

# Momentum Estimation, Planning and Control for Force-Centric Bipedal Locomotion

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## 1 Introduction

The stability of a humanoid robot is ensured by constraining its Center of Pressure (CoP) within its support polygon; using a simplified model such as the Linear Inverted Pendulum Model (LIPM) allows for a linear mapping between Center of Mass (CoM) and CoP motion. This enables the use of linear Model Predictive Control (MPC) methods to generate a CoM trajectory which realizes a desired CoP motion for the LIPM [1]. Traditional approaches to walking resolve the planned motion for joint trajectories and track these using stiff position control. However, the CoP is defined by interaction forces - not positions. Since position control offers no direct control of force, this method relies on trajectory engineering and tuning. On a torque-controlled robot, however, one can directly track LIPM-consistent forces rather than COM motion. This allows for control of impedance, yet even this fails to work well without tuning for several reasons. First, the simplified model forces - even if reproduced exactly on the robot - will not generate the desired CoP motion due to model differences between the robot and the LIPM. Second, inverse dynamics solvers do not account for discrepancies between planned and measured forces due to perturbations, unobserved terrain and so on. In order to generate dynamic reactive behaviors on the real robot, we need to use descriptive simplified models which are consistent with the full dynamics and make use of endeffector force/torque (F/T) sensors for state estimation.

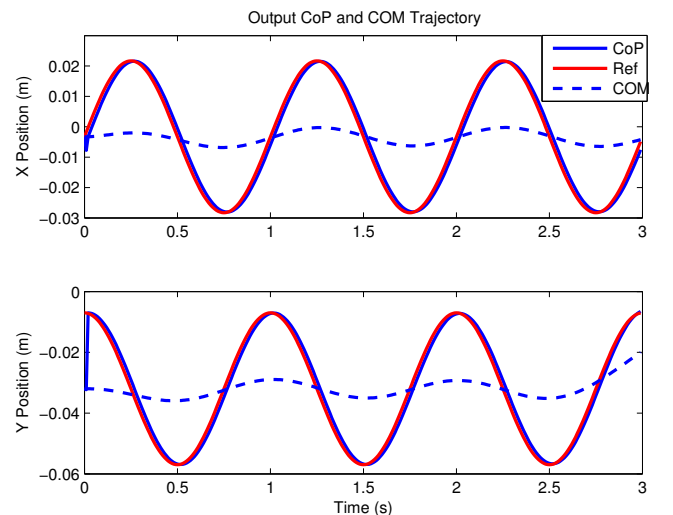
## 2 Approach

Recent work has shown the utility of the momentum dynamics for humanoid control [2],[3],[4]. These dynamics are nonlinear due to the presence of the angular momentum; the LIPM is a special case in which angular momentum is neglected and COM motion is constrained to a plane. While planning using the nonlinear dynamics is promising [5], the momentum dynamics can be linearized and used for MPC in the same way as the LIPM is currently used. In contrast to the LIPM, the momentum dynamics provide a simplified yet *consistent* model with respect to the full robot dynamics; they allow for planning directly in terms of forces rather than motion, removing the ambiguity between models and making them amenable for torque control. In addition, this simplified model eliminates the point-mass assumption of the LIPM, allowing control of the CoP by generating angular momentum.

Dual to the problem of planning forces is that of using measured wrenches for estimation. While we have already implemented momentum controllers on our humanoid [6], results have been limited by the fact that our CoM and momentum estimates rely on imperfect models and noisy joint velocities computed by numerical differentiation. Low-pass filtering these estimates creates delays which can lead to instability. However, endeffector F/T sensors can be integrated to yield the time-evolution of momentum; this information can then be fused with model-based estimates.

## 3 Results - Control

We have implemented a finite-horizon preview controller using the linearized momentum dynamics to generate contact wrench trajectories which realize a desired CoP motion. The resulting plan takes the form of a feedback controller on the COM and momentum of the system; by replanning online using force-based state estimates, we indirectly perform feedback control using F/T sensors. Preliminary results demonstrate that arbitrary CoP motions such as a circle in the ground plane can be tracked by planning contact wrenches. The momentum dynamics were integrated using the contact wrench trajectories from MPC to produce the following figure.

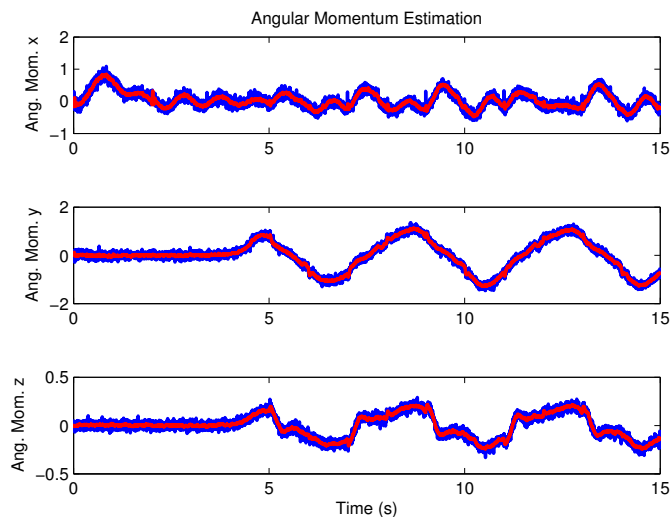


**Figure 1:** Momentum-based preview control for CoP tracking of a circle over a three second horizon in simulation assuming perfect state estimation.

Note that the desired CoP trajectory is achieved despite the COM moving relatively little - this is possible because the planned contact wrench trajectory also uses angular momentum to control the CoP. An additional state tracking cost can be added to generate solutions which balance desired COM and CoP motions, making this formulation more flexible than those using the LIPM. This linear MPC problem has an analytical solution and can be computed efficiently using optimal control methods; alternatively, it can be formulated as a quadratic program with constraints on contact wrenches such as foot CoP limits, friction cones and so forth.

#### 4 Results - Estimation

In order to achieve good tracking in the MPC problem, we need accurate estimates of the COM and momentum. We have developed an Extended Kalman Filter (EKF) which fuses integrated contact wrench measurements with kinematics-based estimates of the COM and momentum. The resulting estimates are considerably less noisy without relying on delay-inducing filtering. The following figure shows the angular momentum during a simulated walking task in which realistic amounts of joint position/velocity noise and F/T sensor noise were added; the kinematics-based estimates are in blue and the EKF estimates are in red.



**Figure 2:** Angular momentum estimation during a fifteen second walking task. Fusing integrated F/T measurements with kinematics provides clean estimates with minimal delay.

In addition to handling sensor noise, we are extending this estimator to deal with drifting F/T sensor biases as well as COM offset errors, both of which exist on the real robot.

#### 5 Outlook

We have developed methods for leveraging the descriptiveness of the momentum dynamics with traditional linear MPC and have begun testing in simulation, with early results demonstrating successful tracking of arbitrary CoP trajectories by exploiting both CoM motion and angular momentum in planning. At the same time, we have implemented a momentum estimator which fuses measured contact wrenches

and dynamic model information. By using momentum estimated from measured forces in planning contact wrenches to achieve desired CoP motions, we are able to close the loop between planned and expected CoP motions in order to generate dynamic reactive behaviors directly through force control. A whole-body controller is being implemented to generate joint torques and motion from the planned contact wrenches; once this is complete, we will begin testing this approach in an on-line fashion first on a full-robot simulation of our SARCOS hydraulic humanoid and then on the actual robot for balancing, CoP tracking and ultimately for walking.

#### References

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