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Whole-body balance control of a humanoid robot in real time based on zmp stability regions approach

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Real time whole-body balance control of humanoid based on ZMP stability regions

One of the most important and complex tasks for a humanoid robot is to avoid overturning during a bipedal gait. This work aims at setting the base for designing a general balance controller to be used with any humanoid robot. In addition, it is based on a strong simplification of humanoid model which attempts to be used in real-time applications. In particular several “stability zones” are defined as function of the criticalness of balance. The results are presented in simulation and experimentally, using the humanoid platforms HOAP-3 and TEO.

Keywords: Humanoid robot; double inverted pendulum; balance controller; stability zones.

Introduction

In the last years, many authors have studied the subject of whole-body humanoid balance control. The key-issue in such matter is to look for a fast algorithm which allows a control even if the robot is subjected to impulsive disturbances.

Algorithms based on computed-torque control (Ott, Dietrich, and Roa 2015; J.H. Park and Kim 1998) and hybrid impedance/computed-torque control (Jong Hyeon Park and Chung 1999) have been proposed. An impedance control for supporting the feet or hands allowing the robot to adapt to low-friction ground without prior knowledge of the ground friction is considered in (Hyon 2009).

Jung-Hoon and Jun-Ho (Kim and Oh 2004) presented three online controllers for maintaining dynamic balance of a humanoid robot using a force-torque sensor

placed in the ankle: damping controller, landing orientation controller and landing position controller.

Okumura et al. (Yu Okumura et al. 2003) presented a real-time Zero Moment Point (ZMP) compensation method using adaptive inertia force compensation, which was implemented on the humanoid robot Morph3, while a hybrid force/position control in task space together with an inner joint position control loop is proposed by Lohmier et al. (Lohmeier, Buschmann, and Ulbrich 2009). The contact force trajectories are modified in an outer control loop to provide inertial stabilization. The method uses a kinematic model of the robot describing the dependency of the workspace trajectories on the generalized coordinates. The workspace trajectories include relative positions of the feet with respect to the Center of Mass (CoM), and the orientation of the feet with respect to the upper body.

Other control methods based on impedance and compliant control have been proposed in (Jong Hyeon Park 2001; Sentis, Park, and Khatib 2010; Stephens and Atkeson 2010). As an alternative, Choi et al. (Choi et al. 2007) suggested a posture/walking control scheme divided as the kinematic resolution of the CoM Jacobian with embedded motion and ZMP/CoM control. Experiments were presented in order to show the stability and robustness of the humanoid motion control system to unknown disturbances.

A kinematics-based approach was presented by Wollher and Buss (Wollherr and Buss 2004): the Jacobi compensation to modify pre-calculated step trajectories for a humanoid robot. The authors propose to modify pre-calculated gait trajectories in order to compensate the errors or adapt the trajectories to make them applicable to situations other than those they have been computed for.

Sugihara (Sugihara and Nakamura 2002) studied the balancing of a humanoid robot by the combination of two kinds of absorption of disturbances. In the first phase, the referential Center of Gravity (CoG) displacement is decided in accordance with both the short-term and the long-term absorption of disturbances. And in the second phase, the COG is manipulated with the whole-body cooperation, using the COG Jacobian.

Other authors (Hirai et al. 1998; Huang et al. 2000) discussed methods to plan an off-line walking pattern, based on a complex humanoid model, and then, modified it in real-time based on sensor feedback. Besides, a task-oriented control through prioritization (Sentis and Khatib 2006) has been used to accomplish task proximities at the same time as physical constraints.

Within the works on this topic by RoboticsLab research group, and from the skills learning field, an interesting proposal has been presented in (M. González-Fierro 2014), where the whole-body postural control of a humanoid robot is achieved based on imitation learning and skill innovation. In this line, a novel control architecture based on generation and adaptation of robot skills has been recently published (García, Monje, and Balaguer 2015).

A common factor to the majority of the approaches cited before is that they are based on complex or complete models of the robot, and many of them are platform-oriented. It is our purpose to present an alternative that allows the use of a simplified model of the robot for the balance control, which will allow a faster computation of the control algorithm and its implementation in a wide variety of bipedal robotic platforms.

In recent years, a growing number of experimental humanoid robot platforms have become available, which has triggered the deployment on real robots of the theoretical outcomes of research in this field. WALK-MAN, CoDyCo, and KoroïBot are examples of new research projects addressing issues in this domain. The particular and

unique characteristics of some of these robotic platforms have led to the design of platform-oriented control algorithms which cannot later be easily generalized and applied to other types of humanoid robots. In this sense, the Darpa Robotic Challenge (DRC) presents a more application-oriented development of these control methods, which favours the development of platform-independent control techniques.

In this line, the work we propose here presents a generalized control approach so that the balance control of a humanoid robot can be achieved in a simpler and robust way in real time, with independence on the particular robotic platform it is implemented on. Our study focuses on a novel technique based on a very well-known simplified model: the double inverted pendulum, which is common to the most popular humanoid platforms existing nowadays and makes the control strategy applicable to humanoids with different complete kinematics. Besides, this model permits having a real-time control of the structure while submitted to external forces/disturbances. The control actions are strongly dependent on three stability regions, which are determined by the position of the ZMP in the support polygon. Besides, multiple extremities are considered to control the balance.

The novel contribution of this work, in comparison with others cited before, is the integration of the dynamic balance control and the simplified model of the robot that, together with the identification of the three stability regions, makes it possible for the robotic platform to operate in real time keeping the stability while performing other tasks with its free Degrees of Freedom (DOFs). Besides, the establishment of these regions makes the operation of the robot safer. These regions are related with physical limitations of the robot that can be used to keep its integrity and switch among different control strategies (e.g. ankle strategy, step strategy, etc.) (Winter 1995).

The stabilizing control algorithm for a humanoid robot may be faced in several ways. This work tries to solve the problem of maintaining the humanoid in an upright position using two types of controllers, as shown in Figure 1: the attitude controller is actually regulating the roll and pitch angles of the robot CoM, whereas the balance controller is balancing the robot, controlling the ZMP.

Figure 1. Attitude and balance control scheme

Following the full control architecture in Figure 1, the attitude estimation is achieved using the information of the IMU sensors, using an Extended Kalman Filter. The robot attitude may be easily controlled using the inverse kinematics with the Jacobian of the supporting leg regarding the roll and pitch rows.

The force/torque sensors in the robot feet are used to estimate the ZMP position which feeds the ZMP controller. In this paper we are going to focus only on this balance controller. Two kinds of balancers are proposed, whose use depends on the degree of severity of the situation. When the robot is subjected to small disturbances, a static low-gain controller is used. In the critical case of a large disturbance, a dynamic controller is used which properly generates fast control actions. In the Figure 1, the ZMP controller is actually working as the switch between the static controller and the dynamic one.

The whole-body balance control strategy proposed here has been implemented and tested on the low size humanoid HOAP-3 robot and the full size robot TEO. HOAP-

3 robot is a commercial system that is currently being used by RoboticsLab research group as a test bed for real world robotic applications. TEO humanoid robot is a robotic system developed entirely by the research group from scratch.

The rest of the paper is organized as follows. ‘ZMP regions’ section introduces the concept of ZMP regions. ‘The Humanoid Body as a Composition of Inverted Pendulums’ presents the body simplifications using a composition of inverted pendulums. In ‘Balance Control: Discussion of Results’ section the balance control strategy is presented, discussing the simulation results. ‘Experimental Results’ section discusses the experimental results obtained. For simplification, the concepts are illustrated only with results from experiments performed with the robotic platform HOAP-3. Similar results have been obtained with the humanoid robot TEO and some of them have been used to complete the results explanation. Finally, in ‘Conclusions’ section, the main conclusions and future works are outlined.

ZMP Regions

In this section, the concept of ZMP regions is introduced. In particular, three regions are defined depending on the position of the ZMP, as suggested in (Vukobratovic, Borovac, and Potkonjak 2006). In Figure 2, an example of such regions is given for the humanoid robots standing on the right foot. The foot origin is graphically represented by origin of coordinates.

The control action applied by the stabilizer will strongly depend on the position of the ZMP with respect to the support area. In the balanced area (*safe region*), the control action will not actuate, leaving the vector of the secondary solution (vector of joint accelerations) to be used for other purposes.

Figure 2. Graphical example for stability regions: humanoid standing on right foot

In the *nearly critical region*, the control action will actuate as a secondary solution. This may be the case of a walking task. As humans do, the robot may use its arms in order to move the ZMP position closer to the safe region. Finally, in the *critical region*, the stabilizer will actually disconnect the ongoing task and actuate on the whole body. Even if this region is still stable, the balance may be easily lost.

These regions will be established depending on the physical characteristics of the robot. In particular, we have selected the ankle torques of the supporting leg in single support phase. This is one of the most restrictive parameter to regain balance while standing still or during walking. If the joint torque's limitations are exceeded, the robot would not be able to keep balance and it could fall down. Another restrictive condition is the height of the robot, that is related to the pendulum modelling explained in next sections. A lower height of the CoM reduces the need of high torques to regain balance. The previous conditions are more related with the influence of dynamics on balance control but a mechanical constraint must be also considered. Joint angle mechanical limits must be observed. This static constraint has influence on a possible saturation of the control system whether one joint is not able to move against a perturbation. The last condition is the design of the base of support for each foot. It is of course close related with the ZMP position and has influence on its absolute limits.

For

instance, the combination of all these constraints results in the establishment of the stability regions illustrated in Figure 2 for HOAP-3 robot. Similar areas can be depicted for TEO robot related with its footprint size.

The Humanoid Body as a Composition of Inverted Pendulums

The whole humanoid robot may be simplified using a combination of different double inverted pendulums. An example is given in Figure 3. This simplified model has been widely studied in the literature, and a complete review on that is presented in (Pierro 2012).

Figure 3. Humanoid robot model based on a composition of inverted pendulums. (a) HRP2 robot, (b) TEO robot

Let us consider the robot state to be

$$\chi = [\chi_{sl}, \chi_{fl}, \chi_{ra}, \chi_{la}]^T, \quad (1)$$

where $\chi_i = [a_i, \gamma_i]^T$ with $i = sl, fl, ra, la$ represents the state (roll and pitch angles) of the standing leg, the floating leg and right and left arms, respectively. The position of the ZMP can be then calculated as:

$$pZMP = ([\beta_{sl} \beta_{fl} \beta_{ra} \beta_{la}]\ddot{\chi} + [0 \kappa_{fl} \kappa_{ra} \kappa_{la}]\dot{\chi} + 1), \quad (2)$$

where the total mass of the robot is $M = m_b + m_l + 2m_a$, m_b being the standing bodies masses, m_l the leg mass and m_a the arm mass. pZMP is calculated using the sum of the effects of every inverted pendulum. The acceleration contribution of the standing leg is:

$$\beta = l^2 M \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}. \quad (3)$$

The acceleration contribution of the floating leg, right and left arm is $\beta_i(\chi_{sl}, \chi_i)$, with $i = fl, ra, la$:

$$\beta_L = m_i l_b l_i \begin{bmatrix} 0 & -\cos(\gamma_{sl} - \gamma_i) \\ \cos(\alpha_{sl} - \alpha_i) & 0 \end{bmatrix}. \quad (4)$$

The velocity contribution of the floating leg and right and left arms $\kappa_i(\chi_{sl}, \chi_i, \dot{\chi}_i)$ is:

$$\kappa_i = m_i l_{sl} l_i \begin{bmatrix} 0 & -\sin(\gamma_{sl} - \gamma_i) \dot{\gamma}_i \\ \sin(\alpha_{sl} - \alpha_i) \dot{\alpha}_i & 0 \end{bmatrix}. \quad (5)$$

And gravity $\mathfrak{u}(\chi_{sl})$:

$$\mathfrak{u} = M l_b g \begin{bmatrix} \sin(\gamma_{sl}) \\ -\sin(\alpha_{sl}) \end{bmatrix}. \quad (6)$$

It has to be noted that χ is a function of the pendulum position:

$$\chi = \begin{bmatrix} -\text{atan}\left(\frac{y}{z}\right) \\ \text{atan}\left(\frac{x}{z}\right) \end{bmatrix}, \quad (7)$$

$$J_p = \begin{bmatrix} 0 & -\frac{z}{y^2+z^2} & \frac{y}{y^2+z^2} \\ \frac{z}{x^2+z^2} & 0 & -\frac{x}{x^2+z^2} \end{bmatrix}, \quad (8)$$

where J_p is the Jacobian of the vector χ and x , y and z are contextualized with respect to a reference system with origin at the center of the foot and positive directions as in the reference system of Figure 2.

Balance Control: Discussion of Results

The objective of the balance control is to find a proper control action for reducing the distance of the ZMP from the foot center.

Static balance control

For a static balance, *i.e.*, for balancing the humanoid platform without taking into account CoM accelerations, the stability may be achieved using the standing leg and waist joints, considering that:

$$\dot{p}_{ZMP} = \frac{\partial p_{ZMP}}{\partial \chi_{sl}} \frac{\partial \chi_{sl}}{\partial p_{sl}} \frac{\partial p_{sl}}{\partial q_{sl}} \dot{q}_{sl} = J_{ZMP}(\chi_{sl}) J_{\chi_{sl}}(p_{sl}) J_{p_{sl}}(q_{sl}) \dot{q}_{sl}, \quad (9)$$

where q_{sl} is the joint position vector of the standing leg and p_{sl} is its position vector. From such equation, it is possible to determine the desired control actions for the joints under consideration.

The simulation results obtained from the ZMP control are shown in Figure 4. For HOAP-3 (Figure 4(a)), the robot is standing on its right leg and receives a push, modelled by an impulse disturbance that, around time $t = 0s$, causes the ZMP to leave the safe region (within the green lines) and enter the nearly critical region (within the yellow lines; red lines limit the critical region). The scale of the measurements shown is directly related with the size of the robot (HOAP-3 low size (mm), TEO full size(cm)).

As can be observed in the Figure 4(a), the static controller actuates against the disturbances (around $t = 0s$ and $t = 1.6s$) in order to make the ZMP evolve to the safe

region. A similar behavior can be observed in Figure 4(b) for robot TEO, where the disturbances appear around $t=87s$ and $t=105s$.

The reference positions for HOAP-3 joints angles corresponding to this control performance are shown in Figure 5 and 7, and the corresponding submitted joints torques in Figure 7 and 9, showing the feasibility of the control actions. Red lines indicate the physical limits (saturation) for each joint angle and torque in the case of HOAP-3 robot. For simplification, the simulation results corresponding to robot TEO have not been included, showing an equivalent performance to those of the robot HOAP-3.

Dynamic balance control

In the most critical case, the simple solution of a static balance controller is not enough. In this case, it is necessary to efficiently use the pendulums accelerations in order to achieve the balance.

The control action for the humanoid balance may be found using Eq. (2) in order to set the ZMP position:

$$\hat{p}_{ZMP} \approx J_c \ddot{q}_c + \eta(\chi, \dot{\chi}, \ddot{\chi}_{fl}). \quad (10)$$

The approximation in such equation is due to the fact that second order derivatives can be neglected, since they have been proven to be very close to zero after some simulation tests.

Figure 4. HOAP-3 (a) and TEO (b) ZMP position for the static balance control

Figure 5. HOAP-3 right leg joint angles for the static balance control

The $\eta(\chi, \dot{\chi}, \ddot{\chi}_{fl})$ terms take into account the velocity and gravity contributions of the double pendulums together with the acceleration contribution of the pendulums which are not being controlled. In this case, the floating leg is not controlled for the balance:

$$\eta(\chi, \dot{\chi}, \ddot{\chi}_{fl}) = \frac{1}{gM} (\beta_{fl} \ddot{\chi}_{fl} + [0 \quad \kappa_{fl} \quad \kappa_{ra} \quad \kappa_{la}] \dot{\chi} + \iota). \quad (11)$$

In this case the Jacobian J_c is:

$$J_c = \left([\beta_{sl} \quad \beta_{ra} \quad \beta_{la}] \begin{bmatrix} J_{sl} & 0 & 0 \\ J_{sl} & J_{ra} & 0 \\ J_{sl} & 0 & J_{la} \end{bmatrix} \right) \ddot{q}, \quad (12)$$

and a generic J_i is:

$$J_i = J_{ZMP}(\chi_i)J_{\chi_i}(p_i)J_{p_i}(q_i), \quad (13)$$

where J_i stands for J_{sl} , J_{ra} and J_{la} , as defined previously.

Figure 6. HOAP-3 waist angles for the static balance control

Figure 7. HOAP-3 Right leg joints torques for the static balance control

Figure 8. Waist torque for the static balance control

The ZMP measurements from the dynamic ZMP control are shown in Figure 9, with impulsive disturbances occurring along the simulation time. The situation demonstrated in this case, in comparison to Figure 4 (static controller), shows a more

critical case of stability since the disturbances applied along the test make the ZMP present dynamics with more abrupt changes than in the case of the static controller, making the ZMP leave the safe region (within green lines) in several occasions and even overpass the nearly critical region (within yellow lines) at certain times during the test. This behaviour is explained in more detailed in ‘Experimental Results’ section, where the algorithm is implemented and tested in the humanoid robot HOAP-3, which has to use its arms to keep the balance when the disturbances are critical.

(b)
Figure 9. HOAP-3 (a) and TEO (b) ZMP position for the dynamic balance control

For HOAP-3, the joints angles are depicted in Figure 10 and 12 for the right standing leg and the waist joint, respectively.

The feasibility of the control actions is shown in Figure 12, 14, 15 and 16, where the joints torques are depicted. Notice how both arms also contribute to the stability in this case (Figure 14 and 16).

Experimental Results

The balance control strategy proposed in this paper has been tested in the experimental robotic platforms HOAP-3 and TEO. Due to the difference of size of the robots, the

controller for robot TEO is being improved to add more balance strategies to ensure balance in more complex situations. In the case of HOAP-3, the performance can be seen at the following internet site:

<http://www.youtube.com/watch?v=d6j-xsXAULYfeature=youtu.be>

First of all, the static balancer is tested. At a first moment the robot stands on its right leg, which is the goal position, and then starts receiving several pushes (small ones). The controller actuates keeping the ZMP in the safe region. In this case, the arms and floating leg are not used for the control purpose (static control), only the standing leg is used. In the following part of the video ($t = 8s$), the dynamic balancer performance is shown. The main task for the robot is to stand on its right leg. In the absence of disturbances (or small ones), the ZMP keeps in the safe region (static controller is acting) and the arms and floating leg could be used for other secondary tasks than for keeping the balance (manipulation, for instance).

Figure 10. HOAP-3 Right leg joints angles for the dynamic balance control

Figure 11. HOAP-3 waist angles for the dynamic balance control

When due to a larger disturbance (push in the video at $t = 15s$) the ZMP reaches the nearly critical region, then the robot uses its free DOFs available to lead the ZMP to the safe region again, cancelling the secondary tasks for the sake of the stability. In the video, it can be observed how the robot uses its arms for the control action.

Figure 12. HOAP-3 Right leg joints torques for the dynamic balance control

Figure 13. HOAP-3 waist torques for the dynamic balance control

Figure 14. HOAP-3 right arm joint torques for the dynamic balance control

Figure 15. HOAP-3 left arm joint torques for the dynamic balance control

Nevertheless, the main task is still achieved and the robot keeps standing on its right leg. However, when the push is as large as to make the ZMP enter the critical region, the main task has to be abandoned and all the resources are devoted to guarantee the stability. In the video ($t = 24s$), it is shown how the robot has to lean on its left leg, too, to keep the balance, using also both arms.

When the disturbance stops ($t = 34s$), the robot recovers its initial position and stands again on its right leg thanks to the action of the balance controller. Then, a new push is given to HOAP-3 and a double support is needed again to fulfill the stability.

Due to the properties of size and weight of the robotic platform HOAP-3, it is not trivial to prepare a testbed for the application of significant impacts on the robot. For this reason, the disturbances have been applied manually, which allows a better control of the impact magnitude according to the robot limitations. The authors state that the robot is not assisted at all during the tests.

Conclusions

In this work a balance controller for humanoid robots has been proposed. The balance control is achieved by the action of a static controller or a dynamic controller, depending strongly on the stability region the ZMP position is located at. Three stability regions are statically defined, basing on the support polygon: a first inner region is

considered safe in terms of the robot balance. The outer regions are less stable and need the use of a dynamic controller in order to avoid the drift of the ZMP away from the support polygon.

The robot stabilizer selects the controller which best fits the situation. In particular, when a small disturbance is present, the static controller is used. This controller is actually controlling the configuration of the robot, without taking into account inertial terms. For large and impulsive disturbances, the inertial effects have to be used to dynamically control the robot. Thus, the robot reacts immediately to the disturbance and moves the required body parts in order to guarantee the stability.

Thanks to the integration of the dynamic balance control and the simplified model of the robot, together with the identification of the three stability regions, the robot is able to operate in real time keeping its stability. The effectiveness and feasibility of the presented controllers are shown in simulation and also experimentally, using the humanoid robots HOAP-3 and TEO as testbed.

Nevertheless, the properties of size and weight of HOAP-3 are very different from those of the robot TEO. The effects of these characteristics, such as higher ground impacts, make the application and any control approach more complicated. For this reason, the controller is being applied and improved carefully in the full-size humanoid robot TEO and only partial results have been presented. This robot is able to deal with higher levels of disturbance and has more capabilities (computing, actuation, etc.) that can be used to improve the control algorithms. This will allow the preparation of some impact tests in order to show more clearly how the robot is acting to the disturbances and to establish the real limitations of this approach. Some balance tests can be seen at:

<https://youtu.be/em9WIGG9AVs>

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