Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

Miomir Vukobratović

Institute Mihajlo Pupin, Volgina 15, 11000-Belgrade, Serbia
vuk@robot.imp.bg.ac.yu

Branislav Borovac

Univ. of Novi Sad, Faculty of Technical Sciences, Trg D. Obradovića 6,
21000-Novi Sad, Serbia
borovac@uns.ns.ac.yu

Abstract: During a day, moving in an unstructured environment, man is realizing different types of walk, requiring from him on-line trajectory planning and permanent changes of gait parameters (turning, stopping, speeding up and slowing down, switching from the walk on a flat ground to the walk on inclined surfaces or staircases, etc.). Besides, apart from realizing the motion, there appears frequently the need to perform some additional tasks, e.g. manipulation. In view of the expectation that the future robots will share with humans their living and working environment, it is expected from them to be endowed with similar capabilities of motion. We think that a necessary prerequisite for fulfilling all these tasks is a permanent maintenance of dynamic balance, which may be achieved by the realization of a regular gait. Therefore, one of the basic characteristics of regular bipedal walk of humanoid robots is the maintenance of their dynamic balance during the walk, whereby a decisive role is played by the unpowered degrees of freedom arising at the foot-ground contact. Hence, the role of Zero-Moment Point (ZMP) as an indicator of dynamic balance is indispensable. On the other hand, we are witnesses of the diverse realizations of locomotion systems, from those with human-like feet, aiming to mimic in full the human gait, passive walkers, which practically roll on specially profiled feet, to the footless locomotion systems. It is quite clear that any of these systems can realize a gait (very often such gait is not dynamically balanced), but our present study shows that the performances of such walking systems are essentially different and inapt to meet the requirements that are put before the humanoids in a human environment. The work points out the indispensability of the regular, fully dynamically balanced gait for the simultaneous realization of locomotion-manipulation activities, as well as for the walk in an unstructured environment.

Keywords: humanoid robot, regular gait, irregular gait, stability, dynamic balance, ZMP

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

1   Introduction

In the recent years we have witnessed an explosive development of Humanoid Robotics, which has finally become a distinctly differentiated scientific discipline within Robotics itself. Part of the "roboticist community" might be surprised by such an abrupt growth of interest in Humanoid Robotics. However, a careful chronicler could observe that from the very beginning of modern robotics, and even from the ideas of science fiction that preceeded it, the basic goal of robotics has been to copy to a highest possible degree particular capabilities of humans [1-8], whereby the future period of "robot's entering the living and working space of man" will be marked with an even greater degree of anthropomorphism. This research direction in the course of robotics development has been obvious to a lower or higher extent, but it has always been present. Particular periods that have been dominated by the different aspects of robotics such as industrial robots, multi-leg vehicles, etc. appeared to be "side work", but the results gained and accumulated knowledge and technological advancements have enabled an effective switch to the "mainstream work" - Humanoid Robotics.

Now, when we ascertain the reality of the appearance of a special scientific discipline - Humanoid Robotics - we should say that artificial walk and skeletal activities in general, represent one of very active research directions, so that it is necessary to address some formal aspects that may be of essential importance for a further development of high-performance humanoid robots.

We refer to the presence of some kind of inconsistency in the usage and understanding of some basic notions in the sense of their definitions and terms used. For example, there is a pretty great diversity in using the terms stability, dynamic balance and dynamic equilibrium [9]. Majority of such notions and terms have been tacitly accepted, probably because they have been considered to be intuitively sufficiently clear. Hence they have only recently been formally defined in the robotic literature. Because of that we think it would be purposeful to define in a more detailed way the notion of dynamic balance since this notion has been defined in the different ways by different authors, and the terminology has not been brought into concordance.

Let us tackle first the definition of walk, gait and regular gait. Detailed discussion of these issues and the definitions of some basic notions that appear in the area of biped locomotion can be found in [10].

According to [10], under walk is understood the "*move by putting forward each foot in turn, not having both feet off the ground at once*". From this definition it comes out that walk is characterized by such displacement of legs in which both feet are not separated from the ground at the same time, and which ensures the body motion in space – usually forward, though it is possible to consider a backward walk too. We think that this definition, though not originateed from technical literature, satisfies the needs of humanoid robotics.

It is known from experience that the walk of every individual is specific and that a man walks differently in different situations. Each of these particular ways of walking represents a particular gait. Therefore, it can be said that gait represents the "*manner of walking or running*" [11]. Hence, any walk is realized by a certain gait. By recording time changes of the angles at legs' joints during one step, one is recording in fact a particular gait.

Under the notion *regular gait* is understood a periodic gait in which *the leg in the single-support phase is in contact with the ground by the whole foot area or with only its front part* (the toes link with the two-link foot), and in the case of double-support phase the requirement applies to at least one foot. The gait consisting of the parts that are all regular is also regular. For example, climbing the staircases, straight-line gait forward, turning, etc., considered as a whole, represent also regular gaits.

The main task of humanoid in bipedal gait is to avoid overturning. However, this requirement has not been terminologically defined yet in a proper way. For a long time, the accustomed term for the gait that proceeds continuously has been *stable gait*[1]. The term made it possible for someone to grasp intuitively the problem, but it might also cause misunderstanding. The term stability, in this context, is not an appropriate choice because stability in system theory and automatic control has already been clearly and precisely defined, and it strongly concerns the system control. A special aspect of this problem for bipedal walking robots, which does not occur in the case of fixed-base manipulators, is the fact that all joints of the bipedal robot are powered and directly controllable except for the "joint" that represents contact with the ground. This lack of actuated direct control at the ground-contact interface makes the walking robot *underactuated*. The robot may fall due to an external disturbance, or due to an incorrect action of the robot itself. Hence, the way to prevent robot fall is to take control actions at the actuated joints that enforce a desired internal synergy and a desired foot-ground interaction state. In this way the realization of both internal and external synergies is simul-taneously ensured and dynamic balance of the system as a whole is maintained.

Therefore it comes out that if the system is not constantly in the upright position (or in a position corresponding to the concrete task) it will not be capable of realizing the assigned task despite the fact that the movements of all the joints are realized in the predicted way. Let us consider why the notion of stability is not appropriate in the case of humanoid locomotion systems. We will consider two examples.

---

[1]   There are a lot of examples in which under gait stability is assumed the prevention of overturining of the humanoid as a whole. We will give only two. Thus, for example, in [12] (p. 3346) one can read: "Since a biped robot tends to tip over easily, stable and reliable biped walking is a very important achievement", whereas in [13] (p. 65) we find "Since biped robot easily tips over it is necessary to take stability into account when determining a walking pattern".

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

The first example is related to the very end of the single-support phase of a regular gait. Since each person walks in a unique way it is quite possible that among the realizable patterns one can find the one in which the system at the end of the single-support phase is practically falling forward by rotating about the joints' link of the toes that are being by their whole area in contact with the ground. However, in view of the fact that the at the end of the single-support phase the entire locomotion system is already "prepared" for the situation to arise, the contact with the ground will be, after a short time interval, realized via the leg being in the swing phase. Since in this phase it is not practically possible to effect the locomotion system, its "preparedness" is the only way in which is possible to prevent consequences that may arise at the end of this phase. In other words, the phase of the system's free fall (which may be part of the "normal" motion of the system) occurs when the system has already assumed the appropriate configuration by which is possible to prevent it from unacceptably high speed at the moment of the occurrence of the foot-ground contact and appearance of a contact force of unacceptably high intensity. This means that for the situation to the end of the free fall phase we can not speak about stability - dynamic balance is being ensured by the activities determined prior to the occurrence of the free fall.

The second example is related to the situation when the walking locomotion system experiences a disturbance of a substantial intensity, e.g. a lateral force acting on the biped's shoulder by such intensity that the locomotion system can not continue on walk in the intended direction but is forced to step aside, to preserve dynamic balance and continue walking. It is obvious that in this example the system that has been realizing a reference trajectory before the disturbance, in order to prevent falling, abandoned it, and, when the disturbance force ceased, it resumed the realization of the reference motion. In both of these cases, both before and during the disturbance, the system maintained dynamic balance while stability has evidently been lost.

From these examples it follows that:
  a) locomotion systems represent the systems that can change their configuration during the motion (the number of degrees of freedom is different in the single- and double-support phase).
  b) the locomotion system, with the aim of preventing fall, can abandon realization of its reference motion, switch to a new reference trajectory and, after eliminating the danger of falling down, return to the realization of the previous reference trajectory.

Because of that, a better suited term is needed to express the conditions that the gait is sustained, i.e. continued. For this reason we propose to introduce the notion of dynamic balance.

Besides, we are witnesses of the development of robots with the different kinds of legs and foots, even without feet. In this paper we will focus our attention on the notion of dynamic balance of all types of bipedal motions, with and without feet, linear ones, and even with the point-like foot-ground contact.

In the regular biped gait, the contact of the humanoid robot with its environment is realized only via the feet, supported freely on the ground. The motion of the joints (change of the internal coordinates) changes the relative position of the links, which results in a simultaneous change of the relative position of the humanoid robot with respect to the environment (change of the system position described in terms of external coordinates). In order the change of internal coordinates yielded a desired change of external coordinates, it is necessary for the robot-ground contact to be steady during the walk.

2   Internal and External Synergy

Let us focus on the humanoid robot sketched in Fig. 1. Let the coordinate frame representing environment to which external synergy has been defined be $x_{GR}O_{GR}z_{GR}$ (Fig. 1a) and let it be fixed to the ground. Let the internal synergy be defined with with respect to the coordinate frame $x_F O_F z_F$ fixed to the foot tip (Fig. 1a). Both coordinate frames are presented only in the sagittal plane: external by the axes x_{GR} and z_{GR}, and the frame fixed to the foot tip by the axes x_F and z_F, the y axes not being shown in either of the cases.

Let us further suppose that the humanoid is walking (Fig. 1 shows the single-support phase) while trying to reach the object O shown in Fig. 1b. The object position requires that the hand (represented by the point H) approach trajectory is parallel to the x-axis of the frame $x_F O_F z_F$. In case the foot realizes "proper" contact with the ground, (i.e. contact over surface, not line or point) the coordinate frames $x_{GR}O_{GR}z_{GR}$ and $x_F O_F z_F$ will coincide and hand trajectory will also be parallel to the x-axis of the external coordinate frame $x_{GR}O_{GR}z_{GR}$. Suppose further that a disturbance occurred and that the humanoid started falling forward by rotating about the front foot edge (Fig. 1d). In such a case the frames $x_{GR}O_{GR}z_{GR}$ and $x_F O_F z_F$ will not coincide any more (Fig. 1e). They are being rotated by the angle φ. If the humanoid is continuing to realize joints trajectories exactly as before the occurrence of disturbance the hand trajectory will remain parallel to the x-axis of the frame $x_F O_F z_F$, but will not be parallel to the x-axis of the external frame $x_{GR}O_{GR}z_{GR}$. In other words, in the case of a "non-proper" foot-ground contact the internal and external synergies will not coincide. This means that the hand trajectory with respect to the environment (external synergy) will not depend now only on the joint angles q_i, i=1, ... n, but also on the angle φ between the foot and the ground. We think it obvious that this non-coincidence of the hand trajectories is caused by the foot rotation relative to the ground and that it influences the behavior of the overall system. Thus, we can say that in case of biped locomotion a unique relationship between internal and external synergies is ensured by relative immobility of the robot's foot (more precisely, the legs' terminal links) and environment in contact.

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?
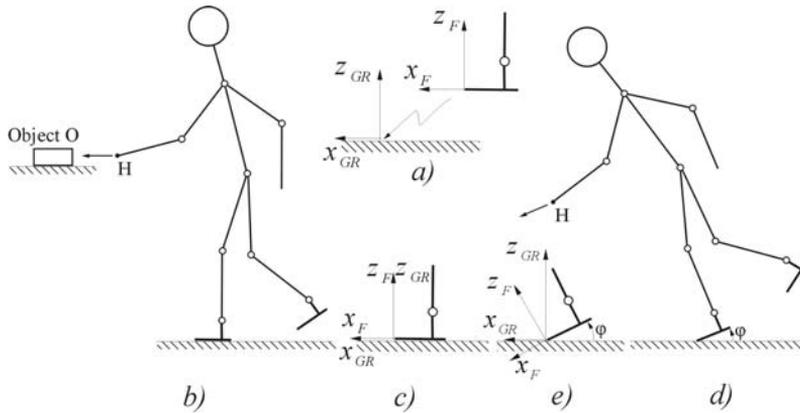
Figure 1

Illustration of internal and external synergy

If this holds, the robot is dynamically balanced. This means that if a proper internal synergy results in the proper external synergy we say that the robot is dynamically balanced, or, more specifically, dynamic balance can be represented by relative immobility of the coordinate frames $x_{GR}O_{GR}z_{GR}$ and $x_F O_F z_F$ representing internal and external synergies.

As the contact with the ground is realized through the feet, this means that in the case of a regular gait the terminal link of the supporting leg (one-link foot or only the toes link of a two-link foot) being in direct contact with the ground does not move with respect to it.

It should be noted that it is possible to realize a gait which is not dynamically balanced, as, for example, the walk on the crutches. Consequences of the absence of dynamic balance with such type of gait will be discussed later on.

3 The Notion of Dynamic Balance, Prerequisite for its Existence and ZMP

In this section we will consider in more detail the notion of dynamic balance and show that the ZMP is its indicator, whose approaching the edge of the support area indicates the rise of the danger of the system's falling down. Finally, we will show that a prerequisite for the existence of dynamic balance is the existence of the support area.

3.1   Notion of Dynamic Balance and ZMP

As defined in [11], under walk is understood the "move by putting forward each foot in turn, not having both feet off the ground at once". From this definition it comes out that walk is characterized by such displacement of legs in which both feet are not separated from the ground at the same time, and which ensures that the body in the space moves (usually) forward. In view of the fact that the body is supported on the legs, to ensure that "the body in the space moves forward" is possible only if it is constantly taken care of avoiding overturning, i.e. of preserving dynamic balance of the mechanism. Having in mind that all of the humanoid robot joints are powered and directly controllable except for the contact of the foot and the ground, this contact is essential for the walk realization. The mechanism's position with respect to the environment depends on both the relative positions of the links and relative position of the foot with respect to the ground. In order the humanoid could perform the reference motion it is necessary to realize the predefined motions at the joints, and at the same time to preserve the relative position of the foot with respect to the ground. Therefore, to prevent the humanoid from falling, it is necessary to ensure the appropriate dynamics of the mechanism above the foot to preserve the regular contact of the supporting foot with the ground. In other words, since the sole-ground contact is unilateral, a necessary condition for avoiding overturning is that the motion of the humanoid as a whole is such that, while the regular sole-ground contact is preserved, the overall ground reaction can be replaced by one force only. This can be mathematically expressed as follows.

Let us introduce a Cartesian frame with the origin at the point where the resultant ground reaction (pressure) force is acting, with two axes (x and y) being tangential to the ground and the third (the z-axis) being normal, then a mathematical expression for the fulfillment of dynamic balance is: $\Sigma M_x = 0$ and $\Sigma M_y = 0$. The moments include gravity, inertial forces and other external forces acting on the humanoid body (like wind, strike, etc.). It should be noticed that it is not necessary for the third component of the moment (about the z-axis) to be zero, provided it is compensated for by the friction between the foot and ground. In such case $\Sigma M_z \neq 0$ does not cause motion. The point inside the support area (excluding its edges) for which it holds $\Sigma M_x = 0$ and $\Sigma M_y = 0$ is termed the Zero-Moment Point (ZMP).

To make the above clearer, let us return to the source interpretation of the ZMP. Let us consider the single-support phase of a *dynamically ballanced gait* of the mechanism having one-link foot. The foot of the supporting leg[2] is in contact with

---

[2]   In the case of a one-link foot the whole foot is on the ground, whereas in the case of a two-link foot it suffices that this condition is fulfilled only by the terminal link of the supporting leg, that is the toes link.

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

the support surface in the way presented in Fig. 2. On the basis of the D'Alembert principle applied to the entire system we can write:

$$\sum M_x^{\substack{inertial \\ (without\ foot)}} + \sum M_x^{\substack{gravitational \\ (without\ foot)}} + M_x^{\substack{gravitational \\ (of\ immobile\ foot)}} = 0$$

$$\sum M_y^{\substack{inertial \\ (without\ foot)}} + \sum M_y^{\substack{gravitational \\ (without\ foot)}} + M_y^{\substack{gravitational \\ (of\ immobile\ foot)}} = 0$$

(1)

This holds for the point inside the support area at which ground reaction can be replaced by a single force only. This point is of crucial importance for the *dynamically balanced gait*, and it is termed ZMP. This reflects best the essence of this point, its role of the indicator of dynamic balance of the humanoid robot, as well as the way of its determination and application. It should be noted that equations (1) encompass moments of gravitational and inertial forces of all humanoid robot links with the exception of the foot that is in contact with the ground and immobile with respect to it, and for which only gravity is considered. Let us remind that the source interpretation of ZMP presumes the walk on a fixed support. If the walk on a mobile support is considered, it is necessary to introduce into (1) new terms, but this case will not be discussed here.
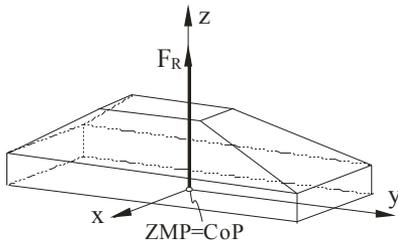

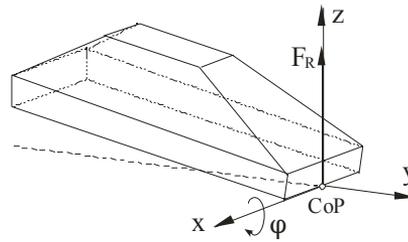| Figure 2	Figure 3
Foot in single-support phase	Rotation of the supporting foot about its edge

Further, let us consider the way how to preserve *dynamic balance* of the mechanism and prevent it from falling. The answer is quite simple: by using an indicator that will warn that a critical situation approaches and that it is necessary to undertake appropriate compensational action. This indicator is the position of ZMP inside the support area, and it corresponds to the position of the ground reaction force. The ZMP position inside the support area can be easily determined with the aid of force sensors on the sole. All the time the ZMP is within the support area there will be no rotation about the foot edge and the humanoid robot will preserve its dynamic balance. Warning means that the ZMP is coming closer to the foot edge.

Let us suppose that a critical situation has evolved and that the humanoid is falling down by rotating about one of the foot axes. Without loss of generality, let us assume that it is the foot front edge, along which we will place the rotation axis (*x*-axis), as presented in Fig. 3. Based on the D'Alembert pricnicple one can write for a rotating foot equations (2), which contain equations (1) along with some

additional terms related to the foot, which in this case moves (there is no link immobile with respect to the ground):

$$\sum M_x^{(without\,foot)\,inertial} + \sum M_x^{(without\,foot)\,gravitational} + M_x^{(of\,rotating\,foot)\,inertial} + M_x^{(of\,rotating\,foot)\,gravitational} = 0 \qquad (2)$$

$$\sum M_y^{(without\,foot)\,inertial} + \sum M_y^{(without\,foot)\,gravitational} + M_y^{(of\,rotating\,foot)\,gravitational} = 0$$

Apart from the introduction of new terms, the existing ones also change their values compared with terms of eq. (1), because the intensities and directions of inertial forces of all the links change when the humanoid robot starts to rotate about the foot edge. In other words, eq. (2) describes a system's motion that is essentially different from the motion described by eq. (1). In this case, functional requirements that are realized with respect to the Cartesian (outer) coordinates (e.g. walking) are not fulfilled despite the fact that the change of joints coordinates may be perfectly realized while the system is falling down. Hence, in the case the humanoid's overturning, the point at which is formally fulfilled $\Sigma M_x = 0$ and $\Sigma M_y = 0$, does not represent the ZMP, because dynamic balance has not been preserved.

Let us consider the case of regular gait of a humanoid robot with two-link foot (Fig. 4). In that case the link representing toes is fixed with respect to the ground, whereas the link of the rear part of the foot moves. In view of the fact that the gait is regular the ZMP is inside the area covered by the toes link, and the system retains its dynamic balance.

We should especially emphasize the difference between the situations illustrated in Figs. 3 and 4. In contrast to that shown in Fig. 3, the humanoid robot whose foot is sketched in Fig. 4, preserved its desired position with respect to the environment. In view of the fact that in the case shown in Fig. 4 dynamic balance
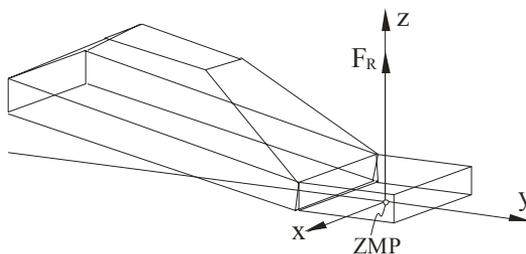

Figure 4
Two-link foot and support area where ZMP can exist

has not been lost, the point inside the support area (and this is the area covered by the toes link) for which $\Sigma M_x = 0$ and $\Sigma M_y = 0$, represents the ZMP. In all above examples, only rigid foot was considered.

Let us try to demonstrate the essence of dynamic balance on one more example.

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

We consider the four-link physical inverted pendulum supported on the ground by its bottom link (Fig. 5). All the joints of the pendulum (J^1, J^2 and J^3) are powered. If the links L^2, L^3, and L^4 move so that the link L^1 remains immobile with respect to the ground (Fig. 6a), then we say that the system as a whole is dynamically balanced. However, if the motion of the links L^2, L^3 and L^4 causes the contact of the L^1 and the ground becomes as shown in Fig. 6b, the system will not be dynamically balanced.
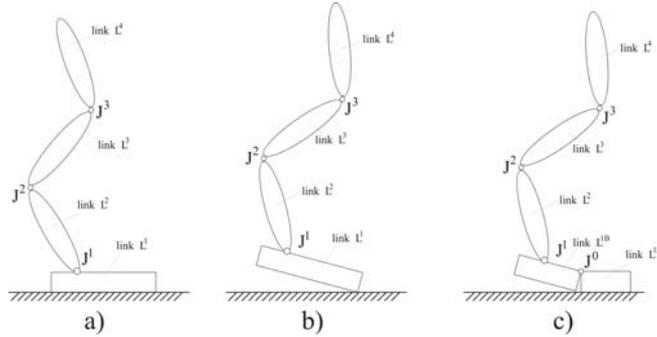

Figure 5
Illustration of the notion of dynamic balance

Further, let us assume the link L^1 consists of two links, link L^{1A} and link L^{1B}, connected via the joint J^0 (Fig. 5c). In the examples shown in Figs. 6a and 6b, the joint J^0 is locked, so that the links L^{1A} and L^{1B} behave as a single solid body. If we assume that the joint J^0 is also active, the system will be dynamically balanced only if the link L^{1A} is immobile with respect to the ground, as presented in Fig. 6c. In this case, the link L^{1B} may move like any other link (L^2, L^3 or L^4), and need not be in contact with the ground.

Let us point now to the obvious analogy between the equilibrium state of the humanoid's static posture and dynamic balance of the system in motion. Suppose the system stands immobile on one leg and that the supporting foot is in full contact with the ground (as in Fig. 2). It is quite clear that such a state is sustainable if the projection of the center of mass (CM) of the system on the horizontal plane is inside the support area. If the humanoid system changes its posture the position of its CM will displace, but all the time it is inside the support area its static equilibrium will not be jeopardized. The closer the CM to the edge of the support area, the smaller the "equilibrium reserve". If the humanoid's position is changed so that the CM projection onto the horizontal ground plane comes out of the support area, the system as a whole will begin to fall by rotating about the foot edge.

In the dynamic case the picture is fully identical provided we take into account these two specific features: a) the vertical projection of the CM onto the ground

plane should be replaced with the ZMP[3] and b) it should be clearly noticed that the existence/absence of dynamic balance is a system's characteristic only in the given instant, and that in the subsequent moment it may be quite different, which is not the case in maintaining the static posture.

In summary, to preserve dynamic balance, the ZMP has to be kept inside the support area (as long as the foot remains immobile on the ground), and by no means at its edge, when the foot loses immobility. When the foot rotates, the ZMP does not exist. But, the CoP (Center of Pressure) will still exist. This is the difference between the ZMP and CoP. Hence, the ZMP should be used as the indicator of dynamic balance, but not the CoP.

And, let us now conclude. We can speak of ZMP only while the humanoid robot is dynamically balanced. When the system rotates about the foot edge and falling down, the ZMP does not exist any more. Thus, the ZMP can be only inside the support area, and by no means at its edge. The determination of the ZMP position on the ground surface without taking into account the size of the support area can result in a calculated ZMP position that is outside this area. It should be noticed that such ZMP position can not exist because the assumption that the foot (or its terminal link which is in contact with the ground) is immobile with respect to the ground has not been fulfilled.

3.2   Prerequisite for the Existence of Dynamic Balance

Based on the above explanation it is clear that a humanoid will be dynamically balanced if in the given instant the ZMP is within the support area. This evidently implies that dynamic balance can not be realized if there is no support area.

In a "normal" gait, the foot-ground contact may be realized via the edge (e.g. the heel edge in switching from the single- to double-support phase) or via surface contact[4]. In some very special situations the contact may be realized only at a point (e.g. when the contact is made via the shoe tip or if the humanoid, instead of the foot has a pin-point prosthesis. In view of the different possibilities for the foot-ground contact it is also possible to have support area of the different shape.

Let us consider first the phases of the foot-ground contact when the humanoid is realizing regular gait (Fig. 6). In the realization of such gait the contact of the foot with the ground in every moment is a surface area, at least with one leg.

---

[3]   This analogy holds all the time the ZMP is inside the support area, i.e. while the ZMP exists. If the system falling occurred by rotation about the foot edge, the dynamic balance is lost and the ZMP does not exist.

[4]   It is important to notice that in the regular gait at least one foot makes a surface contact and that the support area always exists.

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?
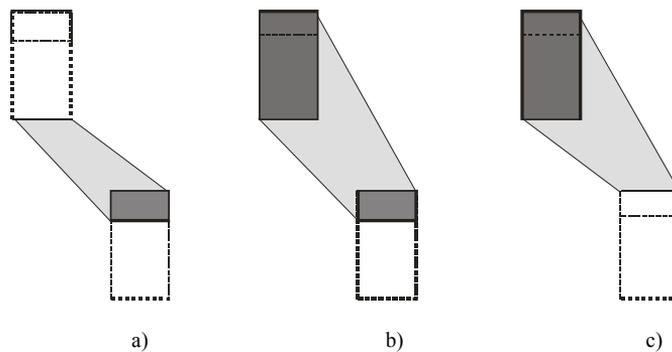

Figure 6
Different phases of the foot-ground contact in the regular gait

Let us suppose that we begin to observe regular gait from the moment when the left leg made contact with the ground (Fig. 6a), whereas the right leg is in contact with the ground via the toes link only. The dashed lines indicate the contours of the foot parts that are not in contact with the ground. In Fig. 6a the left foot contact with the ground is shown as a line and the support area is of the shape shown in the figure. In the next moment the contact of the left foot and ground expands into a surface contact, which increases the support area (Fig. 6b)), in order that in the last phase (Fig. 6c)), just before the right foot separates from the ground and the single-support phase begins, the right-foot contact degrades into a line, while the left foot is in the full contact with the ground. Then ensues the single-support phase, and the cycle repeats, this time with the right foot making a line contact with the ground. Fig. 6 does not show the situation when the contact of both feet make simultaneously a surface contact with the ground. Such situation does not occur in the normal walk of an average person, but such sort of contact with the ground is very useful in the case of the occurrence of disturbance and arising danger of the system's falling down. In that case the humanoid may be forced to switch to the double-support phase with a full contact of the foot with the ground, making thus a maximal support area, which facilitates to counteract the disturbance and prevent the fall.

It is straightforward that, besides of being a surface, the foot-ground contact may be a line or a point. Fig. 7a shows the case when the contact of both feet with the ground is a point, and Fig. 7b when the contact of the left foot is a point and of the right one a line. In the first case (Fig. 7a) the contact is a line, which practically means that the contact area does not exist, while in the second case (Fig. 7b) the contact area is a triangle, the real shape of this area depending on which edge of the right-leg foot is involved in the contact.
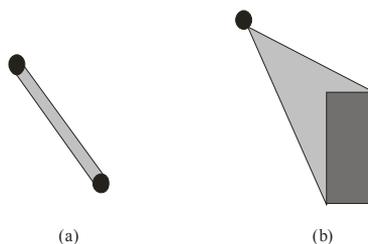
Figure 7

Different shapes of the support areas in the case of line-like foot-ground contact

The figure shows the case when the right foot makes contact with the ground by its inner edge. A similar situation would arise if the contact would be realized by the outer, front, or hind edge of the foot, but in these cases the triangular shape of the support area would be somewhat different.

Fig. 8 illustrates the case when the contact of both feet with the ground is line-like, being realized either by the front, hind or lateral edge of both feet. Fig. 9, however, illustrates the cases when the contact of one foot is realized by the front/hind edge and of the other foot by the lateral edge. In all these cases the support area is a quadrilateral of different sahape, depending on the foot edge by which the humanoid is realizing contact with the ground.

In conclusion to this section we can say that in all the cases when there exists a contact surface it is **possible** to realize dynamic balance. In the cases presented in this section this is possible only in the double-support phase (with the exception of the case when the contact of both feet with the ground is point-like and when the contact area practically never exists), whereas in all the cases during the single-support phase the support area does not exist, and it is not possible to realize dynamic balance.
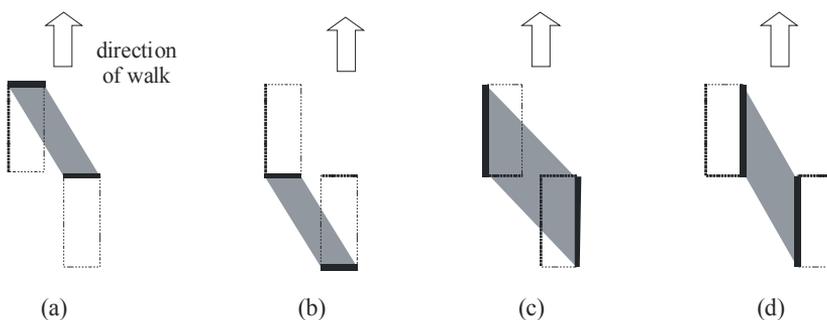

Figure 8

Shapes of the support area in the case of line-like foot-ground contact. Line contact with both feet is realized either by the front or lateral edge of the foot

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

direction of walk

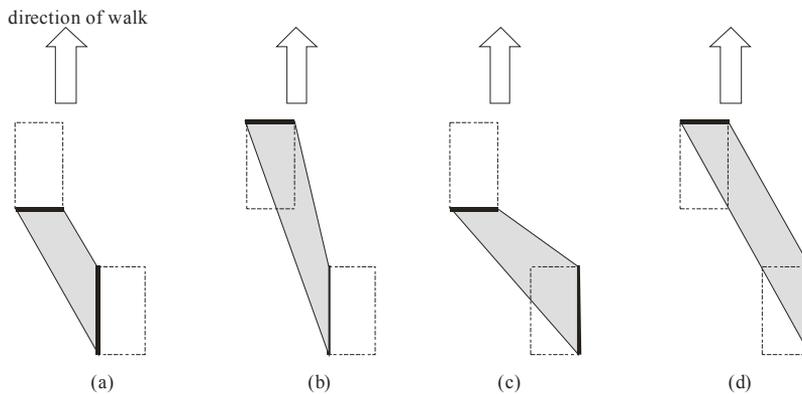(a)   (b)   (c)   (d)

Figure 9

Shapes of the support area when the line-like contact with the ground is realized either by the front or hind edge of one foot and by the lateral edge of the other foot

In the text to follow we will tackle the qustion of whether, despite of the absence of dynamic balance, is possible to realize a gait and what would be its characteristics.

4 Is Biped Walk Possible Without Ensuring Dynamic Balance? Some Special Cases

Very often arises the question as to the indispensability of ensuring dynamic balance for the realization of a bipedal gait. If it is not, the dilemma expands by the question on whether dynamic balance is necessary at all. For a correct understanding of bipedal gait these dilemmas require quite clear answers, which we will provide and illustrate in the subsequent sections.

4.1 Walk Without Feet – Are Sole Force Sensors Necessary?

Let us consider first the gait in which the contact with the ground is not a surface but it is a line or a point. The first example to consider is the ballerina's tiptoe walk. It should be noticed that in this case the contact is not a point but a small area[5], but, because of the area dimension, this fact will be neglected. The

---

[5]   In all other examples too, because of the elasticity of the ground and leg part that is in contact with it the contact surface is never a line or point but always an area. However, because of the small dimension of the contact area, without the loss of generality, in the sequel we will assume the contact is realized at a point or along a line.

ballerina's example has already been discussed in [14], but for the sake of completness we will repeat some basic elements of the discussion. First of all it should be pointed out that such walk can be realized only by some trained persons and only during shorter time intervals. Let us assume first that the ballerina is in the tiptoe posture and that she stands immobile. In that case the ZMP is inside the support area and the ballerina would remain in the same posture untill a disturbance would occur. Under the influence of disturbance the ballerina will lean, there will appear a danger of her falling down and, to preserve the posture, a compensational action has to be undertaken.

Let us consider first the way in which ballerina was forewarned of the threat of falling down: through the information about the reaction force position, i.e. of the ZMP displacement from the balanced position or in some other way. First of all we should bear in mind that man possesses a great number of sensors and that their information are effectively combined. One of these sensors is also the balance sensor, which detects the presence of disturbance, especially in the special cases like this. Hence we think the basic information about balance disturbance is originated from this center, and more so because the toes being in contact with the ground (of course, through special inserts in the ballet shoes) in this posture experience an extremely high load, so that their sensitivity is reduced. Besides, the contact area is very small and very high sensitivity would be needed to detect the ZMP displacement.

The next issue to be addressed is what the ballerina may do when she was warned that the fall can occur? In that moment she has two possibilities. The first is to change the posture and thus generate a moment with respect to the support point that would nullify the tendency to falling. Since it is very difficult to precisely generate a moment which would properly counteract the disturbance it is more likely that the disturbance will "move" to the other side and that, after a certain time, a new action will be needed to eliminate the new disturbance. Another possibility is not to generate corrective movement but allow the disturbance to rise slowly and in the meantime prepare for the event to come. This means that the ballerina has to prepare the other leg for the contact with the ground, realize the double-support phase, and from it switch again to the single-support phase – this time involving the other leg. This procedure essentially describes the way in which such systems can realize the gait. Therefore, the gait begins by initiating a forward fall, continues by stopping the fall by making contact with the ground just in the right moment, and then comes the taking over the role of supporting leg by the leg that just realized contact, and the process is continued on. The appropriate trunk movements may influence the rate of falling in the single-support phase and thus also the walking speed. Also, the appropriate trunk movements can ensure standing, i.e. balancing by standing at the spot on one or both legs. Therefore, it is clear that such systems can maintain the posture balance even without a feedback about the ZMP position, but some other sensors (accelerometers, gyroscopes) have to be included, to ensure information that the balance has been lost.

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

In a similar way move passive walkers[6], which mainly have no trunk and their foot is twisted [15]. Because of that they can not stand on one site if their legs are not straddled apart.

From the above we can draw an important conclusion. A bipedal robot without foot can use its arms, trunk and swing leg to modulate CM moments and stabilize itself as it walks. Because the ZMP does not exist and the robot is not dynamically balanced, even though it may walk perfectly well. It has to be emphasized that the notions of dynamic balance and ZMP are not connected with the robot's ability to perform walk. It is possible to synthesize robot's walk which is not dynamically balanced. However, such walk is little if at all resistant to disturbances (external and internal), and if a disturbance occurred the walk will mainly not be sustainable without corrective actions.

Let us consider now the case of a robot with feet which are not flat on the ground surface, but rather rotated about the front edge (Fig. 10a) contacting the ground in a tiptoe manner, on its heels (Fig. 10b) or on the side feet edges (Figs. 10c and d). In all the cases the contact is realized via both legs, hence we are speaking about the double-support phase. The support area is obtained by connecting with a straight line the front and hind edges of the ground and feet (Figs. 8-9).
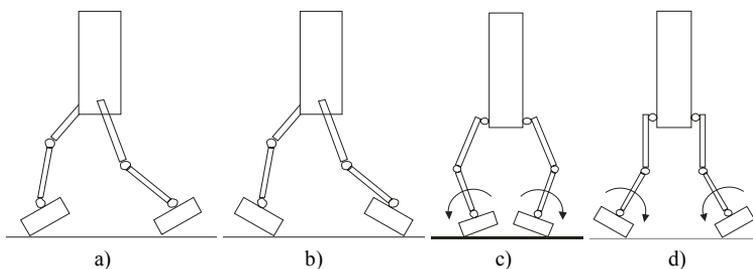

Figure 10
Sketch of the robot with feet walking on its front (a) or back (b) feet edges and on its side feet edges (c and d) Support areas are presented in Fig. 8

If the contact is made via the foot edge, it is clear that there is no support area in the single-support phase and neither there is ZMP, and hence the system is not dynamically balanced. However, in this case too, the system's motion is possible in the way described above. Moreover, the examples shown in Figs. 10c and d are very similar to skate-shoe walking or roller walking, and the example shown in Fig. 10a is similar to tiptoe walk. All these sorts of walk require special skills, such motion is possible but, one has to bear in mind all the constraints imposed by such motions. During the single-support phase the system is not dynamically

---

6   Passive walkers move solely thanks to the moment generated by the body weight with respect to the ground so that they can move only on the slant surfaces. However, to this class we also include the robots having actuators and which can move on a horizontal support, like the Cornell robot [16], as they utilize the same principle as passive walkers.

balanced, whereas in the double-support phase it may be dynamically balanced, depending on whether the contact involving both feet is line-like or point-like.

From this arises a general question: Why artificially constrain a robot to walk with its feet always flat on the ground when it is simply not necessary? If we place a sensor on the bipedal robot that measures lab-frame foot orientation (or trunk orientation), then it is not necessary to have a flat-footed walking gait to achieve mapping between the internal and external degrees of freedom. This is because nothing constrains the robot to walk with its feet not always flat on the ground. Different ways of walking can be synthesized, including tiptoe walk. The only thing to be clear is that in such case there is no ZMP feedback available, and if perturbations occurred the system's motion would be affected by both powered and unpowered joints.

The question can be formulated in another way: Are the notions of dynamic balance and ZMP necessary at all?

From its very beginning, the area of bipedal locomotion has had human's walk as a model. Regular gait is a representative of the usual gait most often practiced by humans in their everyday activities. One of the basic characteristics of such type of motion is a relatively simple way of switching from one regime of walk to another (for example, speeding up, slowing down, turning, switch from the walk on flat support to staircase walk and vice versa, realization of certain postures during walking or standing to execute on line different manipulation tasks, etc.), as man moves in a poorly structured environment and the need for such changes is evident. As such, this type of locomotion has been of greatest interest for studying. Besides, such gait requires the presence of feet, and the multi-link ones, in order the gait would be human-like (anthropomorphic), whereby this assumes the possibility of on-line modification of the planned motion, as well as the possibility of standing (which is with a mechanism without feet hardly possible). Since modern robots are still far from being greatly similar to men, there is still research interest of studying and perfecting them.

Study of special gait types (and the gait of footless mechanisms belongs to this class of tasks) is certainly interesting from a scientific aspect too, but, such gait does not certainly eliminate the need for studying the gait that is practiced most, and hence, needed most.

Bipedal robots of the future will move in poorly or totally unstructured environments. Hence they will not be capable of planning paths and synthesizing gaits in advance, but they will be forced to change often the direction and manner of walking. Because of that we pointed out (Subsection 2.2) that the walk in an unstructured environment requires the constant existence of a unique connection and preservance of the relationship between the internal and external synergies, either under conditions of disturbance action or in the case of an unexpected need to modify the motion. We think this requirement is of crucial importance because the motion is always accompanied by perturbations (mostly, by small ones), whose influence must not jeopardize the motion. On the other hand, the robot

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

itself, by its own decisions, has to be capable to actively interact with the environment (e.g. to avoid obstacles, modify gait parameters in order to move on a terrain of unexpected profile, take an object from a table while walking, stop to grasp it, etc.). In each of these cases the motion is realized by the movements of the joints, and the <u>validity of the action is verified</u> by the results achieved with respect to the environment. A key element of the success is <u>the existence</u> of the relationship between state spaces of the internal and external coordinates. This relationship, which we call <u>dynamic balance</u>, should be not only uniquely identified but also it should be preserved. Nothing is worth a perfect realization of the internal synergy if the relationship with the external synergy changes in an uncontrolled manner. Or, in other words, <u>we will not successfully continue the walk if we are falling down</u> by rotating about the foot edge, despite of the perfect realization of trajectories at all the joints.

This corroborates the above statement "If we place a sensor on the bipedal robot that measures lab-frame foot orientation (or trunk orientation), then it is not necessary to have a flat-footed walking gait to achieve mapping between the internal and external degrees of freedom."[7] because the goal is not only "to achieve mapping between the internal and external degrees of freedom", but to realize efectively the intended action. This is achieved only by <u>keeping constantly</u> the predefined relationship between the state spaces of the interanal and external coordinates in order the intended action could be planned and realized. "Mapping between the internal and external degrees of freedom" in the case that the flat-foot contact is not preserved and the system rotates about the foot edge and falls down may be important only in hazardous situations, i.e. when it is necessary to prevent complete overturning and avoid potential damaging of the robot. The crucial role of ZMP is to allow preventing the fall, i.e. the loss of flat-foot contact.

The ZMP is an indictor of dynamic balance. As has already been pointed out on a number of occasions [6-9] the ZMP does not exist if dynamic balance is not preserved, i.e. if there is no full contact of at least one part of the foot with the support. If the ground reaction force acting point is <u>inside</u> of the support area (in this case that point represents the ZMP) the system is dynamically balanced, i.e. there is no a direct threat of its overtutning. If, for some reason, the ZMP comes close to the edge of the support area (this kind of disturbance when the ZMP deviates from the desired position within the support area but it reached no its edge and dynamic balance has not been directly jeopardized yet, we call small disturbances) it means that the fall is possible and that is necessary to undertake correction immediately in order to safely continue the motion. Large disturbances (disturbances whose action presents a direct threat to dyanmic balance) are not a consequence of only intensive external effects. They may also arise from a combination of small disturbance if care is not taken about their correct compensation. The ZMP's approaching the foot edge is just "heralding" that the

---

[7]   This implies that information about the ZMP position is not necessary.

small disturbances may grow to the big ones and that something has to be undertaken before that occurred. Here we insist again on the fact that the ZMP is the indicator of dynamic balance and the primary role of the ZMP is in the compensation of small disturbances.

However, we want to especially emphasize that the ZMP is an indicator of dynamic balance only in the given time instant and that its position, e.g. at the center of the support area, does no guaranteee that in the period to follow, because of the unadequacy of compensating actions or occurence of disturbances, will not occur the loss of dynamic balance or even the fall. Thus, it is necessary to constantly take care of the ZMP position in order to preserve dynamic balance.

It should also be noticed that the ZMP with real systems can be very easily measured on line with the aid of sensors placed at the foot sole. Thereore, it is not necessary, as it sometimes has been stated, that one has to measure on line positions, velocities and accelerations of all the links and, by a rather complicated computer procedure, calculate all the forces acting on the system and, based on this information, determine the ZMP position. Position of the ZMP can be measured in a direct way.

4.2　Bipedal Running and Jumping – Are Feet and Sole Force Sensors Necessary?

Let us consider the task of running. Running is a task that robots are just about to try to realize in a way close to that as humans do it [17-20]. In [19], running is categorized as a kind of walk. Running differs from walk in that that there is a flying phase instead of the double-support phase. Therefore, running consists of the single-support phase and flying phase, during the latter the runner, with the aid of the supporting leg, takes off of ground and ballistically moves untill re-establishing contact with the ground via the other leg (which now becomes supporting leg). During the single-support phase the locomotion system has to be balanced in the same way as in gait realization, in contrary, it could not prepare for the flying phase.

Apart from the fact that running involves flying phase, when the locomotion system is totally separated from the ground, an important factor is also the occurrence of significant impact forces at the beginning of the single-support phase, and all this takes place much faster than in walking. Hence the way of maintaining dynamic balance[8] is somewhat different from that involved in walking.

---

[8]　In the case of running we will consider only small disturbances, as large disturabances are very difficult to compensate for. If the compensation, peformed with the aim of preventing the fall, is practically possible at all, the departure from the intended course is unavoidable, which practically coincides with the compensation of large disturbances during the gait.

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

As we already said, running consists of two phases: the phase when only one leg is in contact with the ground (single-support phase) and the phase when the runner is in the air, without any contact with the ground (flying phase). All the time the system is in contact with the ground it is possible to perform action at the joints, which will bring about the desired overall state of the system. However, when the system is separated from the ground it is exposed to the action of gravitational and inertial forces and accelerations. Moreover, corrective actions are limited, and if some disturbance occurred in the system as a whole, caused by the action of undesired external forces (wind, strike, etc.), the system has limited possibilities of correcting its state by compensating movements. Compensation is practically reduced to the modification of planned site where the foot will in the subsequent moment realize contact with the ground, which will influence the reaction force position with respect to the system and its "landing".

Maintenance of the system's dynamic balance during the single-support phase, as well as of the regular gait, is performed by ensuring the desired ZMP position inside the support area. The preparatory actions for the realization of flying phase during the single-support phase must be such that the majority of parameters at the end of the single-support phase have the values which will ensure the flying phase is realized in the desired manner. In order to achieve that, it is necessary to include also new types of sensors such as gyroscopic sensors, slant sensors, acceleration sensors, etc. The combination of this information with the information about the ZMP position may provide a more appropriate description of the instantaneous state of the entire humanoid system, and thus a more successful maintenance of dynamic balance during the different kinds of standard and non-standard motions.

We have also to tackle the issue of the persons with prosthesis[9] and who can perform running very well. A question arises as to how is this possible if we advocate that a prerequisit for maintaining dynamic balance is the information about the reaction force position at the foot, and in the case of the prosthesis this information certainly does not exist.

The fact is that the use of a prosthesis has to be learnt, and there is a certain period of accustoming during which, among the others, new feedbacks are formed that are specific for each new type of prosthesis, e.g. tactile feedbacks from the body parts that are in contact with the prosthesis. The ground reaction force is transferred via the prosthesis to the casing which presses the casing walls to the body. Pressure profile depends on the intensity and direction of acting of the reaction force, specificity of the contact between the casing and body part to which it is fastened, and instantaneous position of the prosthesis with respect to the body.

As already noted, running on a flat terrain is a highly automated process during which is voluntarily processed (in real time) only the information about global

---

[9] For example, the sprinter Oscar Pistorius, who has not feet.

requirements for the changes of the system state such as the requirement for the change of trajectory (e.g. because of turning at the curves). Such requirements are then realized using the existing sensory information. In the case of coming to some smaller path roughness, the lack of tactile information from the feet is evident. Path irregularities will not be detected directly by the tactile sensors on the foot but the existing sensors will detect some of the arising consequences, e.g. the disturbed balance of the overall system. Hence the compensation can also be realized only on the basis of information from the middle ear about disturbed balance, and this is done by changing the planned position of the foot-ground contact in the subsequent step, by which is changed the position of the support area and ground reaction force with respect to the system, to make it more favorable than it has been planned previously.

Therefore, thanks to the remarkable characteristics and capabilities of their sensory and control systems, humans have the ability of accommodating their control system so that the absence of certain, essentially important, sensors can be compensated for, but only through training and adapting to the new prosthetic device. Persons that use no prosthesis will never need such type of compensation.

4.3   Walk With Feet – What is Benefit of Feet Having Sole Force Sensors?

Although the gait can be realized without feet, whereby the robot is never dynamically balanced, the gait realization in real world assumes the robot has sensored feet and that dynamic balance is ensured. Feet are needed not only for the purpose that the supporting leg in the single-support phase could safely pass from the front to the rear position and prepare to reverting from the double-support phase to the single-support phase, but also to have the system to be always capable of reacting on-line on the needs to change parameters or direction of the gait and constantly react to the ever-present small disturbances. Appropriate sensoring is indispensable in order to detect position of the ground reaction force inside support area and thus realize the feedback for: a) ensuring dynamic balance, and b) getting information about the exact ZMP position so that the locomotion system in every moment could have correct information about the "dynamic balance margin", for providing adequite and reliable reaction to on-line requirements for modifying the instantaneous trajectory.

In this, for the purpose of realization the highest degree of anthropomorphism, it is necessary that the feet are flexible and that they consist of two links.

Conclusion

Although the last decades have witnessed remarkable achievements in the field of humanoid robotics, there are still some basic issues, such as dynamic balance of bipedal robots, that have no definite and generally accepted answers. The main

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

task of bipedal robots (which is often assumed and is not specially pointed out) is to maintain the gait, i.e. to prevent falling despite of disturbances that are constantly present during the motion. Under the influence of large disturbances the system is under the threat of falling down and, with the aim of preventing this, the robot may unexpectedly switch from the single-support to the double-support phase, whereby the planned motion is abandoned and the number of degrees of freedom change, and, when the disturbance action ceased, return to the realization of the assigned task. Such characteristics of motion require new theoretical notions, so that this work discusses in detail the issue of dynamic balance, bearing in mind that it has to be constantly maintained during a regular gait. Besides, a comparison has been made with the notion of stability since these two terms are often used as synonyms and the reasons are given for which we think that in the case of gait the term stability is not appropriate. Special attention has been paid to the ZMP as it represents an indicator of dynamic balance.

The indicator of the dynamic balance is the ZMP. As has already been noted on a number of occasions, the ZMP does not exist if dynamic balance is not preserved, i.e. if there is no full contact of at least one part of the foot with the ground. If the ground reaction force acting point (in this case that point is the ZMP) is <u>inside</u> the support area, the system is dynamically balanced, i.e. there is no immediate danger of falling. If the ZMP for some reason approaches an edge of the support area (this sort of disturbances, when the ZMP deviates from the desired position within the support area but it has not reached its edge and the dynamic balance is not directly endangered yet, we call small disturbances) represents an alarm that the fall is possible and that corrective actions have to be undertaken in order to successfully continue the walk. Large disturbances (the perturbations whose action directly jeopardizes dynamic balance) are not only a consequence of the intensity of external effects. They may also arise from the amplification of small disturbances if they are not properly compensated for, and just the ZMP's approaching the foot edge "heralds" that the small disturbances may grow to large ones, and that something has to be done before this happened. Here, we insist again on the fact that the ZMP is the <u>indicator</u> of dynamic balance and that a primary role of the ZMP is in compensating for small disturbances.

Also, some non-standard cases of legged motion (tiptoe walk, walk on the crutches, walk on the feet edges) have been discussed along with the question of whether such motions require the fulfillment of the condsitions of dynamic balance. It has been clearly shown that the gait realization is possible even without fulfilling the condition of dynamic balance, and the differences between such motions and a regular gait have been pointed out. This means, first of all, that the absence of the surface contact of the foot and the ground (i.e. the lack of dynamic balance) makes it impossible to realize feedback from the foot about the ZMP position inside the support area, which makes the locomotion system more "vulnerable" to the influence disturbances that are always present during the walk.

The lack of "early warning" about the approaching of the situation that may cause the system's fall makes the gait realization more delicate.

Therefore, regular, dynamically balanced gait is much more suitable for a non-structured and changeable environment that imposes on the moving humanoid not only the requirement to maintain the gait that was planned in advance but also some additional requirements in the sense of modification of planned motion and simulataneous realization of some other (e.g. manipulation) tasks during the motion.

References

[1]   Vukobratović M., Juričić D. (1968), Contribution to the Synthesis of Biped Gait, Proc. of IFAC Symp. on Technical and Biological Problem on Control, Erevan, USSR

[2]   Vukobratović M., Juričić D. (1969), Contribution to the Synthesis of Biped Gait, IEEE Transaction on Bio-Medical Engineering, Vol. 16, No. 1

[3]   Vukobratović M., (1973), How to Control Artificial Anthropomorphic Systems, IEEE Trans. on Systems, Man and Cybernetics, Vol. SMC-3, Sept. 1973

[4]   Vukobratović M., (1975), Legged Locomotion Robots and Anthropomorphic Mechanims, (in English), Mihajlo Pupin Institute, Belgrade, also published in Japanese by Nikkon Shinbum Ltd. Tokyo (1975), in Russian by Mir, Moscow, (1976) in Chinese, Beijing (1983)

[5]   Vukobratović M., Borovac B., Surla D., Stokić D., (1990), Biped Locomotion – Dynamics, Stability, Control and Application, Springer-Verlag, Berlin

[6]   Vukobratović M., Borovac B., (2004), Zero-Moment Point – Thirty Five Years of its Life, Int. Jour. of Humanoid Robotics, Vol. 1, No. 1

[7]   Vukobratović M., Borovac B., Note on the article "Zero-Moment Point – Thirty Five Years of its Life", IJHR, Vol. 1, No. 2, pp. 225-227

[8]   Vukobratovic M., Herr H., Borovac B., Raković M., Popovic M., Hofmann A., Jovanovic M., Potkonjak V., "Biological Principles of Control Selection for a Humanoid Robot's Dynamic Balance preservation" Int. Jour. of Humanoid Robotics, Vol. 5, No. 3, 2008

[9]   Vukobratović M., Borovac B., Dynamic Balance Concept and the Maintenance of the Dynamic Balance in Humanoid Robotics, in Proc. of 6th International Conf. on Intelligent Systems and Informatics (SISY 2008), Invited Plenary paper, pp. 183-187, Subotica, Serbia, 2008

[10]   Vukobratović M., Borovac B., Potkonjak V., Towards a Unified Understandings of Basic Notions and Terms in Humanoid Robotics, Robotica (2007) Vol. 25, pp. 87-101

M. Vukobratović *et al.*

Why Should Robots in Unstructured Environments Perform a Dynamically Balanced Regular Gait?

[11]   A. S. Hornby with assistance of A. P. Cowie, J. Windsor Lewis, Oxford Advanced Learner's Dicitionary of Current English, Oxford University Press, 1974

[12]   Huang Q., Kaneko K., Yokoi K., Kajita S., Kotoku T, Koyachi N., Arai H., Imamura N., Komoriya K., Tanie K,"Balance Control of a Biped Robot Combining Off-line pattern with Real-time Modification", Proc. of IEEE ICRA, San Francisco, April 2000, pp. 3346-3352

[13]   Huang Q., Kajita S., Koyachi N., Kaneko K., Yokoi K., Arai H., Komoriya K., Tanie K., "A High Stability, Smooth Walking Pattern for a Biped. Robot", Proc. of the 1999 IEEE ICRA, Detroit, Michigan, May 1999, pp. 65-71

[14]   Vukobratović M., Borovac B., Potkonjak V., ZMP: A Review of Some Basic Misunderstandings, *Int. Jour. of Humanoid Robotics*, Vol. 3, No. 2 (2006), pp. 153-176

[15]   Collins, S. H., Ruina, A. (2005) A Bipedal Walking Robot with Efficient and Human/Like Gait, Proc. of IEEE International Conference on Robotics & Automation, Barcelona, Spain, pp. 1983-1988

[16]   http://ruina.tam.cornell.edu/research/topics/locomotion_and_robotics/paper s/CornellRanger/index.html (August 30, 2008)

[17]   Hodgins J, Three Dimensional Human Running, Proc. of ICRA 2006, Mineapolis, pp. 3271- 3276

[18]   Kajita S, Nagasaki T, Kaneko K, Hurikava H, ZMP-based Biped Running Control, IEEE Robotics and Automotion Magazine, June 2007, pp. 63-72

[19]   Kajita S, Nagasaki T, Kaneko K, Yokoi K, Tanike K, A Running Controller of Humanoid Bpiged HRP-2LR, Proc. of ICRA 2005, Barcelona Spain, April 2005, pp. 618-624

[20]   Kajita S, Nagasaki T, Kaneko K, Yokoi K, Tanike K, A Running Controller of Humanoid Bpiged HRP-2LR, Proc. of ICRA 2005, Barcelona Spain, April, 2005, pp. 618-624