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Computational Efficient Balance Control for a Lightweight Biped Robot with Sensor Based ZMP Estimation

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***Abstract*— This paper presents a computational efficient balance control algorithm developed for a lightweight biped. A LIP model of the robot is combined with the ZMP calculation to derive a joint space control action based on a PD controller. Furthermore, a method is implemented to estimate the ZMP directly from the center of pressure measured using the force sensors installed under the feet of the robot. This, allows a real time implementation of the controller without using the robot direct kinematics, reducing model inaccuracies and improving the controller reactivity. Simulation results and tests on the real robot prototype shows that the control system is able to compensate for external disturbances forces up to 10N reducing the oscillations of 60%.**

I. Introduction

Humanoid robots are generally sophisticated systems that include an high number of DOFs. Despite their high complexity, if compared with classical industrial manipulators and mobile robots, humanoid robots are capable to perform a more rich and complex range of locomotion and manipulation tasks. In fact, by having a morphology inspired by the human body anatomy, they can inherit the same versatility and capabilities.

We can therefore envision applications in the household and public environment where the robot is required to move in spaces and manipulate tools and objects specifically designed for humans. Anthropomorphic robots can assist elderly and disable people, deliver packages, entertain children, guard and patrolling areas, intervene in disaster and emergency situations, and so on so forth.

Since the birth of humanoid robotics in the 1970s, with the seminal work of Prof. Ichiro Kato, many progresses have been made, and today we can finally assist to the rise of the first commercial applications mainly for entertainment and human guidance purposes. Nevertheless, still a lot of work remains to be done especially for what regard the control, the autonomy and the safety of these machines.

Among others, balance control is very important in a humanoid robot to guaranty a stable posture when manipulating objects and performing stable gaits on uneven surfaces or occluded paths. While interacting or cooperating with humans it is crucial that the robot behaves safely, avoiding to fall down and potentially injure people in its surrounding.

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A lot of work can be found in the literature about the development and validation of balance control systems for bipeds and humanoid robots. We can divide the available algorithms in three main categories: the one that rely on the kinematic and dynamic model of the robot to compute the Zero Moment Point (ZMP) [1], [2], [3], [4], the one that estimate the ZMP on the basis of real time data acquired from inertial measurement units (IMU) and force/torque sensors installed in the joints and under the feet [5], [6], [7], and the one that are a combination of the two with often the application of data fusion [8], [9].

The knowledge of the ZMP is fundamental for balance control algorithms. The ZMP represents the point on the floor where the net moment due to all the forces acting on the robot do not have components on the horizontal axes. Furthermore, it is assumed that the vertical component of the net moment is compensated by the friction forces acting between the feet sole and the floor. Based on where the ZMP point is located we can say whether the robot is in a ”stable” configuration or not. In particular, the more the ZMP is near to the edge of the support area the more is likely that the biped will fall down. Therefore, by calculating the instantaneous position of the ZMP it is possible to take some control actions to modify the posture of the biped.

In [8] a ZMP trajectory with adjustable parameters is proposed. In particular, the ZMP error and the trunk inclination are measured by force sensors and an accelerometer. With this information a fuzzy logic controller applies the proper joint position corrections to implement balance control. In [3] a balancing and posture control system based on the state space model of the robot is instead implemented. Furthermore, a radial basis function neural network was integrated in the control loop to deal with the dynamic model uncertainties. In [2] a control framework is presented that does not require direct contact force measurement. The feet reaction forces are optimally distributed by using the information of the robot state and the Center of Pressure (CoP). Consequently the gait is stabilized computing the required joint torques. In [10] a combination of gravity and friction compensation is integrated with damping regulation and an inverted pendulum model of the robot to implement balance control.

The computation of the ZMP from the dynamic equations of the robot is affected by parameters inaccuracy and lacks of a proper representation of the feet reactions forces. Furthermore, a complete inverse dynamic model calculation requires considerable computational resources when performed on-line [11]. In [9] it was demonstrated that a computed torque method that considers the complete dynamic model of the robot can not achieve high walking speeds due to computation constrains and limited sensors bandwidth. As a better alternative a Linear Inverted Pendulum (LIP) model of the robot was used in combination with the ZMP method to obtain a stabilizing trajectory for the Center of Mass (CoM).

To reduce the computation needed to run the balance control one can precompute off-line the reference ZMP trajectory by using the robot model. However, when the controller is operating on-line it still requires to calculate the current position for the ZMP, thus to compute the inverse dynamic model of the robot.

Information about the ZMP position can also be obtained without the dynamic model of the robot, but using the measurement of the ground reaction forces acting on the feet instead. Thus, when the robot is dynamically balanced it is demonstrated that the CoP coincide with the ZMP [1], [12].

In Erbatur et al. [7] a cost-efficient sensor based ZMP computation algorithm was tested on humans and bipedal robots. It was demonstrated that when the ZMP is close to the edge of the sole not always brings the system to instability. Moreover, it was experimentally proven that a moving ZMP (which periodically crosses the edge of the sole region) was necessary for a human-like gait. The ZMP measurements on human sole showed that in the double support phase the ZMP moves faster than in the single phase mode (when only one sole is in contact with the ground, while the other sole is being transferred). Experimental results clearly indicate that the ZMP behavior of a human gait could be used as a reference for future bipedal robots.

In case of lightweight biped robots, with low inertia and mass, it is essential to implement a balance control system that rapidly react to external force disturbances. Therefore, implementing a control action based on contact force and inertial force measurements is fundamental.

A correct measurement of the CoP and therefore the ZMP can be achieved by installing accurate force sensors under the foot sole. In [5] haptic soles based on three sensing elements are applied to estimate ground slope orientation and to balance the robot body, while in [13] an array of 900 piezoresistive force sensor elements (FSRs) are used to obtain an accurate pressure map of the foot. In [6] a contact model of the sole was instead used in combination with a single mass model of the robot to better control the ground reaction forces at the feet.

Inspired by the approach presented in [14], where instead of employing complex dynamic models of the robot a simpler single-mass model was formalized, this work aims at developing a computationally efficient balance control system for a lightweight robot. As main goal the required algorithms should be able to run on a low computational unit and capable to compensate frontal and lateral disturbance forces. Two different methods are implemented and compared. The first one the Linear Inverted Pendulum (LIP) model of the robot to estimated the CoM and the ZMP, while a feedback control loop based on a PID is used to compensate for external disturbances forces by stabilizing the posture. A second method uses instead the measurement of the CoP to estimate the ZMP and stabilize the robot posture on-line.

The rest of this paper is organized as follow: Section II introduces the robot prototype and the simulation environment, Section III presents the balance control architecture and the LIP model used to calculate the ZMP, Section IV reports the experimental results, finally last section draws the conclusions and points to future work.

II. Experimental Setup and Simulation Environment

Aim of this work is to design a balance control system for the humanoid biped under development at the Robotics and Mechatronics Department of Nazarbayev University. The robot (see Figure 1) was build using a combination of 3D printing techniques and the usage of lightweight materials. This allowed to obtain a full size biped with a weight of only 12.5 kg and 1.1 m tall.

A total of 12 rotational DOFs are present in the kinematic architecture of the robot, three DOFs in the hip which axes intersect in a common point, one DOF in the knee and two DOFs in the ankle. The hips roll joints are actuated by Dynamixel MX-106R servomotors while all the other joints by Dynamixel PRO H-42-20-S300 servomotors, for more details on the robot design please refer to [15].

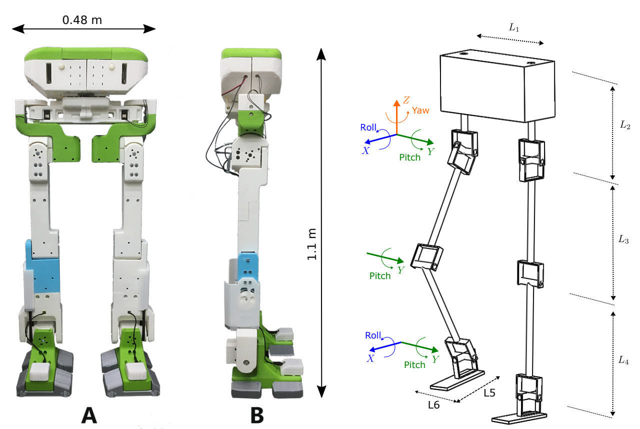

Fig. 1. NU-Biped under development at the Department of Robotics and Mechatronics of Nazarbayev University (height 1.1 m, weight 12.5 kg), its kinematic architecture includes 12 DOFs, the length of the links are reported in table I.

L1	L2	L3	L4	L5	L6
0.31	0.31	0.29	0.31	0.21	0.15

TABLE I

Length of the robot's links expressed in meters.

A. Simulation environment

In our study the usage of a simulation framework is very important in order to conduct different experiments and to test the control algorithms before their implementation on

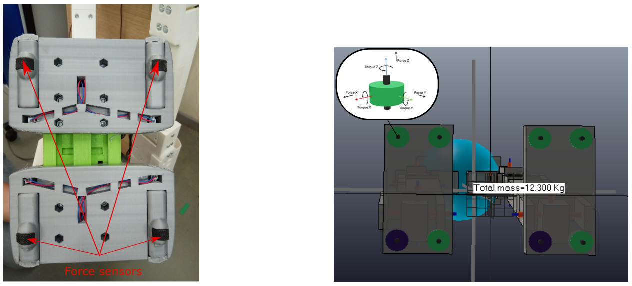

Fig. 2. Displacement of the force sensors under the feet of the NU-biped and its V-REP model.

the real robot. Tuning the algorithms in simulation will avoid situations were the robot get damage when falling down due to failures of the control system. Furthermore, it will allow to acquire the complete state of the robot that may be useful to conduct a more detailed analysis of the control system performances.

The simulation environment we use consists of a combination of the V-REP and Matlab softwares. V-REP [16] simulates the robot dynamics and allows the visualization of the experiments, while Matlab implements the control algorithms and allows saving the data acquired from the experiments.

More in details, V-REP enables for custom robot simulation. It replicates the functionalities and behavior of all the necessary components of a robot and provides script control methods. In addition, it has a package called Remote API that allows to control the robot model through other software environments like Matlab, Octave, Python, etc.

B. Robot Model

The robot model, see Figure 5, was constructed in V-REP by importing the CAD developed in Solidworks and by using primitive shapes, joints and basic sensors. In particular, the real robot masses and inertia matrices were preserved for each part. Four force sensors were included under each feet (see Fig. 2), position and torque sensors in each joint, and a Cartesian position sensor in the CoM of the robot.

In V-REP, joints can be controlled in torque without introducing the actuator model. Therefore, discrepancies in comparison with the real system behavior may occur. However, it is possible to set the maximum torques and velocities values to consider the limitation of the real actuators.

III. Balance Control Architecture

The balance controller of the NU-biped robot, see Fig. 3, continuously tracks the ZMP position, calculates the stability margin and decides whether to take some control actions to restore a stable posture by controlling the robot's joints. The NU-biped has rectangular shaped feet with flat sole surface. The single foot support is stable if the ZMP is inside the contact area of the foot. If instead we consider the biped standing, it is clear that the ZMP can be located inside a wider convex area that includes both feet.

The classical way to estimate the ZMP is to calculate the CoM position, the moment and the force values of the whole mechanism. In the simulation environment we have available the CoM data, and therefore we can concentrate on the control strategy itself.

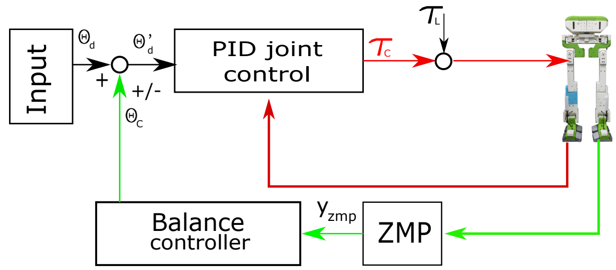

Fig. 3. Balance control architecture.

A. Single-Mass Model and ZMP Calculation

The dynamics of a biped is generally quite complex. When the robot lifts one legs, we have to consider a sequence of 12 DOFs displaced in series. When instead both feet are in contact with the floor a parallel kinematics mechanism needs to be studied. In literature different approaches were proposed to tackle the stability issue of such a system [2], [8], [9], [3]. However, for a lightweight robot like the one we are considering in this work, the masses and the inertial forces of each single leg's link are relatively low. Therefore, for stabilization purpose, it makes more sense to start with a simplified model of the robot.

In our case we can represent the robot as a single mass located in the robot's CoM (see Fig. 4).

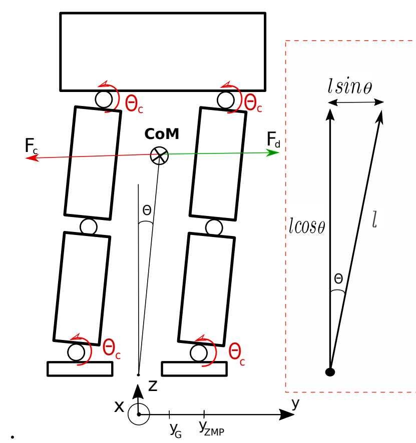

Fig. 4. Single Mass Model.

The linear acceleration and velocity of the CoM can be calculated from the angular acceleration and velocity. Furthermore, assuming that changes in the angle θ are small (thus $sin(\theta) \simeq \theta$ and $cos(\theta) \simeq 1$):

$$\ddot{y}_{CoM} = l\ddot{\theta} \quad and \quad \dot{y}_{CoM} = l\dot{\theta}. \tag{1}$$

The motion of the CoM along the x-axis is defined by the dynamic equation:

$$F_y = ml\ddot{\theta} + cl\dot{\theta} + kl\theta = F_d - F_c, \tag{2}$$

where m is the mass of the robot, l the height of the CoM when the robot is in its home position, c and k the Cartesian damping and elastic constants respectively, F_c the control force and F_d the disturbance force. The net moment along the x-direction and calculated with respect the ZMP is described by the following relation:

$$M_x = -F_y l cos(\theta) + mg(y_{zmp} - l sin(\theta)). \tag{3}$$

To have a stable posture we know that the horizontal component of the moment calculated with respect the ZMP should be zero. In addition, if we make the assumption that changes in the angle θ are small, the following equation can be derived:

$$F_y l - mg(y_{zmp} - l\theta) = 0. \tag{4}$$

Substituting Eq. 2 in Eq. 4 we obtain:

$$ml^2\ddot{\theta} + cl^2\dot{\theta} + kl^2\theta - mg(y_{zmp} - l\theta) = 0. \tag{5}$$

$$mgy_{zmp} = mgl\theta + ml^2\ddot{\theta} + cl^2\dot{\theta} + kl^2\theta = 0 \tag{6}$$

Finally, the position of the ZMP along the y-axis can be found as:

$$y_{zmp} = \frac{l^2}{g}\ddot{\theta} + \frac{cl^2}{mg}\dot{\theta} + \frac{kl^2}{mg}\theta + l\theta. \tag{7}$$

Now that the ZMP is calculated it is possible to implement a feedback control loop which goal is to compensate for disturbances forces acting along the y-axis (a similar strategy can be used for disturbances acting along the x-axis). In particular, the PID in Eq. 8 will regulate the position of the ZMP to zero by adjusting the reference position θ_d that is provided to the joint position controller (see Fig. 3).

$$\theta_c(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau + k_d \dot{e}(t) \tag{8}$$

where $e(t) = -y_{zmp}$.

B. Control Strategy Implementation

At first the control strategy was implemented in Matlab. The main balance control loop operates at a frequency of 100 Hz. At each sample time the current position of the CoM is acquired from V-REP an the ZMP calculated together with the PID's control action. The computed angle adjustment θ_c is then added to the current position of the hip's and ankle's roll and pitch joints and the new reference position for the joints $\theta d'$ is sent to the V-REP robot model.

In order to test our control algorithm a disturbance force was added to the upper part of the hip (see Fig. 5). We implemented and activated two disturbance forces separately: the force along the y-axis F_y and the force along the x-axis F_x. It is also worth to mention that the remote API for Matlab doesn't have the option of adding the force directly. Thus, our approach was to construct a child script in V-REP that generates the force and that can be called from Matlab.

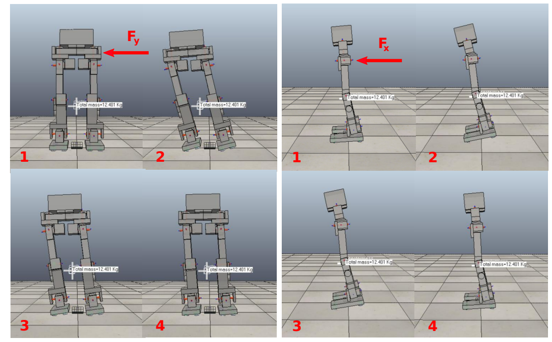

Fig. 5. Disturbance forces applied for one second along the y-axis (left) and x-axis (right).

IV. Experiments and Results

The first set of experiments to test the balance control algorithm were performed in the simulation environment. We introduced a disturbance force along the y-axis $F_y = 10N$ with duration of 1 s and we run the simulation without and with the balance control system activated in order to understand its stabilization performances. In this case the balance control system was initialized with only a proportional gain of $k_p = 0.01$. The graphs of the lateral displacement (as the position of the CoM) and of the ZMP position are reported in Fig 6. As it is shown, the balance control reduces the first overshoot approximately of 50% and restores faster the ZMP at the zero position.

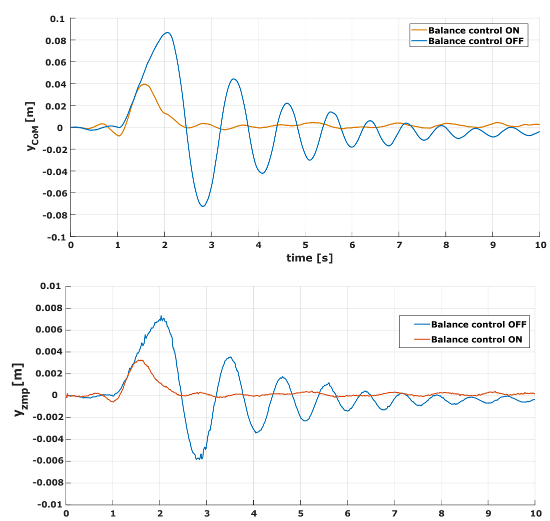

Fig. 6. CoM and ZMP position with balance control ON and OFF.

To implement the aforementioned control strategy it is necessary to calculate the position of the CoM at each sample time. This, in the real robot, requires the computation of the forward kinematics for each link. Considering a total of 12 homogeneous matrices with dimension 4 by 4, it is therefore necessary to calculate 192 multiplications. In addition, to obtain the ZMP position and the control action, the equations from 1 to 8 need to be computed. As a low computation

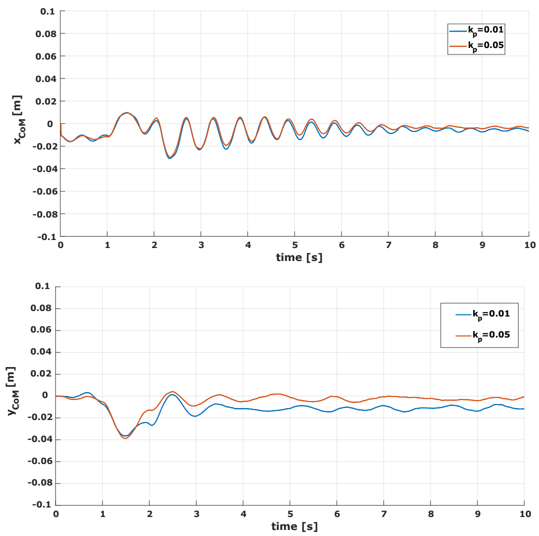

Fig. 7. CoM position along the x-axis and y-axis with $k_p = 0.01$ (blue line) and $k_p = 0.05$ (red line).

alternative we can instead estimate the position of the ZMP by using the CoP. The CoP of a single foot is calculated using the data from the four force sensors located in (x_i, y_i) and the corresponding force measurements F_i. Therefore for the y-axis and x-axis we have

$$y_{CoP} = \frac{\sum_{n=1}^{4}(F_i * y_i)}{\sum_{n=1}^{4} F_i}, \; x_{CoP} = \frac{\sum_{n=1}^{4}(F_i * x_i)}{\sum_{n=1}^{4} F_i}. \quad (9)$$

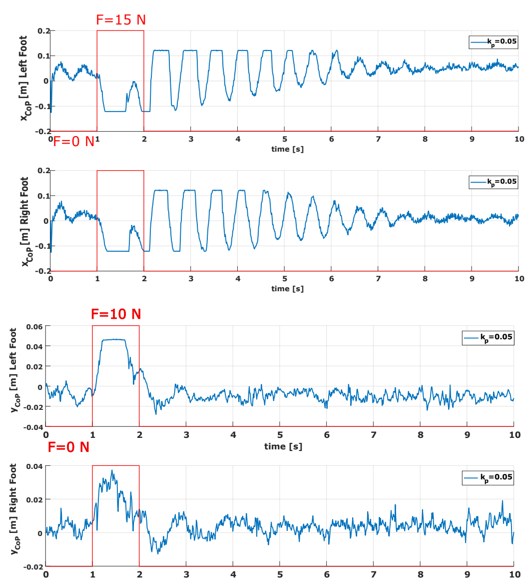

Fig. 8. CoP position along the x-axis and y-axis with $k_p = 0.05$.

A second set of experiments were conducted using the CoP as estimation of the ZMP and applying the disturbance forces $F_y = 10N$ and $F_x = 15N$. As reported in the plots of Fig. 7 , with a Kp=0.01 and Kp=0.05, the CoM oscillates in a range from -0.03 to 0.01 meters for the x-axis and in a range from -0.04 to 0.005 meters for the y-axis. The relative data for the position of the CoP are instead reported in Fig. 8.

By knowing the CoP relative to each foot it is also possible to calculate the superimposed CoP as:

$$x_{CoP} = \frac{x_{CoP_R} + x_{CoP_L}}{2}, \; y_{CoP} = \frac{y_{CoP_R} + y_{CoP_L}}{2} \quad (10)$$

and compare it with the CoM as reported in Fig 9.

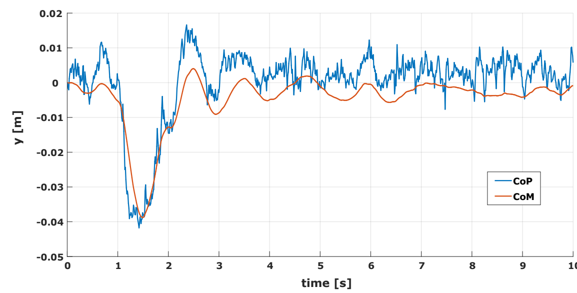

Fig. 9. Comparison of the CoM and CoP position along the y-axis.

In the experiment shown in Fig. 10 we also introduced a derivative control action. As it is possible to see with a $k_p = 0.8$ and $k_d = 0.02$ the biggest pick is reduced of an additional 18%.

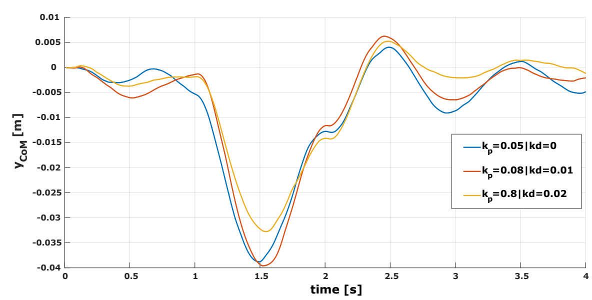

Fig. 10. Response of the balance control system with different PD constants.

The next step was to test the balance control algorithm based on the CoP with the real robot. The NU-Biped presents an on-board low power computational unit based on a Raspberry Pi 3 where the balance control was implemented in C language. The biped was initialized in its home position that corresponds to the upright pose. In the first experiment the balance control was turned OFF and a force of 10 N was applied orthogonal to the frontal plane at the height of the robot's waist. At this point only the internal joint position control is activated that acts to maintain the home position. While performing this experiment the position of the CoP was recorded.

In a second experiment the balance control was turned ON and the same amount of disturbance force was applied. In order to find the PID's parameters we applied the Ziegler-Nichols method. At first we used only a P controller and under an initial disturbance force we increased the feedback gain until the robot was oscillating in a stable manner. We measured the ultimate gain and period of the oscillation as $K_u = 0.3$ and $T_u = 1.1s$ respectively.

In a second phase, after different adjustments, the PD's constants were set to $K_P = 0.05$ and $K_D = 0.3$. By superimposing the results of these experiments from the plots of Fig.11 we can evince that the balance control system reduces the first oscillation of the CoP of 60%.

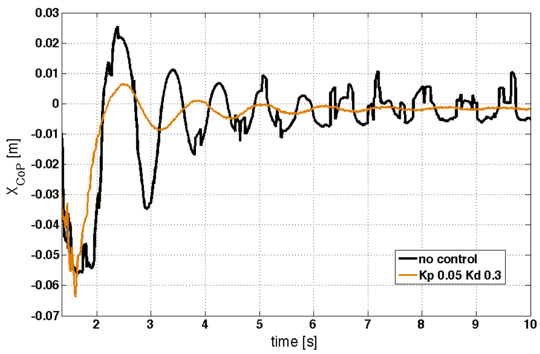

Fig. 11. CoP position without and with balance control activated when a 10 N disturbance force is applied on the frontal plane of the real robot prototype.

During the experiment we noticed that the presence of the synchronous belt that connects the ankle's pitch joint with its motor (visible in Fig. 1) introduces elasticity in the system. This could help to absorb the impact forces when the robot is walking, however to improve the results of our balance controller will be necessary to model this elasticity as in Eq. 2 and implement a variant of the control method described in Section II that uses instead of the CoM a filtered version of the CoP.

V. Conclusion

A balance control system based on the ZMP calculation and a linear inverted pendulum model was developed for a lightweight biped robot. The position of the ZMP is computed assuming that, due to the presence of disturbance forces, the barycenter of the robot accelerates in the horizontal plane. A PD controller is then used to correct the posture of the robot in order to compensate for disturbances and to move the ZMP toward the zero position. Simulations conducted using a realist model of the robot show that the controller is able to damp the amplitude of the oscillations of 50%.

To reduce the amount of computation required to run the control algorithm, a second method was also tested that allows to estimate the position of the ZMP using the CoP. By computing the CoP from the force sensors installed under the robot's feet it is possible to realize a faster control loop and react to more dynamic disturbance forces. Both the experiments on the robot model and the real prototype demonstrated that the control strategy is able to stabilize the system and damp the oscillations.

As a future work we will implement the first method, based on a simplified model, on the real robot and compare the results with the approach based only on the CoP. Will also be necessary to test the balance controller while the robot is performing a walking gait.

Acknowledgment

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