Trajectory Generation for Bipedal Robots Using Recurrent Neural Networks

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The Problem: To develop a control system for bipedal walking robots using a combination of biologically inspired and more traditional control theoretic approaches. The system should be capable of complex error correction, such as the ability to execute a multi-joint movement, possibly one that is not representative of normal walking, to recover from a disturbance.

Motivation: The idea of learning a feedback control function in a neural network has exciting implications. If we could train a neural network to output the optimal control variables for any position in state space, then the walking problem would be completely solved. Unfortunately, our own recent experiments with using neural networks to directly learn the control variables (torques) worked well in simulations of the hopping robots described in [5], but did not scale well to simulations of the 12 degree of freedom 3D bipedal robot described in [3]. Essentially, small errors in torques during learning can result in very large and very complicated errors in performance, making the learning problem very difficult.

In biological systems, the central nervous system does not send pure torque commands to the muscles. It is widely acknowledged that muscles have nice features that could simplify the control problem significantly. For our torque-controlled robot, we can make a similar simplification by only requiring that the learning system generate the desired trajectory and then using traditional control strategies to solve the trajectory following problem. For example, the series of humanoid robots from Honda research have demonstrated that trajectory following algorithms using high-gain feedback can effectively control a humanoid robot[2].

Approach: Honda's approach to the trajectory generation problem was to record humans walking, then to send a filtered version of that data to the robot as a desired trajectory. The major limitation of this approach is that the robot is restricted to a small region of the workspace where the desired trajectories have been defined. Our approach is to learn the desired trajectory in a modular form where we can modify it on a short time scale through feedback and on a long time scale through learning. Recurrent neural networks are one representation where we know how to make both types of changes.

The parameters of the recurrent network will be set initially so that the outputs of the network model data from existing successful simulations of the 3D biped walking forward[4]. This can be accomplished using backpropagation-through-time. The gains necessary to make the robot follow this initial trajectory will be very large. By continuing to train the network while the robot is executing, we can slowly turn down the gains as the shape of the desired trajectory incorporates more information about the physical plant. This idea of learning feedforward control based on feedback error[1] is often discussed in the biological motor control literature.

Finally, by adding sensory inputs to the network, we give the controller the ability to change the desired trajectory according to the current state of the system. This important idea of using feedback in the trajectory generation algorithm as well as the trajectory following algorithm is largely ignored in the walking literature. By including it in our learning system, we can directly allow for complex error correction, which will improve the overall robustness of the walking system.

Research Support: This research is supported by the David and Lucille Packard Foundation, contract number 99-1471.

References:

[1] Hiroaki Gomi and Mitsuo Kawato. Learning control for a closed loop system using feedback-error-learning.

pages 3289–3294. Proceedings of the 29th Conference on Decision and Control, 1990.

[2] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka. The development of honda humanoid robot. pages 1321 – 1326. IEEE Conference on Robotics and Automation, 1998.

[3] Daniel Joseph Paluska. Design of a humanoid biped for walking research. Master's thesis, 2000.

[4] Jerry Pratt and Gill Pratt. Exploiting natural dynamics in the control of a 3d bipedal walking simulation. Conference on Climbing and Walking Robots, 1999.

[5] Marc H. Raibert. *Legged Robots That Balance.* The MIT Press, 1986.