Introduction to Dynamic Balance for Humanoid Robots, the Key of Biped Locomotion

I. García-Manrique

***Abstract*—This paper is devoted to dynamic balance for humanoid robots, widely-studied in biped locomotion issue. No research advances have been introduced here but a State of the Art overview is presented. After a short survey of the walking problem a detailed elaboration of Zero Moment Point notion is given, with a special review concerning to his implication in dynamic balance. In addition, a schematic presentation of control strategies is made, distinguishing between off-line and online strategies, which are presented in a more detailed way. Finally, some conclusion and future lines are considered**

***Index Terms*—Biped locomotion; zero-moment point; foot rotation indicator; dynamic balance; off-line, online, control strategies**

I. INTRODUCTION

THE term ”robotics” appears in the middle of the twentieth century. The peak of this multi-discipline technological branch has been motivated by continuous improvements in sensors, computer algorithms, control systems, power systems, etc.

Humanoid robots are robots which try to reproduce, totally o partially, the shape and the kinematic behavior of the human being.

The first step in humanoid robotics was achieving a whole human body’s structure. Once it has been overcome, human appearance is chased for the robot, in other words, its movements should be fluent. In order to achieve that, movement sequences based in human beings are programmed.

Human robotics is in a very young phase. There are too few developed devices, without practical use and basically destined to their study and research. The first important humanoids were the “E series”, developed by Honda in 1986.

Humanoid robots have sensors, video cameras and other hardware elements trying to imitate human senses working, so that they can act in a freelanced form, in other words, so that they can inter-act with their environment and reply to external stimuli.

One of the most complicated and interesting aspects to develop in this discipline is biped locomotion, specifically, humanoid robots dynamic balance [1]. The aim of this issue is getting robots which balance themselves without a previously recorded sequence.

The main question raised about walking problem is: what needs a humanoid robot to walk dynamically? Humanoid robot should detect balance disturbances, decide appropriated actions to offset them and modify robot motors in real time. Thanks to dynamic balance control, humanoid is able to change its course according to ground characteristics or external forces.

In this paper, an introduction to dynamic balance is presented, giving a general view of different aspects involved in dynamic balance, in such a way that a ”non-initiated” reader is able to obtain a basic knowledge to deal with the different subjects discussed in depth.

Therefore, in section II a detailed description of ZMP is presented in a conceptual point of view. This point is considered the key in dynamic balance control of humanoid robots for last years [2]. Additionally, other points of interest are described, such as CoP (Center of Pressure) or FRI (Foot Rotation Indicator), emphasizing specially their relations with ZMP.

Section III approaches the real problem of biped locomotion as an addition of pre-programmed off-line behavior techniques, which make possible harmonious and balanced movement of the robot. These techniques must be necessarily accompanied by sophisticated dynamic balance control online techniques to guarantee responses to unexpected events or unbalances .

In Section IV three online techniques of dynamic balance control, very representative in bibliography, are studied. The three ones are applied simultaneously for a better performance: Movement Sequence Control, Moments Control and ZMP Control.

Finally, some conclusions from this topic are commented and possible future work lines are proposed, from the point of view of the author.

II. ZERO MOMENT POINT

All of the biped mechanism joints are powered and directly controllable except for the contact between the foot and the ground (which can be considered as an additional passive degree of freedom), where the interaction of the robot and environment only takes place. This contact is essential for the walk realization because the robot’s position with respect to the environment depends on the relative position of the foot with respect to the ground.

The foot cannot be controlled directly but in an indirect way, by ensuring the appropriate dynamics of the structure above the foot. Thus, the overall indicator of the mechanism behavior is the point where the influence of all forces acting on the robot can be replaced by one single force. This point was termed the Zero-Moment Point (ZMP).

ZMP is actually defined as that point on the ground at which the net moment of the inertial forces and the gravity forces

---

I. García-Manrique is a student of I Master in Communications Technologies.
University of Málaga

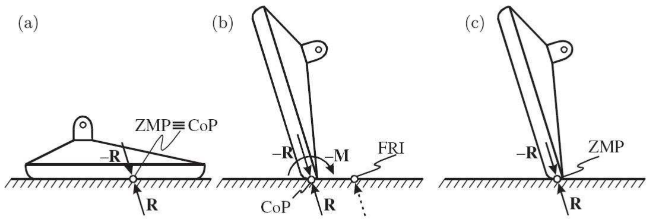

Fig. 1. Dynamic gait in the case of dynamic balance (a), unbalanced moment (b) and balanced situation on the toe tips (c). Figure from [2]

has no component along the horizontal axes. As a result of that, it could be said that ZMP position must be determined in order to investigate the biped gait using a dynamic model.

A complete description of moments and forces involved in analytic ZMP evaluation is presented in Appendix A. In this paper, no real technical measurement has been considered but it would be assumed that ZMP position could be computed. However, the resulted point is just a candidate to be a regular ZMP and its position should be compared with the real support polygon size.

It could be possible that the computed ZMP position results a point outside the foot, this means that the ground reaction force acting point (P) is actually on the edge of the support polygon and the mechanism rotation about the foot edge will be initiated by the unbalanced moment, whose intensity depends on the distance from the edge to the computed position of ZMP. Therefore, in reality, ZMP can exist only within the support polygon, so it could be necessary to find a new definition for all the outside calculated positions of the point.

Nevertheless, this non-existent ZMP coincides with other important point in balance studies: Foot Rotation Indicator (FRI) point. FRI is defined [3] as the point on the ground contact surface within or outside the convex hull of the foot support area, at which the resultant moment of the forces impressed on the foot is normal to the surface. In further bibliography [2] outside ZMP are also called Fictitious Zero Moment Point (FZMP) and only take into account this point instead of FRI.

Here we have to point out another important issue, and this is the difference between the center of pressure (CoP), ZMP and FRI, as it is very important to make a clear distinction between the three notions, which must not generally be regarded as identical. CoP is defined as the point on the ground where the resultant of the ground reaction force acts. If this force balances all active forces acting on the mechanism during the motion (inertia, gravitation, Coriolis and centrifugal forces and moments) its acting point is ZMP. Popovic [4] showed how CoP and ZMP coincide in the case of a dynamically balanced gait. When the gait is not dynamically balanced, ZMP does not exist and the mechanism collapses about the foot edge.

To make the ZMP notion and its relationship with CoP perfectly clear we will summarize in three characteristic cases for a non-rigid foot in contact with the ground, as sketched out in Figure 1. In a balanced gait, the ZMP coincides with CoP Fig. 1(a). In the case of a disturbance that brings the acting point of the ground reaction force to the foot edge, the perturbation moment will cause rotation of the biped system about the foot edge and its overturning. In that case we can speak only of FRI point, whose distance from the foot edge represents the intensity of the perturbation moment Fig. 1(b). However, it is possible to realize the biped motion, for example, on the toe tips Fig. 1(c) with special shoes having a pinpoint area, while keeping the ZMP position within the pinpoint area.

In summary, the ZMP always coincides with the CoP (dynamically balanced gait), FRI indicates the amount of unbalanced moment (foot rotates) and, if FRI is outside foot edge, CoP is at the edge and ZMP does not exist.

Now, a logical question can be posed: given the mechanism dynamics, what should the ZMP position be that would ensure dynamic equilibrium? in the Appendix it is shown that to ensure dynamic equilibrium, an evaluated ZMP must be within the support polygon.

ZMP (and FRI) position is a key indicator of the humanoid dynamic equilibrium. Thus, a crucial question is how to determine it. In the case of a real walking mechanism, information about ZMP position can be obtained by measuring forces acting at the contact of the ground and the robot, with the aid of force sensors on the foot's sole. It should be noticed that measurement could be performed only if all force sensors are in contact with the ground. If some of the sensors deployed from the ground surface, the robot as a whole would rotate about the foot edge and overturn. To overcome such a situation it is necessary to bring into operation a dynamic balance control strategy.

III. DYNAMIC BALANCE CONTROL STRATEGIES

Since a biped robot tends to tip over easily, stable and reliable biped walking is a very important achievement. In this section the different techniques used for dynamic balance control in humanoid robots are presented.

First, a method of generating a highly stable, smooth walking pattern is presented. Then, a method of real-time modification consisting of body posture control, actual zero moment point control and landing time control based sensor information is recommended. By combining the proposed off-line walking pattern with online real-time modification, the biped robot can walk smoothly and adapt to unknown environments.

The control system is broken into two parts. The first, off-line part is given a recording of a walk cycle, a sequence of joint angles and positions. It breaks the continuous motion into a suggested sequence of gross motor movements. These movements are loosely based on the types of motor control seen in some human motion: ballistic launching (the start of a swinging motion), braking (the end of a ballistic swinging motion), and balance (inverted pendulum style maintenance of some parameter).

At the moment of the previous movement commands processing it is studied if the sequence join a stable movement for the humanoid or, on the contrary, the implementation of that sequence can entail any risk for itself.

Off-line techniques allow reschedule the robot path in order to avoid a detected obstacle, for example. In other words, they are actions which are done in a conscious way.

Walking involves a very large number of degrees of freedom, and a much larger possible set of input variables. The recording helps restrict the state space somewhat, but does little to curb the search for appropriated trigger variables.

Online proceedings use the gross motor sequence as a template and the recording of the walk cycle as a guideline and critic to learn to walk. The system adapts both the parameters of each type of motion and their trigger points. The system has fairly rapid reward feedback by tracking its motion against the motion in the recording. There is no need to wait for the entire robot to fall over before deciding that something is wrong. Online techniques try to change, in real time, the sent sequence from the information obtained by robot sensors. System reaction to any kind of situation could be assumed improving process time and system control. Online methods work in a different way the off-line ones, in the way that humanoid modifies its path nearly unconsciously, answering sudden stimuli. Then, robots can correct their position, as when somebody steps another person or stumbles.

IV. ONLINE CONTROL TECHNICS

Online strategies are oriented to guarantee a dynamically balanced movement, so environment state and ZMP position information is needed. Three main strategies can be found in bibliography [5] of Online dynamic balance control in humanoid robots. These strategies should be used in a cooperative way to ensure a complete balance.

1) Movement Sequence Control: This method consists in a robot position readjustment. One step is generated, whose length and direction modify or increase the area over the humanoid is. Thus, the area which the robot can move around becomes bigger, so that the external force disturbing dynamics humanoid balance can be higher, without risk of falling.
2) Moments Control: This technique consists in generating a moment around the mass center to make ZMP move back. It is used when the ZMP Control is not effective. The mentioned moment is generated when ankle motors are unable to counterbalance an external force. Therefore, the moment around the mass center is generated by the hip or opposite leg motors.
3) ZMP Control: This proceedings is the most used in humanoid robots, since pressure sensors placed in the feet to estimate ZMP, and an acelerometer to calculate robot inclination are the only requirement. The aim is maintaining ZMP in a zone nearby the robot's footprint, so that the humanoid can better respond to external forces. In order to achieve that purpose, a change in ankle motor pair of forces is prompted, so ZMP is displaced by moving robot mass center and, at the same time, ground reaction force makes up for external force effects.

V. FINAL REMARKS AND FUTURE LINES

This paper has been pretended to capture the Status of the Art of the different balance studies in humanoid robots. Therefore the important position held by dynamic balance as basis of biped locomotion in current robotics has been emphasized.

In order to solve the walking problem, two aspects coexist and complement each other. On one hand, reproduction of mechanic movements from different degrees of freedom of the robot, which make possible harmonious, previously defined motive sequences. On the other hand, control programs, which are triggered as a consequence of events established with due care, allow the humanoid to face unforeseen unbalances. Therefore, a complete online behavior is subjected to constant robot sensors verification so that it is prevented a unbalanced point of the robot.

These techniques, off-line and online, have the same theoretical basis in common, which relates forces and moments interacting between the feet sole of the robot and the ground. Thus, it has been considered important to give the details of the different magnitudes, especially ZMP, which are dealt regularly in bibliography to introduce the reader to the theoretical basis of dynamic balance.

An obvious evolution of this work would be studying in depth how to the obtain the necessary information to activate balance control events. Fitzpatrick and McCloskey describe in one of their papers [6] how pressure sensors in sole feet are the first detecting slight balance variations. It would be possible, therefore, to study the most common types and distributions of pressure sensor in depth.

In the same manner, in this work the development of balance control us missing, because of it is an inherent characteristic in each machine. Constant hardware advance, together with specific software for robots make this field a favorable place to develop innovative ideas.

Obviously, practical application of these aspects in a commercial robot is a repetitive subject in bibliography. Recently, a work has been presented [7] in which two online control techniques have been applied successfully in a cooperative way in a HOAP-1, a Fujitsu robot. This work can be a starting point to make progress in dynamic balance understanding.

From the author's point of view, robotics is a never ending source of future investigation lines. From the biped locomotion's point of view, the possibility of introducing advances from other outstanding stuff, like Visual Perception, is specially attractive. The possibility of obstacles recognition getting to work off-line movement sequences, together with a good online balance control, is a key aspect to develop.

Nowadays, a new robot (Runbot) has been developed in Europe on the basis of the work of the Russian neurophysiologist Nikolai Bernstein. Runbot is a small biped robot, which is able to walk more than three strides per second, almost like a human being. Runbot is 30 cm tall, has a sensor which detects ground contact and another one which registers movement forwards, facts that make possible doing movement variations on very variated grounds. Sensors send information to a neuronal program, which analyzes and readjusts it in real time.

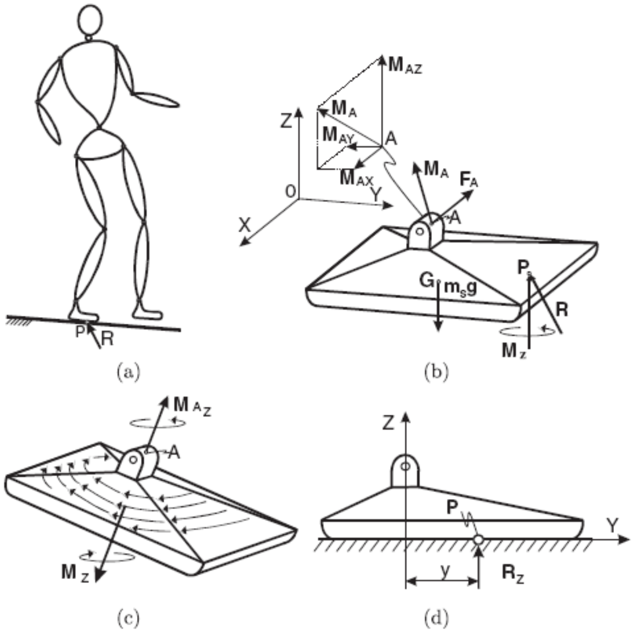

Fig. 2. Biped mechanism and forces acting on its sole. Figure from [2].

When a slope is found in front of the robot for the first time, the unbalance caused by normal movement of Runbot causes it to fall. Nevertheless, thanks to system basis on neuronal networks, robot learns from the experience and adapts its movements to the ground when it faces one similar situation again. It is also a highly interesting example of multi-discipline interaction to solve the biped locomotion issue.

APPENDIX
DYNAMIC BALANCE: ZMP EQUATIONS

We can say that the necessary and sufficient condition for the locomotion mechanism to be in dynamic equilibrium is that for the point P on the sole where the ground reaction force $\mathbf{R}$ is acting,

$$M_x = 0$$

$$M_y = 0$$

where $\mathbf{M} = \{M_x, M_y, M_z\}$ are the total ground reaction moment.

Since both components relevant to the realization of dynamic balance are equal to zero, a natural choice to name this point was Zero-Moment Point. Now, a logical question can be posed: given the mechanism dynamics, what should the ZMP position be that would ensure dynamic equilibrium? To answer the previous question [2] [9] let us state the static equilibrium equations for the supporting foot Fig. 2(b).

$$\mathbf{R} + \mathbf{F}_A + \mathbf{m}_s g = 0 \qquad (1)$$

where $\mathbf{F}_A$ and $\mathbf{M}_A$ are the equivalent force and moment defined over the ankle joint.

$$\overrightarrow{\mathbf{OP}} + \mathbf{F}_A + \mathbf{m}_s g + \overrightarrow{\mathbf{R}} + \mathbf{M}_A + M_z + \overrightarrow{\mathbf{OA}} + \overrightarrow{\mathbf{OG}} = 0 \quad (2)$$

where $\overrightarrow{\mathbf{OA}}$, $\overrightarrow{\mathbf{OG}}$ and $\overrightarrow{\mathbf{OP}}$ are radius vectors from de origin of the coordinate system to the ankle joint, the mass center and reaction force acting point respectively. If we place the origin at the point P and a z-axis projection of Eq.(3) is made, the vertical component of the ground reaction moment is

$$M_z = M_{fr} = -(\mathbf{M}_A^z + (\overrightarrow{\mathbf{OA}} \times \mathbf{F}_A)^z) \qquad (3)$$

what projected on the horizontal plane gives

$$(\overrightarrow{\mathbf{OP}} \times \overrightarrow{\mathbf{R}})^H + \overrightarrow{\mathbf{OG}} + \mathbf{m}_s g + +\mathbf{M}_A^H (\overrightarrow{\mathbf{OA}} \times \mathbf{F}_A)^H = 0 \quad (4)$$

This equation is a basis for computing the position of the ground reaction force acting point (P). Equation (4), representing the equation of the foot equilibrium, answers the above question concerning the ZMP position that will ensure dynamic equilibrium for the overall mechanism dynamics, but it does not answer the inverse question: whether for the given motion the mechanism is in dynamic equilibrium?

To answer this question we have to consider the relationship between the computed position of P and the support polygon. If the position of point P, computed from Eq. (4), is within the support polygon, the system is in dynamic equilibrium. However, in reality, the point P cannot exist outside the support polygon, as in that case the reaction force R cannot act on the system at all. From this follows a straightforward but very important conclusion: in reality, in order to ensure dynamic equilibrium, a point P that satisfies Eq. (4) must be within the support polygon.

ACKNOWLEDGMENT

The author would like to thank members of Electronic Technology Department and Communication Engineering Department of University of Málaga their unselfish work to make this Master possible.

REFERENCES

[1] Vukobratovic, M and Borovac, B “Biped Locomotion. Dynamics, Stability, Control and Application”, Springer-Verlag, Berlin, 1990.

[2] M. Vukobratovic and B. Borovac, “Zero-Moment Point – Thirty Five Years of Its Life”, *International Journal of Humanoid Robotics*, 1(1): 157-173, 2004

[3] Goswami, A. “Postural stability of biped robots and the foot-rotation indicator (FRI) poin”, *International Journal of Robotics Research*, 18(6):523-533, 1999

[4] Popovic, M. B., Goswami, A., Herr, H., “Ground Reference Points in Legged Locomotion: Definitions, Biological Trajectories and Control Implications”. *International Journal of Robotics Research*, 24(12):1013-1032, 2005.

[5] Hofmann, A., “Robust Execution of Bipedal Walking Tasks From Biomechanical Principles”, 2006

[6] Fitzpatrick, R., McCloskey, DI., 1994. “Proprioceptive, visual and vestibular thresholds for the perception of sway during standing un human”, *Journal of physiology*, 1994

[7] A. Carmona, . Proyecto Fin de Carrera, Departamento de Tecnología Electrónica, Universidad de Málaga, 2007.

[8] Kim, D., Seo, S.-J. and Park, G.-T., “Zero-moment point trajectory modelling of a biped walking robot using an adaptive neuro-fuzzy system” *IEE Proceedings-Control Theory and Applications*, 152(4): 411-426, 2005.

[9] Hauser, H. “Stability Criteria for Humanoid Robots”, *Institute for Theoretical Computer Science*, Seminar, 2005