A MODEL FOR MOTOR CONTROL AND LEARNING

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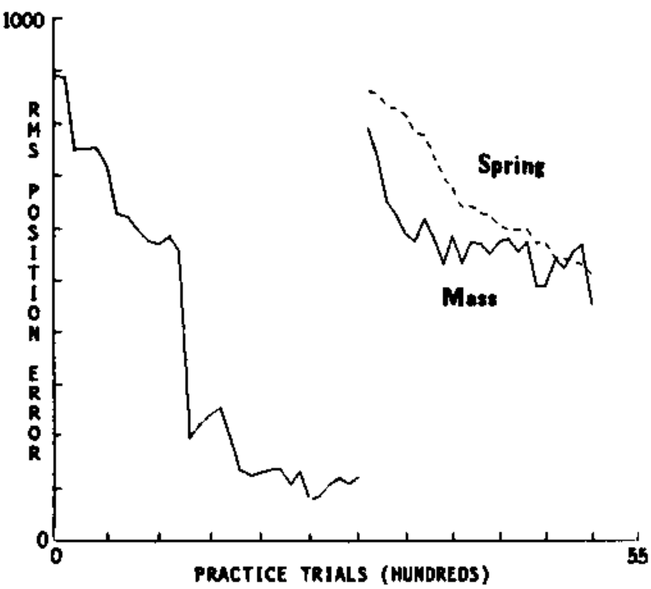
The human motor system acquires control of each limb in the body, adapts to mechanical and sensory changes, performs coordinate transformations from visual space to motor space, and uses limbs Interchangeably in executing motor programs. It is supposed that any flexible motor control system, biological or otherwise, can be viewed in terms of high- and low-level processes which accomplish these tasks; High-level processes generate descriptions of desired trajectories without considering the mechanical properties of any one effector system, and low-level mechanisms, tailored to the kinematic and dynamic properties of a particular effector system, translate these descriptions into motor plans. I propose a controller which uses an 'internal *inverse* dynamic model' to perform these low-level translations for a mechanical arm [Raibert 1976].

The translator employs a form of the equations of motion that allows a tabular representation of a manipulator's state dependent mechanical behavior. The table, actually a multi-dimensional memory organized by state variables, is supplied with data derived from the analysis of 'practice' movements. When a movement is practiced, accelerations and actuator torques are estimated and stored in a temporary buffer until analysis can be performed. During analysis sets of acceleration estimates, made while the manipulator was near a single state, are inverted in order to find *constants of mechanical description.* This procedure is quite simple and does not employ iterative error correction techniques, as do other learning schemes described in the literature [Albus 1975, Tsypkin 1971]. Since iterative methods are avoided problems involving local minima are not encountered. Once the analysis is performed, the resultant mechanical constants are stored in the state-space memory in weighted combination with previously stored data.

When presented with explicit descriptions of desired trajectories, the translator uses the tabular equations of motion in conjunction with the state-space memory to produce motor plans. A controller that operates in this way should have a number of desireable properties:

1. The non-linear dynamic properties of the arm are controlled.
2. The quality of control improves with practice.
3. The controller adapts to mechanical changes.
4. Practice generalizes between similar movements.
5. Trajectories may be specified in any one of a variety of coordinate systems.

Three Joints of the MIT-Scheinman arm, each powered by a DC torque motor and provided with position and velocity sensors, were used to implement the controller and assess its properties [Raibert 19771 Each Joint is completely backdrivable, allowing for the type of interactions that characterize the manipulator control problem. A PDP-11/45 was used to perform all information processing and real-time functions required by the model. To date I have demonstrated the controller's ability to acquire usable mechanical descriptions of the manipulator from practice data, to adapt to mechanical disturbances (inertial and elastic loads), and to generalize Information derived from the practice of one movement to the execution of other similar movements. (See Fig. 1.) Preliminary data also show that desired trajectories may be specified In any of a large class of coordinate systems, provided practice measurements are available in that system.



Fie. 1 These learning curves show the controller's ability to acquire new movements and adapt to mechanical disturbances. The initial learning (left) was produced by executing 3000 practice trials. After every block of 100 trials a test movement was made and the performance index, root mean square position error, was applied to the movements of all joints. After initial acquisition loads were applied to the manipulator (discontinuity). The two learning curves on the right show the system adapting to the new mechanical situations caused by attaching: a) a weight to the third link of the arm, b) a spring from link 2 of the arm to ground. See [Raibert 1977] for more details.

References

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