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IMPLEMENTING A ICP BASED CONTROLLER FOR SKIPPY

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Abstract. This paper presents the implementation of an Instantaneous Capture Point (ICP) based controller for the Skippy robot. Skippy is a robot with a single point foot and only two actuated Degrees of Freedom (DoF), one in the sagittal plane (hip) and one in the frontal plane (shoulder). In this work we focus on maintaining balance without changing the position of the foot point (stepping or hopping). Balance of the robot is achieved through exploring the dynamic relationship between the ICP and the Centroidal Moment Pivot (CMP). The control approach is based only on the generation of angular momentum. Results showing controller performance during balancing upright, crouching, and recovering from pushes are presented in simulation with the Skippy robot. The work validates the ICP control approach for angular momentum based balancing in a very underactuated, low DoF robot.

Keywords: Skippy, ICP, CMP, Angular Momentum, Balance Control

1. INTRODUCTION

According to biomechanical investigations, the spin angular momentum, which is the body's angular momentum about the CoM, remains small and is highly regulated about the three body axes throughout the entire human walking cycle Popovic *et al.* (2002). Angular momentum based control strategies have been used in bipedal robots to change the direction of ground reaction forces exerted by the legs. They can be used for walking Koolen *et al.* (2016), push recovery Pratt *et al.* (2016), walking on partial footholds Wiedebach *et al.* (2016), etc. under which the robot exhibits human-like behaviors like arms windmilling and torso lunging.

Bipedal walking has been a challenging control problem because of its nonlinear nature, the high number of DoFs in humanoid robots, and the equilibrium dynamics change due to stepping. One approach to control such a system is to use a simplified model of the robot such as a linear inverted pendulum. From this idea the concept of the ICP was derived Pratt *et al.* (2006); Pratt and Drakunov (2007); Koolen *et al.* (2012).

The ICP is the ground point at which the robot's foot needs to be, such that its Center of Mass (CoM) will come to a stop above the foot. Linear inverted pendulum model can be extended by a flywheel Pratt *et al.* (2016) to include angular momentum in robot's balance. It's worth noting that in applying such simplified models to complex robots there is always a trade off between mathematical simplicity and validity of the model.

We believe that Skippy Featherstone (2017) is an excellent model of humanoid balance based on angular momentum strategies. It captures everything that is important to balance humanoid robots using angular momentum. It has a hip and shoulder joint (see Fig. 1) and can use its upper body to maintain balance. At the same time it has only two actuated degrees of freedom and is therefore one of the simplest robots that can balance itself. This is the reason why we decided to validate ICP based balancing control on that robot. Previous work has shown that the ICP is a good model for balancing based on Center of Pressure (CoP) and on stepping strategies Pratt *et al.* (2012); Koolen *et al.* (2016). Skippy has a point foot so it can not use the CoP strategy and in this work we focus only on angular momentum based balancing. We present an ICP based controller for Skippy and compare the performance to other control approaches.

2. THE ROBOT

Skippy, Fig. 1, is an under actuated mechanism with 6 DoF at the foot (floating joint), one at the hip and one at the shoulder, actuated only on the hip and shoulder joints. It is a simple robot capable of using angular momentum to balance. The real robot does not exist yet but it will weight 2kg, be able of hopping 4m high, and to balance and steer in 3D, while

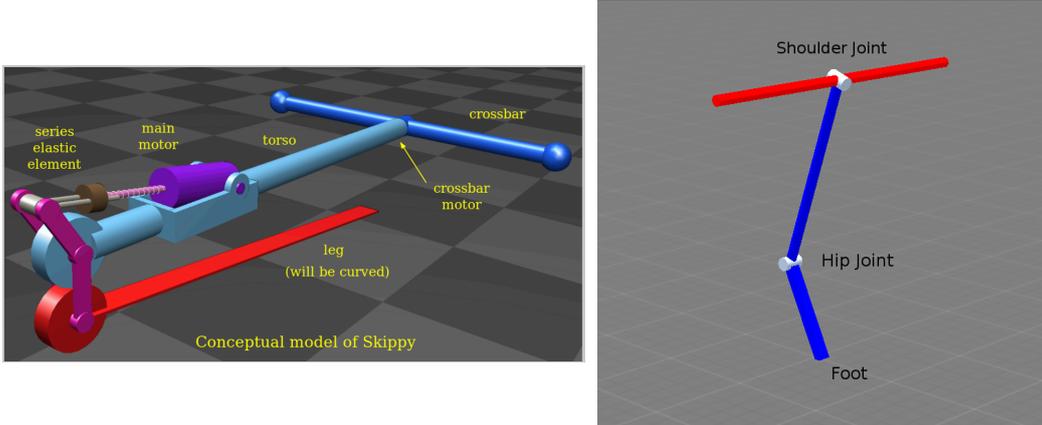


Figure 1. Two images of the Skippy robot can be seen. The left one shows the robot as seen in Featherstone (2017). The right picture shows our simulation model of Skippy.

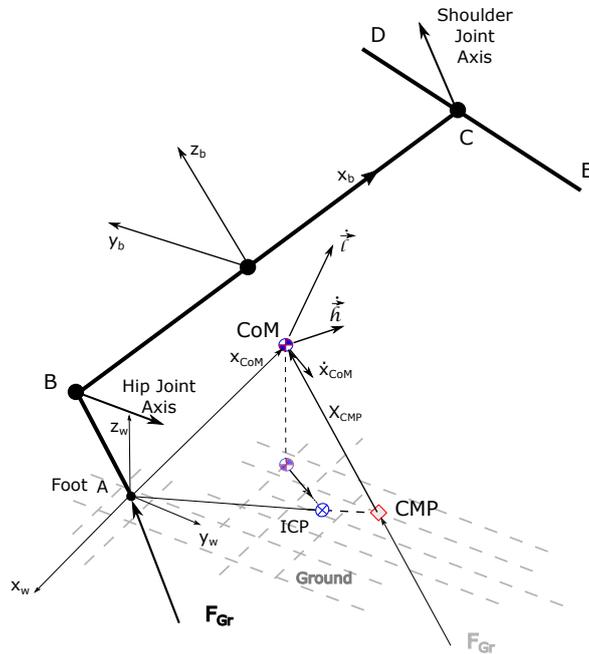


Figure 2. The Skippy robot model with variables and reference frames shown.

being mechanically simple, robust, and affordable. It is meant to explore the limits of physical performance with robots. Figure 2 introduces the variables and reference frames we use when deriving the controller.

2.1 Motivation

The idea is to explore the limits of physical performance with a robot that is simple, robust and fairly cheap. Skippy captures everything that is important to balance humanoid robots using angular momentum approach. In this paper, it's presented an ICP based controller for Skippy's model from Fig. 1; results are shown for the robot coming from a crouched position to upright in a vertical and in a sideways leaned plane.

3. INSTANTANEOUS CAPTURE POINT (ICP)

The ICP Pratt *et al.* (2006); Pratt and Drakunov (2007); Koolen *et al.* (2012), is the ground foothold to which a legged system can step to a stop, with the CoM coming to a position above the foot with zero velocity.

Setting to zero the Orbital Energy (E_{Lip}), Kajita *et al.* (2001), noting that X and Y linear inverted pendulum dynamics are decoupled since the CoM is restrained to move in a horizontal plane resulting $\ddot{z}_{CoM} = 0$, and solving for $X_{ICP} = XFoot$, it follows:

$$\vec{X}_{ICP} = \vec{X}_{CoM} + \sqrt{\frac{z_0}{g}} \dot{\vec{X}}_{CoM}$$

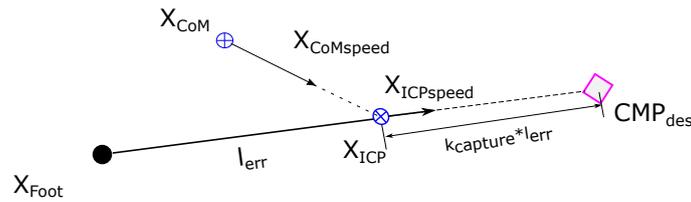


Figure 3. ICP and CMP coupled dynamics.

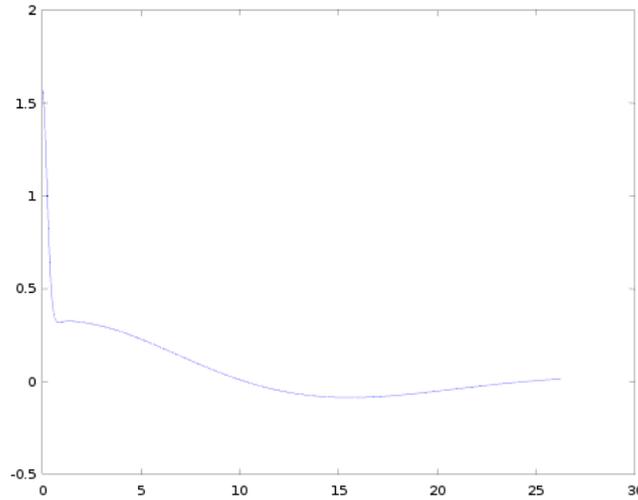


Figure 4. Hip angle from crouched pose to standing upright.

where $\vec{X}_{..} = (x_{..}, y_{..}, z_{..})$ and $\vec{X}_{ICP} = \vec{X}_{Foot}$ when $E_{LIP} = 0$. The ICP concept was independently developed by different research groups which referred to it as the extrapolated center of mass and showed that it's a better indicator of balance in human walking than the CoM alone Pratt *et al.* (2016).

4. ICP CONTROLLER

In Pratt *et al.* (2016) it is shown that the position of the ICP can be controlled by modulating the CMP Popovic *et al.* (2005), which is the point where a line \vec{X}_{CMP} parallel to \vec{F}_{Gr} passing through CoM , crosses the XY plane, and $(\vec{X}_{CoM} - \vec{X}_{CMP}) \times \vec{F}_{Gr} = 0$.

From ICP and CMP dynamic relationship, as depicted in Fig. 2 and 3:

$$\vec{X}_{CMP} = \vec{X}_{ICP} + k_{capture}(\vec{X}_{ICP} - \vec{X}_{Foot}),$$

where the \vec{X}_{CMP} is the target CMP to balance the robot and $k_{capture}$ is a gain to keep the desired rate of change of centroid angular momentum.

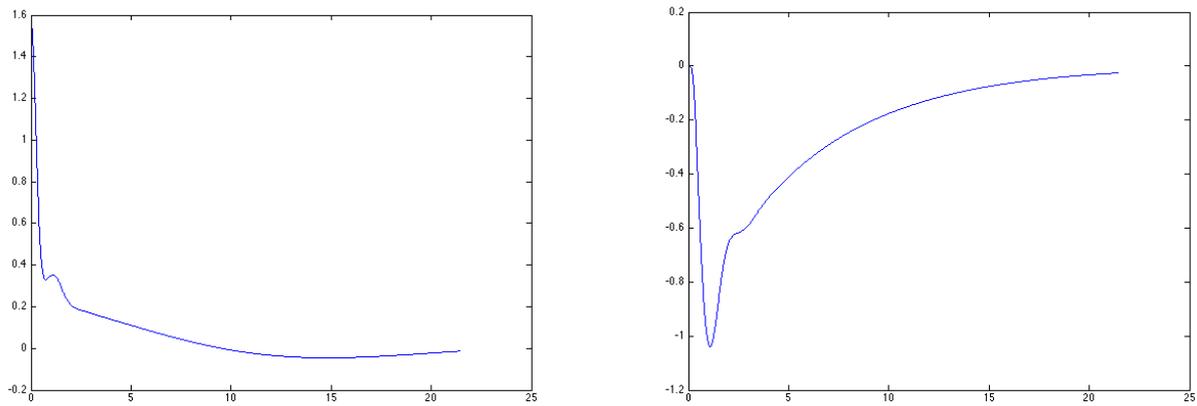
The position of the CMP is a function of the joint torques of the robot and is considered a control input. If the CMP diverges from the point foot, angular momentum is generated that drives the ICP. This can be used to keep the ICP at the foot position.

We translate the reaction force to the CMP and apply the resulting torque through the cross product of the reaction vector $\vec{F}_{Gr} = \frac{mg}{\lambda_z} \vec{\lambda}$, to hip and shoulder joints, being $\vec{\lambda} = [\lambda_x, \lambda_y, \lambda_z]$ the unit vector from CMP to CoM, m the robot mass and g the gravity.

To run the model dynamics, we tune the CMP to match \vec{F}_{Gr} and actual reaction angles through proportional controllers on hip and shoulder angle errors, and on angular momentum rate of change.

5. RESULTS

In a first experimental validation of the control approach Skippy starts in a crouched position. Then a desired hip angle of 0 rad is requested. This is equivalent to an upright standing pose. Figure 4 shows the evolution of the hip joint angle during this experiment. The fast motion in the first second corresponds to the robot balancing itself. Figures 5(a) and 5(b) present the hip and shoulder angles as Skippy stretches itself from a crouched position, sideways leaned with 0.235rad, to upright. It shows that the controller can achieve balance if the robot starts in a difficult (leaned) configuration. The joint accelerations shown in Fig. 5, are associated with a nonzero rate of change of the angular momentum, achieved



(a) Hip angle from crouched to upright with sideways lean of 0.235rd. (b) Shoulder angle from crouched to upright with sideways lean of 0.235rd.

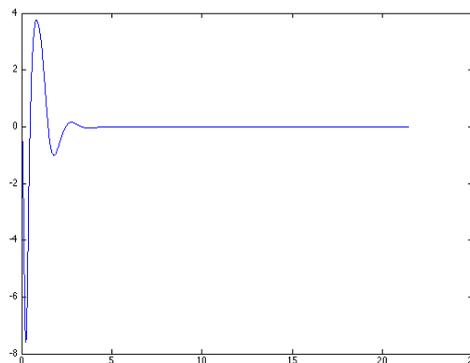


Figure 5. Shoulder acceleration from crouched to upright with sideways lean of 0.235rd.

by lunging of the upper body. This is similar to the balance behavior shown in Wiedebach *et al.* (2016) where the same control approach is used in combination with CoP strategies in a more complex robot.

Future work will be to apply a momentum controller strategy such as in Koolen *et al.* (2016), improving Skippy skill for jump, trajectory tracking and performing of animations.

6. ACKNOWLEDGEMENTS

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