# Control of Humanoid Walking as an Instantaneously Coupled System

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## Abstract

For a special type of system, which we call an Instantaneously Coupled System (ICS), it is possible to construct an optimal controller by coordinating optimal controllers for augmented subsystems. We model walking as an ICS and use dynamic programming to generate optimal subsystem controllers. Coordination of the subsystem controllers produces a controller that simultaneously optimizes center of mass motion, step timing and step location.

## ICS: Definition

A system consisting of multiple subsystems that have independent dynamics except at specific instants.

## ICS: Optimal Control

1. Partition the state
2. Augment each subsystem so that you can:
    1. Model the coupled dynamics
    2. Write the cost function
    3. Determine when coupling occurs
3. Generate optimal subsystem controllers
4. Add the subsystem value functions
5. Minimize the value function with respect to the augmentation variables
6. Look up the optimal actions from the subsystem policies

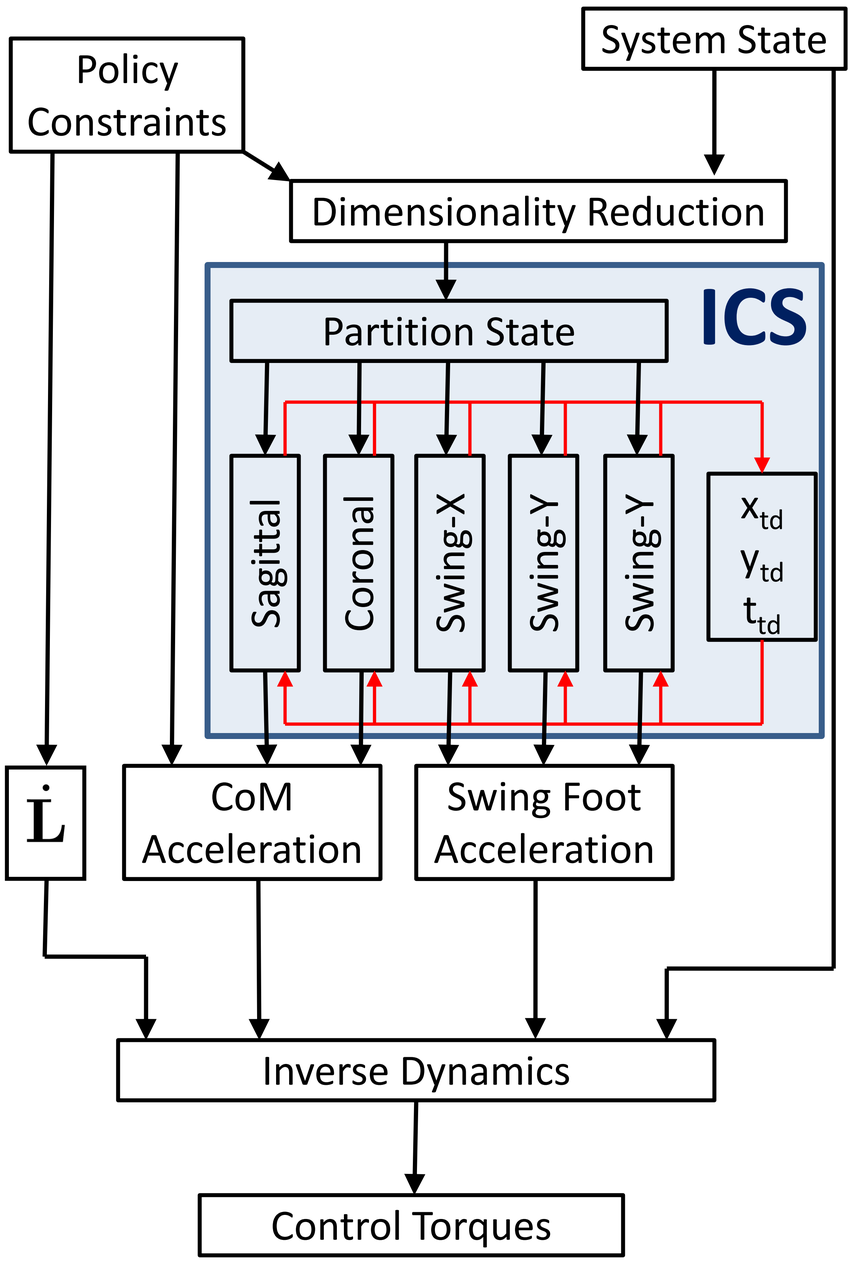
[1] Mike Stilman, Christopher G. Atkeson, James J. Kuffner, and Garth Zeglin, "Dynamic programming in reduced dimensional spaces: Dynamic planning for robust biped locomotion", in *Proceedings of the IEEE International Conference on Robotics and Automation*, 2005, pp. 2399–2404.

[2] Michiel van de Panne, Eugene Fiume, and Zvonko G. Vranesic, "A controller for the dynamic walk of a biped across variable terrain", in *Proceedings of the 31st conference on decision and control*, December 1992, pp. pp. 2668–2673.

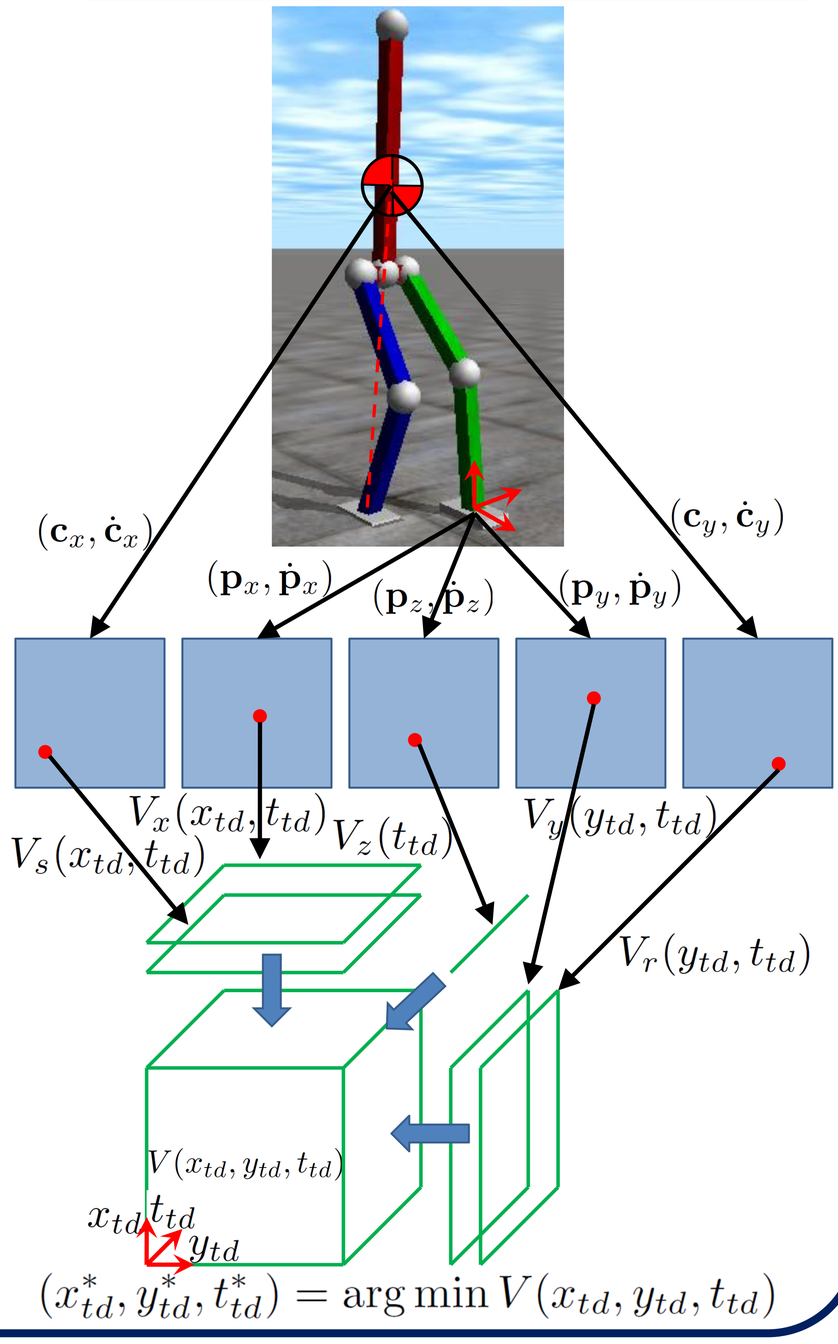
[3] Benjamin J. Stephens, "Dynamic balance force control for compliant humanoid robots", in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010, Available online at www.cs.cmu.edu/~bstephe1/papers/iros10.pdf.

## Control Architecture

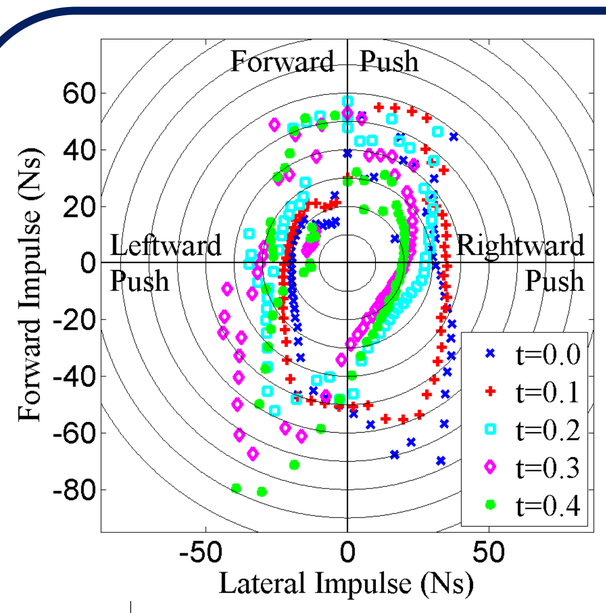
### Overall Architecture



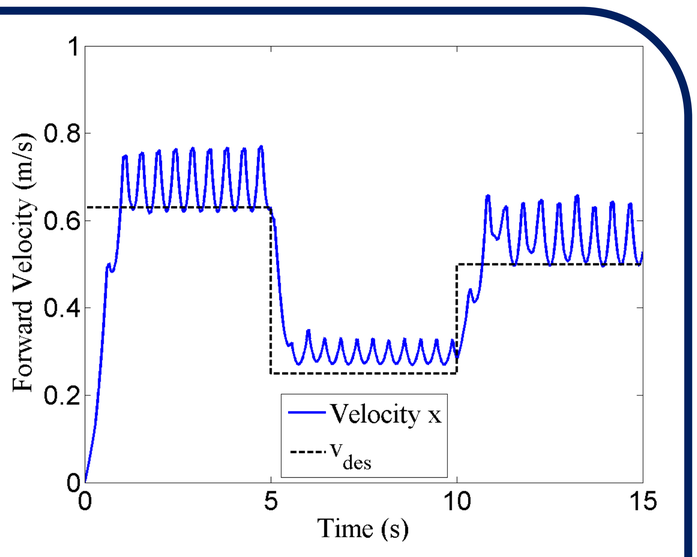

### Step Timing & Location

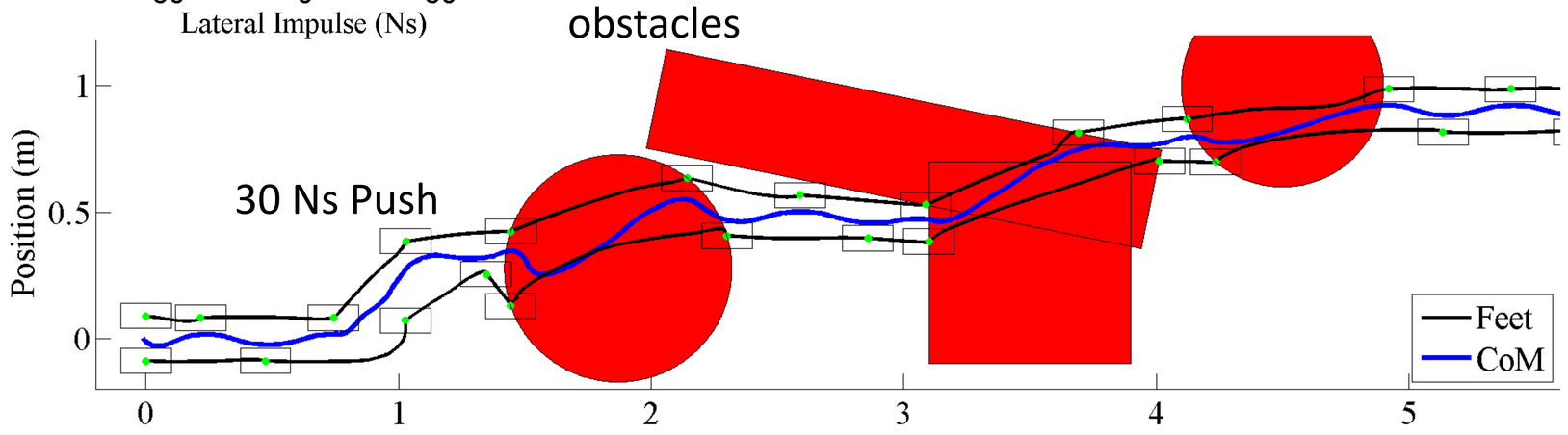



## Simulated Walking Results




**LEFT:** Robustness to perturbations by time after left foot liftoff
**RIGHT:** Control speed by changing sagittal policy
**BOTTOM:** Walking with a push and obstacles

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