola 56F807) controls walking motion of the robot by sending the desired joint trajectory signals to various leg joint motors. The ZMP at each instant is measured using force sensors located at the corners of each foot bottom. The DSP controller receives and processes the data from force sensors. Compensation for the ankle reference angles is calculated according to the deviation of the ZMP due to external disturbances.

IIIai. BIPED MODEL

During walking, when one leg is swinging, the mass of the whole body can be replaced by the total mass of the robot located at the center of mass (CM) of the robot as point-mass and is connected to the foot at stance like an inverted pendulum. The simplified model shown in figure 7 is used to approximate the biped model.

In figure 7, 'c' is the CM of the robot with one leg swinging and 'a' is the ankle-joint of the other leg which is on the ground. x_i and $y_i, i = (1,2)$ are the positions of the force sensors in x and y directions, in sagittal and frontal plane respectively. l is the distance of the CM from ankle-joint in sagittal plane. L is the distance of ZMP from the ankle joint. l can be considered as a link with concentrated point-mass at the end. ϕ is the angle between the link and the z-axis. α is the angle between L and the z-axis. τ is the torque at the ankle-joint about y-axis. F_{ext} is the disturbance force applied to the robot as disturbance. F_i are the reading of force sensors in the respective plane. 'm' is the total mass of the robot and 'g' is the gravitational acceleration. The motions in the sagittal plane and frontal plane are considered separately because the motions in these two planes are weakly coupled [18].

IIIaii. MEASUREMENT OF ZMP USING FORCE SENSORS

Tekscan FlexiForce force sensors are used to measure the forces acting on the feet of the robot.

$$F_1(x_1 - x_{zmp}) - F_2(x_2 - x_{zmp}) = 0$$

$$\Rightarrow x_{zmp} = \frac{F_1x_1 - F_2x_2}{F_1 + F_2} \quad (4)$$

Similarly, ZMP is calculated in frontal plane using force sensor reading.

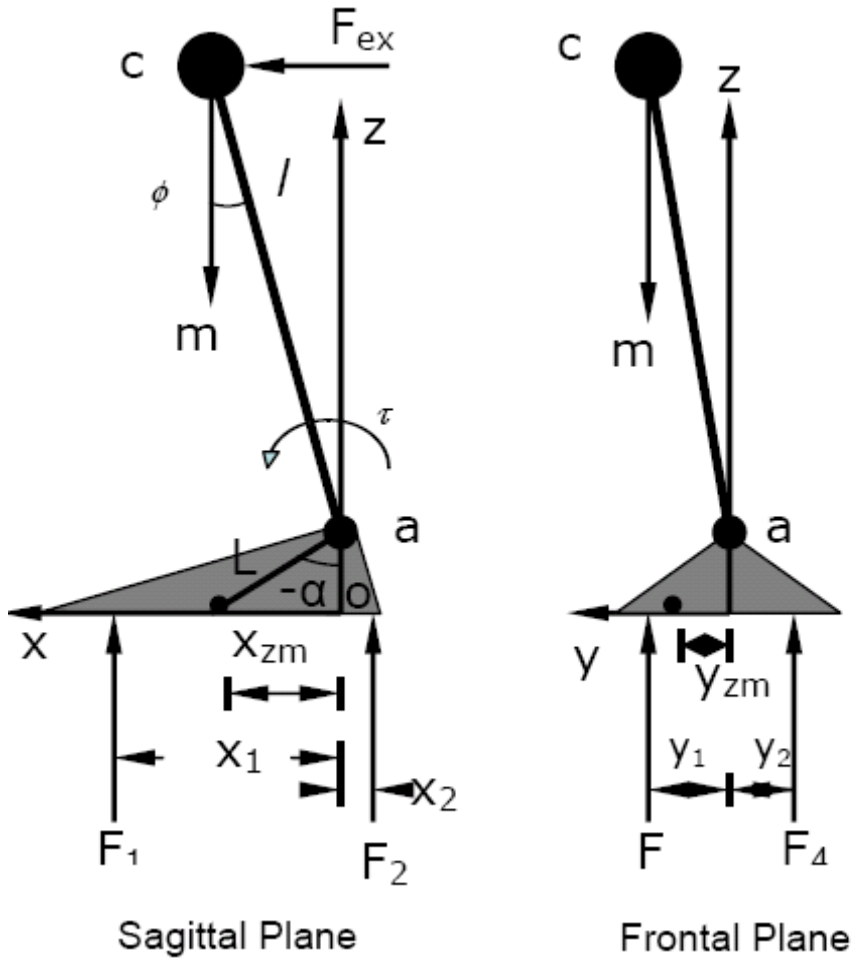


Figure7: Simplified Biped Model.

$$\Delta \tau_{ankle} = -M^K \quad (7)$$

The overall block diagram of the compensation technique is shown in the figure 9.

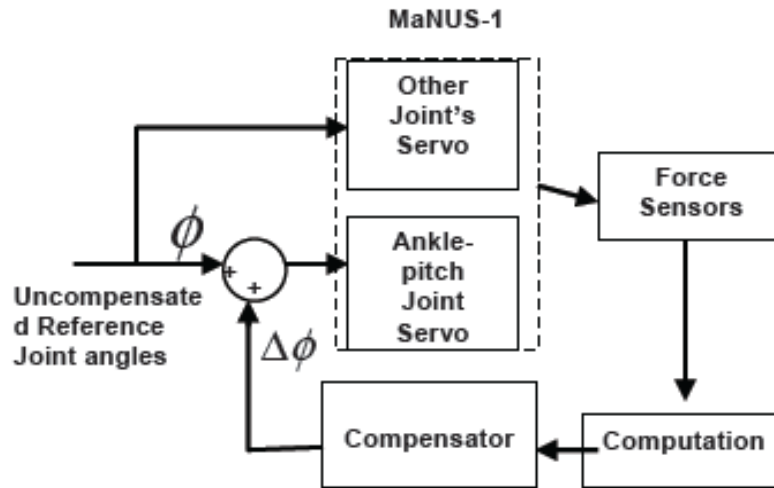


Figure 9: Online ZMP Compensation

IIIaiv APPLICATIONS AND EXPERIMENTS

The effectiveness of the compensation method is verified on a humanoid robot, MaNUS-I. With the compensation technique, the robot successfully rejected disturbances in different forms.

A. IMPROVEMENT OF WALKING ON FLAT SURFACE

x-ZMP positions of the robot are computed from the force measurements while walking on a flat surface using (4). The compensation technique comes into play whenever the x-ZMP position goes beyond the 'Safety Zone'. The compensation angle at the ankle-joint is calculated using (6) and (7). The robot is made to walk on a flat surface without compensation and with compensation over a period of 20 seconds. Figures 10 and 11 show the recorded x-ZMP positions once the walking gait is stabilized starting from a standing position. It is clear from the results that the compensator is able to reduce the magnitude of fluctuation of the ZMP keeping its value within the 'Safety Zone'.

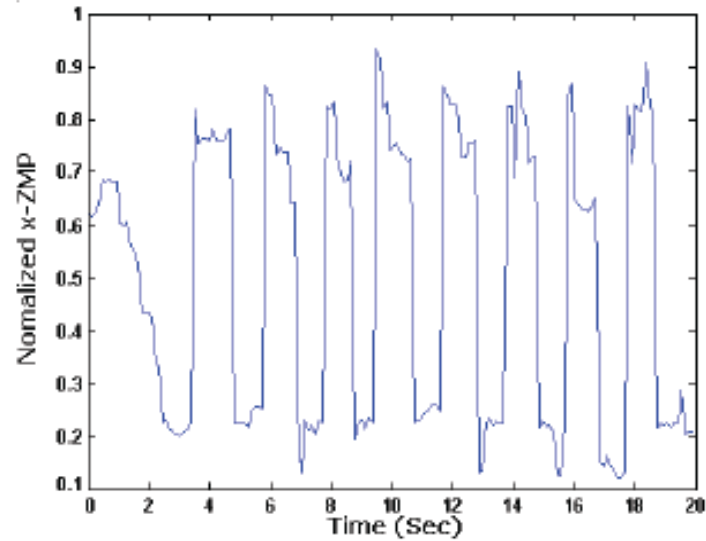


Figure 10: x-ZMP position during walking without compensation

D. CARRYING WEIGHT DURING WALKING

For walking with additional weight, a basket is attached on the back of MaNUS-I (figure 14). After the compensation technique is applied, the robot is able to carry a maximum of 26 batteries including a metal basket with a total weight of 390 gm and continue walking on a flat surface. The mass of the robot being 2.36 kg, the additional weight is approximately 17% of the robot's weight.

As the constant additional weight causes the ZMP to shift, the compensation method adjusts the ankle-pitch-angle gradually until the ZMP moves within the 'Safety Zone'.

VI. CONCLUSIONS

Postural stability in bipedal systems has been a research challenge for more than three decades. Until late nineties the concept of ZMP was the only technique to analyse the stability of the legged systems. After the idea of FRI point is introduced, the bipedal stability analysis is able to address a wider class of bipedal motion where the foot of the robot rotates during walking. Due to the rotation of foot, one more DOF is added to the system making the system *under-actuated*. To

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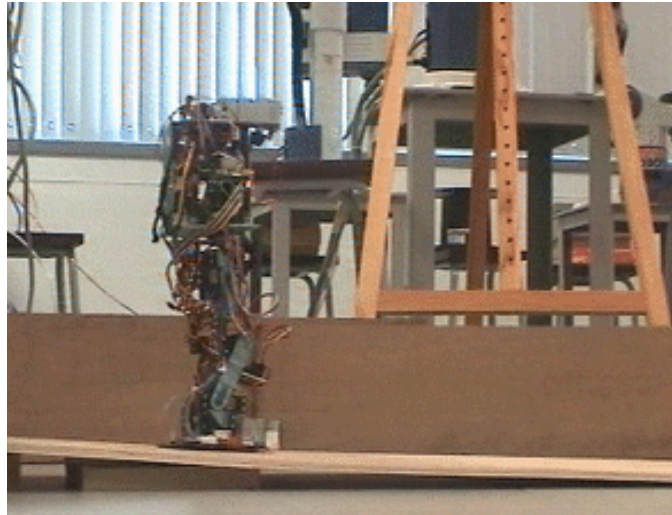


Figure 13: Walking down a slope

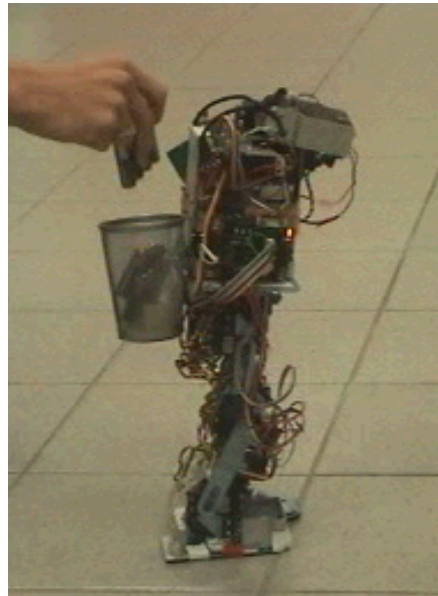


Figure 14: MaNUS-I carrying additional Weight

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