Footstep Control for the NAO Humanoid Robot using the Extrapolated Center of Mass

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1 Introduction

The development of stable, omnidirectional bipedal gait is fundamentally critical and has been addressed through numerous approaches in control systems adapting to unconstrained environments and rejecting random perturbations [1]. Our goal is to improve stability through control of foot placement in reaction to instantaneous changes in the state of the center of mass (CoM) of the biped.

Our control concept is based on Hof's 'extrapolated center of mass' [2]. The extrapolated center of mass (XcoM) is based on the inverted pendulum model and is the point where the foot should be placed such that the passive pendulum will come to a complete stop in its vertical position. By placing the foot on either side of the XcoM, the pendulum can be made to either continue its forward motion, or turn around before the vertical position is reached [2]. Inspired by this work, we aim to implement this control scheme on a NAO bipedal robot (Aldebaran Robotics). First, we will replicate Hof's existing theory of the extrapolated center of mass with NAO specific system properties, and then translate this approach into a controller on the actual NAO.

2 Methods

Linearized inverted pendulum dynamics was used to model the biped in the single-support phase. The extrapolated center of mass (XcoM ξ, ζ) depends upon the state $[x\ y\ v_x\ v_y]^T$ of the center of mass and eigenfrequency of the inverted pendulum model $\left(\omega_0 = \sqrt{g/l}\right)$ according to:

$$\begin{bmatrix}\xi\\ \zeta\end{bmatrix} = \begin{bmatrix} x + \frac{v_x}{\omega_0} \\ y + \frac{v_y}{\omega_0}\end{bmatrix} \tag{1}$$

At the beginning of each stance phase, the desired forward and lateral positions of the center of pressure (CoP u_x, u_y), i.e. the position of the base of the pendulum, were set as a function of the XcoM. A constant offset control (b_x, b_y) was applied to generate a stable periodic walk [2]:

$$\begin{bmatrix}u_x\\ u_y\end{bmatrix} = \begin{bmatrix} \xi_n - b_x \\ \zeta_n + (-1)^n b_z\end{bmatrix} \tag{2}$$

The system was simulated in MATLAB for a fixed step duration of 0.7 s. The effect of the offset control parameters (b_x, b_y) on step length was determined for various pendulum lengths, ranging from human-like to NAO dimensions.

Our controller was implemented on the NAO humanoid robot using the NAO Python SDK, following the feedback control diagram in Figure 1. This was developed with respect to a complete gait cycle that included both the left and right single-support phases (N, N+1). We hypothesize that stability will be achieved by measuring the state of the support leg during perturbation to control the consecutive recovery step. Center of mass position and velocity was obtained from the built-in sensors SDK function calls. Doing this continuously across the gait cycle allowed us to extract the final state in the step trajectory that may require compensation in the following step. Real-time trajectory tracking for foot placement was used to approximate the placement of the center of pressure, as well as the switching control between support phases.

Figure 1 describes the step planner as a function of available sensory data, actuators, and feedback control. The ability of real-time computed step placement adjustment gives the possibility of successful recovery from larger disturbances. Our experimental response allowed us to quantify and compare the robustness of our reactive approach. We compared our XcoM controller to that of the built-in NAO 'Whole Body Balancer' by recording the center of mass motion, and the variables used in the controller.

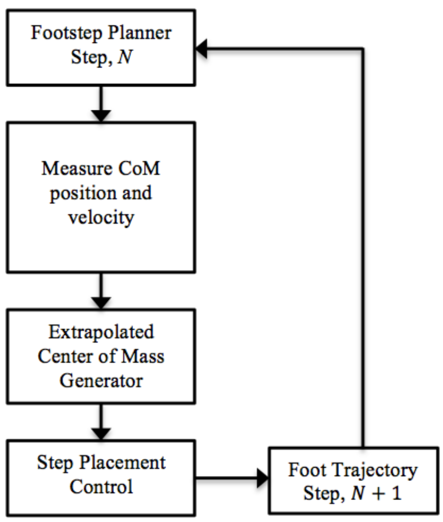

Figure 1: Architecture of XcoM controlled gait.

3 Results and Discussion

Figure 2 shows a typical example of simulated inverse pendulum motion controlled by placing the foot (CoP) according to equation (2). The diagram shows how the CoP is placed behind and outward of the XcoM to maintain lateral stability as well as stable forward motion.

The simulations with different pendulum lengths and offset parameters produced Figure 3. The step length was inversely proportional to the offset parameter and directly proportional to effective pendulum length. This relationship was used to select the appropriate offset control parameter *b* for desired step lengths.

Figure 4 demonstrates the proposed 'extrapolated center of mass' controller implemented on the NAO humanoid robot. This shows footstep placements of the NAO, where the motion in the direction of walking is plotted against time.

Using real-time state-space tracking, we were able to calculate the XcoM (green) and intended CoP (red) with respect to the CoM (blue) position and velocity. The XcoM and footstep placement indicated the result of our offset control. The CoM was stabilized with respect to the foot placement command (red -o). The NAO maintained an average walking speed of 0.17 m/s.

We observed increased variability in footstep placement when using the XcoM controller compared to the existing balance controller (Figure 4).

Although human gait demonstrates optimal versatility and robustness, humans may not use the simple XcoM based control that we simulated in MATLAB. Humans may not have the required response time, especially when affected by age and physical ability. Furthermore, they may not prefer to react instantaneously for reasons of safety. In fact, it is observed that human response to gait perturbations require several steps, similar to our control law for consecutive step placements on the NAO humanoid robot.

4 Conclusion and Future Work

Our theoretical simulation, combined with experimental results, demonstrates that Hof's XcoM control can be used to generate footstep placement in a physical robot. Our implementation mimics a human-like system that is not able to operate with optimal reaction time and physical ability. The additional recovery step ensures safety by eliminating the need for instantaneous recovery.

Future work will aim to further develop the operating speed of our controller for continuous, faster, and more dynamic gait. Perturbation experiments will be done to quantify the stability of the robot, in comparison with the built-in balance controller.

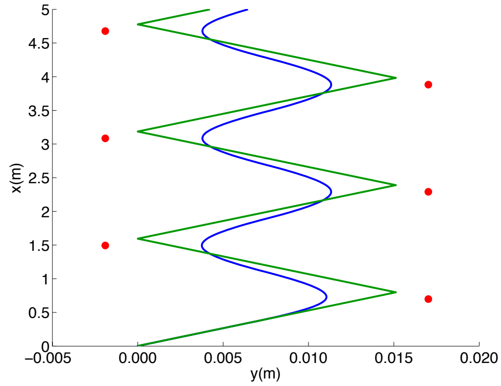

Figure 2: Theoretical simulation of human-like CoM (blue –), XcoM (green –), and CoP (red -o) trajectories in the forward (x) and lateral (y) directions.

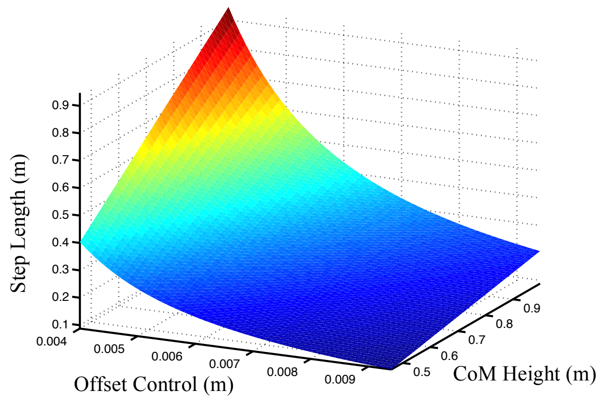

Figure 3: Step length dependency upon offset control parameter and inverted pendulum model length.

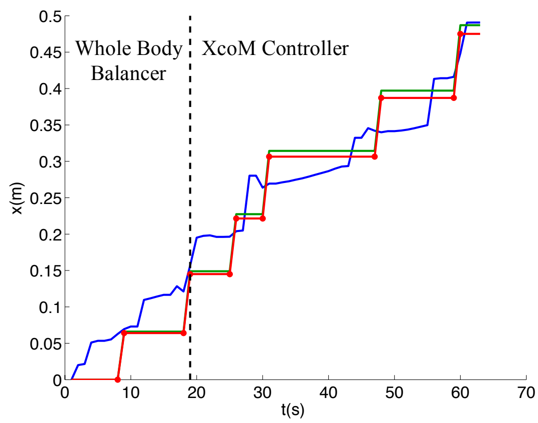

Figure 4: Stabilization of NAO's CoM (blue –) with foot placement command (red –o) where our XcoM controller was implemented after initial steps. The distance between XcoM (green –) and intended CoP (red –) represents the forward offset control.

References

[1] Stephens, B. Integral Control of Humanoid Balance. IEEE/RSJ Intl. Conf. on Robotics and Systems, pp. 4020-4027, 2007.

[2] Hof AL. The 'extrapolated center of mass' concept suggests a simple control of balance in walking. Human Movement Science 27, 112-125, 2008.