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Balance Computation of Objects Transported on a Tray by a Humanoid Robot Based on 3D Dynamic Slopes

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Abstract— **Humanoid robots are designed to perform tasks in the same way than humans do. One of these tasks is to act as a waiter serving drinks, food, etc. Transporting all these items can be considered a manipulation task. In this application, the objects are transported over a tray, without grasping them. The consequence is that the objects are not firmly attached to the robot, which is the case in grasping. Then, the complexity of robotics grasping is avoided but stability issues arise. The problem of keeping balance of the object transported by a robot over a tray is discussed in this paper. The approach presented is based on the computation of the Zero Moment Point (ZMP) of the object, which is modelled as a three dimensional Linear Inverted Pendulum Model (3D-LIPM). The use of force-torque sensors located at the wrist enables ZMP computation, but the main problem to be solved is how the robot should react when the object losses balance. One strategy is to rotate the tray to counteract the rotation of the object. This rotation has to be proportional to the ZMP variation and the object's rotation angle. This issue is solved by applying the concept of three dimensional dynamic slopes. It helps to avoid kinematic problems and make balance computation independent from the angle of the tray.**

I. INTRODUCTION

In the last years, many pieces of researches have been focused on different aspects of robotic grasping. Their studies chase an important objective: transport objects by robots. There are many interesting investigations that explain how to grab an object: the best way to do it [1], the most efficient way [2], or the ability to grasp different objects with different shapes [3]. The systems used in these researches have a high degree of computational complexity and use many sensory systems that produce a big amount of data.

However, to transport objects without grabbing them simplifies, at first sight, the study of this task. The main reason is that it is not necessary to deal with the intrinsic requirements of gripping, such as the kinematic computation of each finger or the control of the forces exerted by the hand. There are other methods of transporting object without grasping them. Specifically, this article presents a method to achieve a non-grasping objects transporting task. It avoids the complexity of grasping but, on the other hand, it requires the balance control of the transported object. A bottle is placed on a tray without any fixed physical union. The bottom surface of the bottle is the only contact with the tray, and the robot has only control of the bottle controlling the relative position between the tray and the bottle. Therefore, this type of graspless transporting task leads to a problem of balance control that is not necessary to take into account when the object is being grasped. If a hand is not used to grasp the object (non-rigid/solid union), its stability cannot be ensured. As a consequence, it is mandatory to apply any kind of criterion to maintain balance.

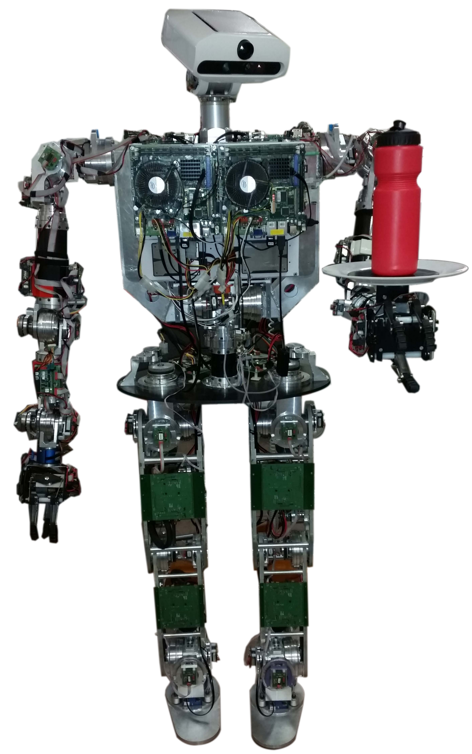

Fig. 1. The humanoid Robot TEO performing the waiter application.

The well-known Zero Moment Point (ZMP), a useful concept exposed by Vukobratovic [4], is one of the earliest and well-known approaches to study the problem of biped robot stability. From the robot motion viewpoint, this approach was derived from the dynamical analysis. The term of ZMP can be defined as a point on the ground where the resultant moment caused by robot gravity and robot body inertia is closed to zero [5]. This idea assures the dynamical balance of the biped robot, while the ZMP is located in the support polygon. The support polygon is formed by the feet surface on the ground [5][6].

This article is within the development of a Waiter Humanoid Robot. For this purpose, the humanoid robot TEO (Task Environment Operator) [7] has been used by the "RoboticsLab" Research group from the Carlos III University of Madrid (Figure 1).

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This paper deals with transportation by non-grasping manipulation. In section 2, different researches related to the use of models for balance control are explained. And also, non-grasping manipulations are classified. Some problems are presented and discussed as a possible waiter task solution. The choice of an appropriate mechanic structure and the problem related to the sensors' pose are shown in section 3. Then in section 4, the methodology and tools used applying the 3D dynamic slopes concept are presented. Experiments and results are presented in section 5 to verify the proposed approach. Finally, in section 6, conclusions related to the effectiveness of this method are discussed.

II. BACKGROUND

This article focuses on two major topics; the first one is related to the idea of developing a future balance control system on an uneven or inclined ground, based on "Simplified Model's Methods". There are many types of research related to this topic, like in [8][9][10][11], that inspire this investigation incorporating the LIPM techniques. Or other works based on ZMP like in [12][13].

The simplest model for representing the robot's kinematics and dynamics is the two-dimensional inverted pendulum with one DoF [14]. This model represents a concentrated CoM (Centre of Mass) linked rigidly to the ground by one rotational joint shown in Figure 2. In the case of Figure 2, the movement of the CoM is defined by the following equation:

$$\tau = -ml^2\ddot{\theta} + mgl\sin\theta \tag{1}$$

Where m is the mass of the CoM, l is the pendulum longitude, τ is the torque at the pivot point, and θ is the pendulum angle. The three-dimensional linear inverted pendulum model (3D-LIPM) proposed by Kajita [15] (Figure 2) overcomes the non-linearity problem. The main advantage of 3D-LIPM is that the linear equations are very easy to program in a computer. They are mainly used for walking pattern generation and balance control. This balance control will be achieved by the use of F-T (Force-Torques) sensors placed on the robot's wrist, such as JR3.inc sensors assembled in TEO robot's hand (Figure 3) (between the wrist and the hand).

The development of future humanoid balance control architecture is mainly related to the study of two specific reference points. The first is the CoM used to model a humanoid body as described previously. However, the CoM does not provide useful information about the body balance status. The ZMP introduced by Vukobratovic in [5] is the first and primary tool developed for describing the body's equilibrium.

$$X_{ZMP} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i\ddot{x}_i z_i - \sum_{i=1}^{n} I_{iy}\ddot{\theta}_{iy}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \tag{2}$$

$$Y_{ZMP} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)y_i - \sum_{i=1}^{n} m_i\ddot{y}_i z_i - \sum_{i=1}^{n} I_{ix}\ddot{\theta}_{ix}}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \tag{3}$$

X_{ZMP} and Y_{ZMP} are the x and y coordinates of ZMP, respectively. z_i, $\ddot{z}_i$, x_i, $\ddot{x}_i$, y_i, and $\ddot{y}_i$ are the position and the acceleration of the robot's parts along the z, x, and y coordinates, respectively. m_i is the mass of the robot's parts. I_{ix} and I_{iy} are the inertial components of the robot's parts around the x and y coordinates, respectively. $\ddot{\theta}_{ix}$ and $\ddot{\theta}_{iy}$ are the rotational acceleration of the robot's parts, respectively. Finally, g is the gravitational acceleration.

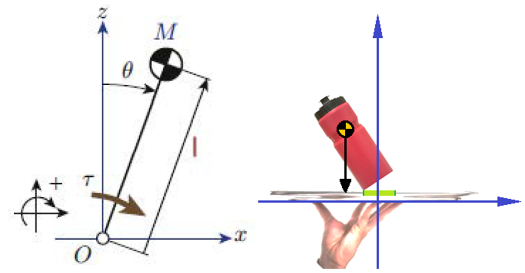

Fig. 2. 3D-LIPM for bottle balance modeling.

The second topic is related to the idea of transport an object in a graspless task, where the object is not attached to the hand's robot. In general, Non-grasping manipulation task is done by an effector without holding an object rigidly. In robotics, several types of research have studied the non-grasping manipulation. Pushing [16], tumbling, pivoting [17], hitting, throwing [3], juggling [18][19] and so forth.

The method of graspless manipulation used in this article is pivoting, in which the robot's tray manoeuvre an object (the bottle) as if making it walk on the floor by using appropriate points as its virtual feet. Pivoting is frequently observed when a human moves a large or heavy object like a piece of furniture by raising it up on a vertex, sliding it, turning it, supporting it, pushing it, and so on.

III. PROBLEM STATEMENT

The robot's mechanics and the complexity of the task of object balance cause two problems to take into account (Figure 3). On the one hand, the mechanics of the tray on the robot's arm and the location of the force sensor will make it difficult to read the sensors data and therefore calculate the ZMP. On the other hand, the task of balancing the bottle will cause the tray to stop from being on the horizontal plane, inducing a reward of forces and torques on other axes.

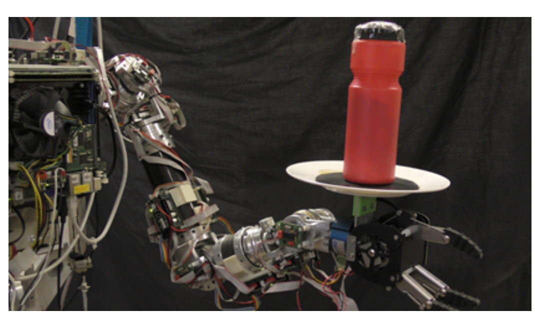

Fig. 3. Bottle on a tray transported by TEO robot

A. Mechanic Architecture

The first problem, that arises to calculate the equilibrium state of the bottle, is the robot's structure. As seen in Figure 3, this robot has both a hand and a tray. But it has been considered that it is necessary to place the TCP (Tool Centre Point) of the arm in the centre of the tray and not in the hand. The main reason is related to the possible future control, which should be on the Cartesian space. By controlling the pose of the tray, it can be positioned and oriented according to the state of the bottle. And to facilitate this task, the axes of the TCP coordinate system of the tray (SoC_{tray}) have been equalled to the root coordinate system (SoC_{root}). In any case, the SoC_{tray} is not inertial with respect to the SoC_{root}, because the tray will describe an accelerated movement with respect to the SoC_{root} of the robot (Figure 4).

On the other hand, the TCP position makes the bottle rest in the centre of the tray. It can be proposed that the 3D-LIPM, which models the bottle, can pivot on the TCP of the tray. Therefore, all the forces and torques that are generated will be related to this pivot point (TCP). The problem arises because the sensor, which measures the forces and torques, is not located exactly in the TCP (or at least under the tray). The sensor is just after the front wrist joint and therefore there is a link connecting the sensor with the tray rigidly (Figure 4).

This mechanical arrangement causes that the coordinate system of the force-torque sensor (SoC_{FT}) is not the same as SoC_{tray}, because the origin of both systems is different. In this case, both systems are inertial, since they are rigidly joined and there can never be an accelerated movement between them. And therefore, the forces and torques read from the sensor are not equal to the force and torques applied to the 3D-LIPM model in the tray.

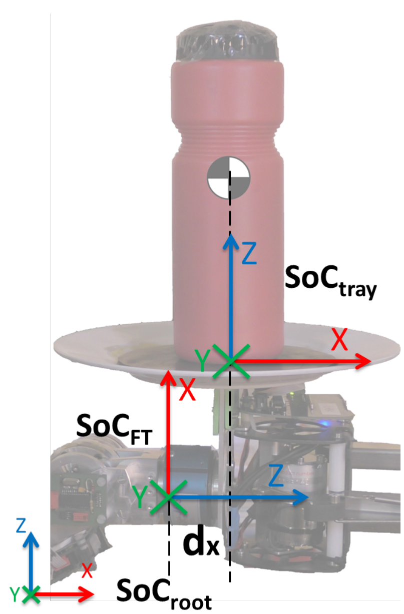

Fig. 4. Representation of SoCs involved in the computation of the object balance with an horizontal orientation of the tray.

In addition, it must be added that SoC_{FT} is an **anti-clockwise** system. Unlike SoC_{root} and SoC_{tray} systems that are **clockwise**. This makes it difficult to interpret the forces and torques from the F-T sensor that will be necessary to calculate the stability of the bottle through the ZMP. In section 4 together with Figure 4, this problem will be thoroughly explained and solved.

B. Sensor Pose Dynamic Estimation

The second problem is related to the computation of the ZMP and the sensor's pose. It depends on the position of the F-T sensor and the location of the COM of each limb to be balanced (in our case, only the bottle). If the bottle is modelled as a 3D-LIPM model, the forces and torques needed to calculate the ZMP will be simpler. And therefore the ZMP calculation will be easier. There are two main reasons why this assumption can be performed.

The first reason is the possibility of using F-T sensors to measure all the forces and torques needed. The 3D-LIPM model relates forces and torques with the movement of the pendulum. Therefore, if the robot has an F-T sensor, it will be useful to apply the 3D-LIPM model.

The second reason is related to the material of the tray. The roughness of the tray has been created as high as possible. In this way, the object will have a very high friction coefficient and therefore the bottle will not slip (only pivot, like a 3D-LIPM). With this assumption and at the same time requirement, we make the bottle behave similarly to the 3D-LIPM model.

However, when the F-T sensor is used, a problem related to its orientation appears. As it is presented in Figure 5. To follow the ZMP equations presented in the background section, the tray should always be aligned with the horizontal plane. In this way, all the forces and torques exerted by the bottle would be reflected correctly in the sensor (ignoring the first mechanical problem) and therefore, the ZMP equation could be applied.

However, the sensor and the tray will have different orientations during a future bottle balance control (Figure 3). These orientations, related to the stable state of the bottle, generate readings in the sensor that cannot be applied in the model. To be able to use them, it is necessary to apply a transformation based on the *"3D Dynamic Slopes"* concept. This concept allows interpreting the data from the sensor correctly according to the estimation of the angle of the tray. It is applicable both in the frontal plane and in the sagittal plane.

IV. METHODS AND EXPERIMENTAL PROCEDURE

The purpose of this article is to use the ZMP equations. For this, the goal is to obtain the suitable F-T values. The solutions proposed below attempt to place virtually SoC_{FT} at the pivot point of the bottle and always on the axial plane (dynamic SoC''_{FT}).

A. Study of Bottle ZMP

As it has been explained in the previous section, there are two basic problems related to the mechanical structure of the robot. These ones must be taken into account to make an effective calculation of the bottle's ZMP. For this purpose, the essential goal is to apply equations 1 and 2. And therefore, the necessary requirement to apply these equations is that the forces and torques used must be applied on the SoC_{tray}.

On the one hand, it is necessary to solve the problem related to the type of coordinate system of the F-T sensor. As a reminder, both SoC_{root} and SoC_{tray} are clockwise systems. By contrast, SoC_{FT} is an anti-clockwise system. Figure 4 depicts this trouble. It has been solved by applying two transformations. The first one is based on a reflection matrix. The second one is a rotational transformation. The reflection matrix is applied in the XY plane on SoC_{FT} and then the rotation matrix (90 degrees) is applied on the Y axis to align all the coordinate systems.

On the other hand, it is necessary to solve the problem related to the origin of SoC_{FT} and SoC_{tray} systems. As a reminder, both SoC_{FT} and SoC_{tray} have a different coordinate origin, and as a consequence, the forces and torques applied in both systems are not the same. In Figure 4, this problem is shown again. Now only one basic translation matrix has been used. The reason is that both systems are inertial. That is, both systems are linked through a link rigidly.

The translation matrix is applied to the vector that joins the origins of the SoC_{FT} and SoC_{tray} systems. In this way, the F-T sensor would be virtually placed in the TCP of the tray and the data from the F-T sensor will be able to associate with the inclination of the 3D-LIPM model or bottle as pretended. In the equation 4, the SoC calculation shows the SoC'_{FT} conversion from anti-clockwise to clockwise and the translation.

$$\begin{pmatrix} X'_{FT} \\ Y'_{FT} \\ Z'_{FT} \end{pmatrix} = I_{ref}(XY)Rot_Y(\frac{\pi}{2})Tras\begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix}\begin{pmatrix} X_{FT} \\ Y_{FT} \\ Z_{FT} \end{pmatrix} \quad (4)$$

Finally, applying these corrections over the F-T values from the sensor, the new bottle ZMP is represented in equations 5 and 6. The equations consider subtracting the d value from all x_i and y_i. Where d_X is the distance on the X-axis between both SoC. d_Y is the distance on the Y-axis. And d_Z is the distance on the Z-axis. In our case, $d_Y = 0$ and d_Z has an imperceptible effect on ZMP equations. Moreover, the inertias of the bottle have not been considered.

$$X'_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)(x_i - d_X) - \sum_{i=1}^{n} m_i \ddot{x}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \quad (5)$$

$$Y'_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)(y_i - d_Y) - \sum_{i=1}^{n} m_i \ddot{y}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \quad (6)$$

B. Bottle ZMP equation with 3D Dynamic Slope

If the tray was always placed in the axial plane, the problem of calculating the ZMP would be solved. However, during a possible control, there will be instants when the tray will be in another plane. The reason is associated with the control strategy. As there is no motor control over the bottle (non-grasping task), it is mandatory to move the tray to counteract the degree of instability of the bottle. To do this, the tray must be tilted at an angle in the opposite direction to the bottle's movement. Therefore, that angle will be related to the value of the bottle' ZMP. But before this angle can be obtained, it is necessary to know the value of this ZMP.

As mentioned above, the use of equations 5 and 6 is conditioned to the tray being horizontal, but there may be cases where this situation does not occur. Therefore, the concept of 3D Dynamic Slope has been applied to deal with the problem of the horizontality of the task.

As explained in the previous section, it is necessary that the virtual pose of the F-T sensor is always in the TCP of the tray and also its orientation is always on the axial plane (SoC''_{FT}). Only in this way, the values read by the sensor can be applied to the ZMP equations.

For this, the solution of 3D Dynamic Slope consists of obtaining the angle of inclination of the tray θ and the rotation's axis $\vec{n}$. The $\vec{n}$ vector has to be perpendicular to the tilt axis of the bottle and go through the origin of SoC'_{FT}. Then, a θ rotational transformation on the axis of rotation $\vec{n}$ is applied over the SoC'_{FT} system to obtain SoC''_{FT}.

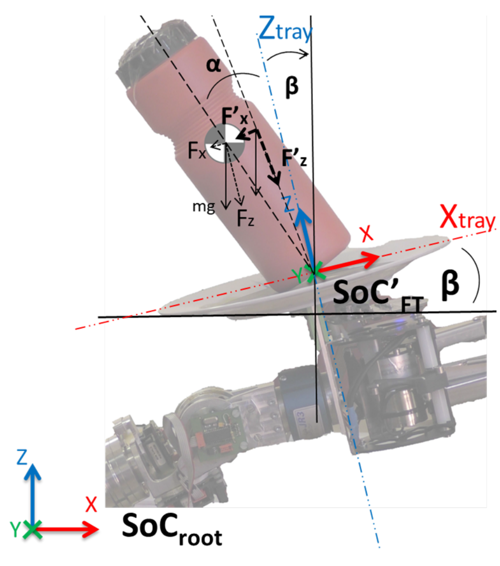

Fig. 5. Representation of the rotational transformation on the sensor's forces as a function of the angle of inclination (slope).

In Figure 5, the process is shown. In this situation (frontal plane), both the bottle (α) and the tray (β) angles are inclined, and the F-T sensor is reading the forces F'_x and F'_z. But when the rotation transformation (θ) on the Y-axis is applied, the new virtual forces become F''_x and F''_z (Equation 7). The angle of the bottle (α) can be calculated geometrically with F''_x and F''_z, which is needed for a future control.

$$\begin{pmatrix} X''_{FT} \\ Y''_{FT} \\ Z''_{FT} \end{pmatrix} = Rot_{\vec{n}}(\theta) \begin{pmatrix} X'_{FT} \\ Y'_{FT} \\ Z'_{FT} \end{pmatrix} \quad (7)$$

Finally, applying these corrections over the F-T values from the sensor, the new bottle ZMP are represented in equations 8 and 9. The equations take into account subtracting the d values from all x_i and y_i. And also the inclination angle with respect to the ZMP calculation plane. Where β is the angle of inclination for the frontal plane. Analogously, it will be necessary to obtain and apply an angle β' for the sagittal plane. The geometric sum of β and β' is related to the angle of inclination θ of the tray.

$$X''_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)(x_i - d_X) - \sum_{i=1}^{n} m_i \ddot{x}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g) * cos(\beta)} \quad (8)$$

$$Y''_{zmp} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)(y_i - d_Y) - \sum_{i=1}^{n} m_i \ddot{y}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g) * cos(\beta')} \quad (9)$$

V. EXPERIMENTS AND RESULTS

In this section, the results of the proposed 3D Dynamic Slope method for ZMP calculations are discussed in four experiments. The tests were carried out on TEO humanoid robot using the YARP middleware platform. TEO is a whole-body humanoid robot capable to handle 2.5kg in each arm. To test this concept, the bottle used weights 1kg.

Related to the set-up, four tests have been carried. All tests try to verify the 3D dynamic slope concept, applying four different slopes. For this purpose, the tray will be reoriented in the Cartesian space, rotating on a fixed point (the origin of the SoC_{tray}) to change the slope (the inclination of the tray).

The first two experiments evaluate the ZMP for **positive** slopes. The range of slope values is [0,9] degrees. In Figure 6, the slope of the tray changes with positive values and rotates respect to the X-axis of SoC_{tray}. In Figure 7, the slope of the tray changes with positive values too and rotates respect to the Y-axis of SoC_{tray}.

The other two experiments are very similar. They evaluate the ZMP for **negative** slopes. The range of inclination values is [-9,0] degrees. In Figure 8, the slope of the tray changes with negative values and rotates respect to the X-axis of SoC_{tray}. In Figure 9, the slope of the tray changes with negative values too and rotates respect to the Y-axis of SoC_{tray}.

In all the figures in this section, three variables are shown. $Ang_{ref-tray}$ is the orientation angle (slope) applied to the tray. β and β' are the calculation of the theoretical angle that the tray is having for the X-axis and the Y-axis respectively. These values are calculated from transformed forces $F''x$, $F''y$ and $F''z$. And X_{zmp} and Y_{zmp} are the values of stability of the bottle according to the equations 8 and 9 and to the $Ang_{ref-tray}$ angle.

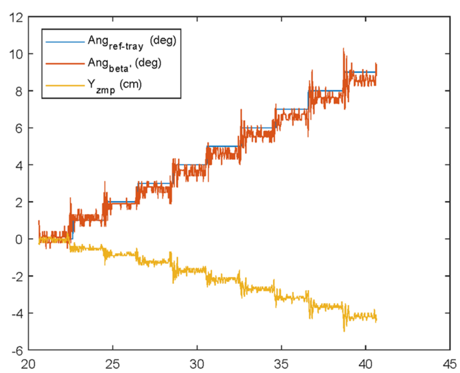

Fig. 6. Evaluation of positive slopes in the X-axis.

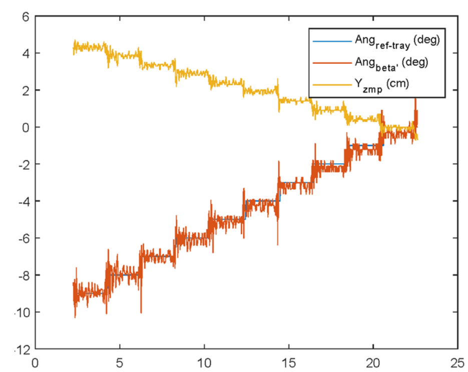

Fig. 8. Evaluation of negative slopes in the X-axis.

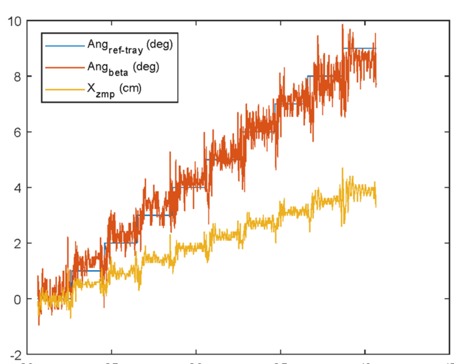

Fig. 7. Evaluation of positive slopes in the Y-axis.

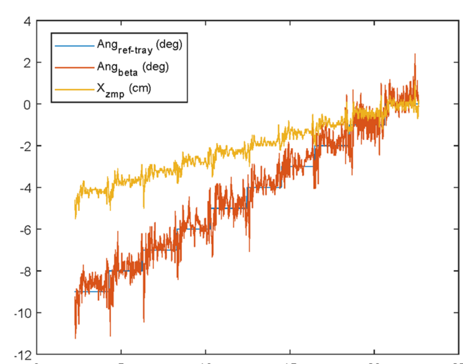

Fig. 9. Evaluation of negative slopes in the Y-axis.

In Figures 6 and 7, for positive slopes, the β and β' angles are fairly close to the reference. The error does not exceed 5%. And there is no notable difference in the rotation between the X-axis and the Y-axis. Also, the ZMP values are consistent with the $Ang_{ref-tray}$ angle; the same value of ZMP is obtained in both axes.

The same argument is valid for negative slopes in Figures 8 and 9. Both β and β' angles coincide with the reference $Ang_{ref-tray}$. The error continues to be less than 5%. Also, the ZMP behaviour is good. In fact, also in this setup both X_{zmp} and Y_{zmp} have the same value for the same $Ang_{ref-tray}$ reference.

VI. CONCLUSIONS

In this article, a mathematical process is proposed. This method is able to calculate an effective ZMP calculation independently of the slope value and the inclination vector. Dynamically, the corresponding ZMP is being obtained while the tray changes its pose.

Through the experiments, some important points have been verified. $Ang_{ref-tray}$ reference and the theoretical angle (β) are equal. Therefore, the forces' transformations needed to calculate beta are correctly done. The ZMP values are accurate too. In all tests, X_{zmp} and Y_{zmp} have similar values for the $Ang_{ref-tray}$ reference. These results demonstrate the validity of this method in any rotation axis.

For future works, two ideas are proposed. On the one hand, the F-T sensor data acquisition should be improved. The noise in both beta and ZMP values is appreciable. Adding a signal filter could help to solve this but it is important to trade the task performance off. On the other hand, the balance control of the transported object will be integrated into the whole body control architecture of the robot TEO. The controller will be able to counteract different disturbances in the bottle or in the arm at the same time the robot controls body balance.

ACKNOWLEDGMENT

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