# A Step-to-Step Dynamics based Control Approach for Bipedal Robotic Walking Realization

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Realizing bipedal robotic walking involves complex motion planning and feedback control synthesis on the high dimensional degrees of freedom of the robot. Unlike other robotic systems such as robot arms or vehicles, the planning and control on bipedal robots have to be aware of the problem of balancing [1], [2] in terms of not falling. To better understand and solve this problem, our recent work [3]–[7] explore the idea of dynamics approximation of using simple models to design stepping controllers for walking realization.

We formulate a discrete step-to-step (S2S) dynamics that represents the evolution of the horizontal center of mass (COM) at the pre-impact event. We then formally translate walking planning and balancing as a discrete feedback control problem. By constraining the vertical COM and creating periodic lift-off and touch-down behaviors, we find a linear S2S dynamics can be used to approximate the actual S2S dynamics of the robot, which takes step sizes as control inputs. Desired walking behaviors in terms of pre-impact horizontal COM states are directly identified on the linear S2S dynamics.

The discrepancy in terms of the model difference between the robot and the simple model is small and is bounded in a subset of realizable walking behaviors (with bounded walking velocities). Stepping controllers that change the step length and width are thus easily synthesized to realize desired walking behaviors on 3D bipedal robots. Optimization-based controllers are then utilized for trajectory tracking to realize walking on the high-dimensional hybrid dynamical system. Moreover, once walking is realized on the robot, an improved S2S dynamics approximation can be directly learned from the walking data. The model discrepancy is then reduced, and so is the accuracy in terms of walking velocities.

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We demonstrate the S2S dynamics based controller for realizing periodic walking [3], global trajectory tracking [7], walking on rough terrains [5], risk-sensitive planning [8], and robust push-recovery behaviors [6] on 3D bipedal walking robots. In the future, we will investigate in the integration of the discrete S2S dynamics based approach with continuous motion stabilization on robots with complete upper bodies.

## References

[1] M. H. Raibert, *Legged robots that balance*. MIT press, 1986.
[2] J. Pratt, T. Koolen, T. De Boer, J. Rebula, S. Cotton, J. Carff, M. Johnson, and P. Neuhaus, "Capturability-based analysis and control of legged locomotion, Part 2: Application to M2V2, a lower-body humanoid," *The Int. J. of Rob. Res.*, vol. 31, no. 10, pp. 1117–1133, 2012.
[3] X. Xiong and A. D. Ames, "3d underactuated bipedal walking via h-lip based gait synthesis and stepping stabilization," *arXiv preprint arXiv:2101.09588*, 2021.
[4] ——, "Dynamic and versatile humanoid walking via embedding 3d actuated slip model with hybrid lip based stepping," *R-AL*, 2020.
[5] ——, "Slip walking over rough terrain via h-lip stepping and backstepping-barrier function inspired quadratic program," *R-AL*, 2021.
[6] X. Xiong, Y. Chen, and A. D. Ames, "Robust disturbance rejection for robotic bipedal walking: System-level-synthesis with step-to-step dynamics approximation," in *Under review*, 2021.
[7] X. Xiong, J. Reher, and A. D. Ames, "Global position control on underactuated bipedal robots: Step-to-step dynamics approximation for step planning," in *ICRA 2021, arXiv preprint arXiv: 2011.06050*.
[8] M. Ahmadi, X. Xiong, and A. D. Ames, "Risk-Sensitive Path Planning via CVaR Barrier Functions: Application to Bipedal Locomotion ," in *arXiv preprint arXiv: 2011.01578*, 2020.

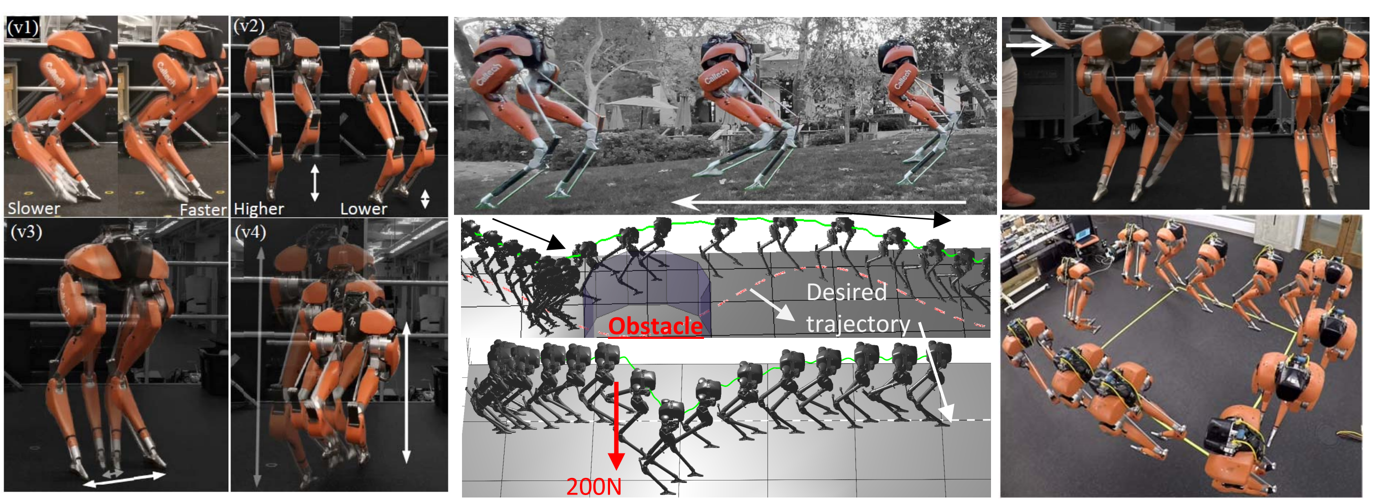


Fig. 1. Illustration of the realized walking behaviors: high versatility of changing step frequency, swing foot clearance, step width, and stance height; robustness of walking that tolerates push disturbances and ground uncertainties; global trajectories tracking that can also avoid obstacles and reject pushes.