LEARNING MOTOR CONTROL OF REDUNDANT SYSTEMS

RESEARCH THESIS

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Abstract

The biological motor control system is an adaptive system exhibiting a vast redundancy at all its hierarchical levels. The main asset of redundancy is the ability to perform the same task in more than one way. Redundancy improves reliability and flexibility and it might be the salient reason for the superb dexterity of human motor control. However, introducing redundancy in an inversely controlled object results in an ill-posed problem, a problem that is obviously solved by the biological system.

Most previous research addressed this issue using a pseudo-inverse or other related criterion to find a single solution. The recent progress in computer technology, and in the field of neurocomputation, enables us to consider an architecture that finds and retains all the solutions, and chooses one of them in real time according to criteria that might be altered under different circumstances. This topic involves many new problems in control and learning theory. In this thesis, we describe a general model for redundancy control. This model includes single solution selection by the dynamics of the mechanical system at the lower level, and multiple controller at the higher level.

The lower level of the general model suggests that the dynamics of the joints, the muscles and the spinal cord has a major role in simplifying the control strategy that is needed in order to produce the typical behavior. Therefore, in this level the dynamics determine the single solution. We explain this idea with various examples from the literature and perform simulations of two mechanical models that demonstrate the role of the non-linear properties of the muscles in producing stereotypical features of rapid movements. The first model is a Hill type mechanical model of the muscle. We show that the nonlinear properties are essential in order to produce the smooth bell-shaped speed profile with a simple rectangular excitation to the muscles. The second model is the one-fifth-power law model, which is a fractional-power-damping model of the

muscles and the spinal cord. We show that the well-observed relationships between the duration amplitude and peak velocity can be reproduced with a simple pulse and step control signal. These simulations demonstrate that in many cases there is no need for complex computation by the nervous system since the dynamics of the lower level facilitates a simple control strategy.

The higher level of the general model is based on the notion of a multiple controller. We suggest to learn all the possible solutions in a parametric representation that enables the selection of a specific solution in real time, and therefore enables the use of different solutions under different circumstances. We suggest a novel architecture as well as algorithms for many-to-one function approximation and inversion. We suggest learning a piecewise linear approximation by the Hinging Hyperplanes algorithm of Breiman, and then transforming the parameters to a mixture-of-experts architecture and inverting each expert separately in order to construct the multiple inverse controller. This architecture is a modified mixture-of-experts architecture named the Polyhedral Mixture of Linear Experts (PMLE). The PMLE is shown to be capable of approximating inverse functions and of serving as a multiple controller. We also justify our method of indirect learning with a rigorous comparison between direct and indirect learning methods of artificial neural networks for control. We further suggest an extension to the definitions of learning theory in order to include the case of one to many relations that is needed in analyzing the properties of any multiple controller learning algorithm.

This thesis provides a general model, as well as theoretical framework and analytical tools that could be useful for modeling, analyzing, and designing adaptive control of redundant systems. We hope that the tools and insights provided in this work will assist physiologists in modeling the biological motor control system, and engineers in exploiting the virtue of redundancy in artificial systems.

List of Abbreviations and Symbols

ANN	Artificial Neural Networks
APG	Adjustable Pattern Generator
ARMA	Auto Recursive Moving Average
BEI	Best Estimated Inverse
EM	Expectation Maximization
EMG	Electromyography
CNS	Central Nervous System
DDSS	Dynamics Determine Single Solution
EPH	Equilibrium Point Hypothesis
FNS	Functional Neuromuscular Stimulation
HFA	Hinge Finding Algorithm
HH	Hinging Hyperplanes
IBE	Inverse of the Best Estimation
IID	Independently Identically Distributed
LP	Linear Programming
LTI	Linear Time-Invariant
MC	Multiple Controller
ME	Mixture of Experts

MI	Multiple Inverse
MI-PMLE	Multiple Inverse – PMLE
MIMO	Multiple Inputs Multiple Outputs
MMSE	Minimum Mean Square Error
MSE	Mean Square Error
MTO	Many To One
OS	OverShoot
PMLE	Polyhedral Mixture of Linear Experts
QED	[Latin Quod Erat Demonstrandum] which was to be demonstrated
RSS	Residual Sum of Squares
SEM	Sample Error Minimization
STD	STandard Deviation
a	A parameter, or gain
$\hat{a}$	An estimation of the parameter
B	The viscosity
B_P	Parallel viscosity
β^+, β^-	The regression vector for each side of the hinge function
B^+, B^-	The matrix of all β^+ or β^- for a sum of hinge functions

C	The transfer function of the controller
Δ	The hinge location vector
$\tilde{\Delta}$	The hinge location vector without the first element.
D	A matrix of all Δ for a sum of hinge functions
$D(f)$	Discrepancy measure
$D^{MC}(f^{MI})$	Discrepancy measure for multiple controller
d	The duration of the pulse
E	Expectation operator
F	The transfer function of the feedback
F_m	Muscle Tension
F_0	Normalized force command
$F(x)$	The input/output function of a system
F_p^m	A class of functions from R^p to R^m
$\hat{f}(\ )$	An approximation function
$f_m(\ )$	An approximation that is based on *m* samples.
$f^*(\ )$	The best approximation function according with the MSE criterion.
$f^{MI}(\ )$	Multiple inverse relation

H	Heaviside function
$h(x)$	Hinge function
INV	The inverse function approximation ability
K	The stiffness
K_s	Serial stiffness
ξ	Damping coefficient
M	Mass
n_i	Neural input
p	The regulation parameter that specifies one of the many solutions
P	The regularization domain space, or the transfer function of the Plant, or internal force in the muscle.
p_i	Poles
W, w	Weight, a learned parameter of an ANN
w_n	Natural frequency
S	A set of possible control signals
S_H^K	Sensitivity of the system H to changes in the parameter k
T	The sampling interval
T_o	Hypothetical tension in the muscle

T_t	The duration of the movement
$t_{\max}$	Time to reach the maximal amplitude
Θ	The vector of the gate parameters (in chapter 2, a group of functions)
U, u	The control command
V	The maximum velocity
X	The input domain or length of the muscle
x	The vector of inputs augmented by the unit element, or the control command from the domain X
$\tilde{x}$	The vector x without the first element.
x_{eq}	The control command to the joint, the equilibrium position
X_p	The height of the pulse
X_s	The height of the step
X_t	The final position of the joint
Y	The output domain, or the output vector
Y_d, y_d	The desired output
z	Zeros
Z	Z transform operation

Chapter 1

Introduction

This chapter describes the motivation for the study of human motor control and introduces the subject of this thesis. The main problem and thesis are stated, the organization of this dissertation is outlined and illustrated, and the contribution of each chapter is briefly specified.

1.1. The Motivation

This dissertation is about a study of the biological motor control system that is performed by building a model of its operation, and examining the properties of this model with analytical tools as well as numerical simulations.

Three different reasons motivate the study of human motor control: the patient, the robot and the brain: (i) Crippled and paralyzed patients can improve their quality of life by artificial limbs or with external stimulation of their muscles. In order to design these aids, one needs a model of the biological motor control system. (ii) Robots are inferior to people and animals in many aspects. One of the promising directions of improving our technology is by imitating nature and learning from its ingenious solutions. (iii) The main outputs of the nervous system are the muscles, and motor control is the salient evolutionary drive for the development of the brain. Therefore, the act of modeling and understanding the motor control system can be symbolized as polishing the window to the secrets of the brain.

Two salient features of the biological system are adaptation and redundancy. The quality of adaptation allows us to develop the optimal behavior and to be able to respond to changes in the environment and in ourselves. A child has to learn how to move and how to perform simple and complex motor skills. Children and adults have a superb ability to learn new motor tasks and to adapt to changes in the environment and in their own body. Adaptation in the wide sense is one of the most important characteristics of all living things (see Holland 1995)

The quality of redundancy improves our flexibility and reliability. We have excess resources in many parts of our body, and this property allows us to perform the same task in many different possible ways. The Russian physiologist Bernstein considered redundancy as the most remarkable feature of the biological system (see Bernstein 1967, and Latash and Turvey 1996)

Therefore, as the name of this dissertation implies, we suggest a model for learning motor control of redundant systems. We describe its relation to the biological system and supply analytical tools and a theoretical framework to analyze it and examine its performance.

1.2. The Main Problem and the Main Thesis

The general question is how the biological motor control system learns to master many possible solutions and how it chooses a single solution for the specific execution of a given motor task. We address some aspects of this question in this work and in order to describe them properly we have to narrow the scope of the problem.

We concentrate on open loop feed-forward control. This view is justified for rapid movements where there is no time for effective use of the sensory information due to the large delays in the biological system.

In this setup, we examine two different approaches to the problem. The first puts the emphasis on the dynamic properties of the muscles and the spinal cord, and the second approach emphasizes the higher nervous system and computational methods to learn the control commands. We suggest that there is no contradiction between these approaches since we locate them in different places in the motor control hierarchy.

We address the properties of the lower level dynamics and their role in simplifying the control that is needed at the higher level. We then suggest an algorithm to learn all the possible control commands for redundant systems, and an architecture that can represent these control commands in a parametric fashion that allows using and switching between different solutions in real time.

We use engineering and mathematical tools in order to develop a model of the biological system. In this combination we aim to contribute to both disciplines: to the biological motor control research by introducing rigorous definitions and analyzable models, and to control engineering by new ideas of using the system dynamics and exploiting the redundancy.

1.3. Outline of this Dissertation

The rest of this dissertation is organized as follows (see also Figure 1): Chapter 2 is a general description of the human motor control system from both biological and engineering points of view. Chapter 3 describes the problem and the general architecture that is suggested in order to learn to control redundant systems. It includes the description of the hierarchy in learning and adaptation and the formal definition of redundancy. Chapter 4 describes the lower level of the general model. The idea that the dynamics determine single solution is explained and two models are simulated in order to describe and demonstrate the possible role of the nonlinear properties of the muscles dynamic model in simplifying the control strategy. Chapter 5 describes the notion of multiple controller and the suggested architecture, the polyhedral mixture of linear experts. Chapter 6 discusses some problems in learning from examples. Some notions of learning theory are extended to the case of approximating one-to-many relations and the difference between direct and indirect methods to learn an inverse controller is analyzed. Finally, Chapter 7 contains a discussion and conclusion of this thesis and some suggestions for future research.

1.4. Thesis Contribution

We focus our attention on the virtue of redundancy and suggest a general model and a theoretical framework for learning motor control of redundant systems. This contribution might be useful for the biological motor control community as well as for the control engineering and the computational learning theory communities.

Chapter 2 reviews the current state of the art in the field of human motor control, biological and artificial. Parts of this chapter appear in Karniel and Inbar (2000)

Chapter 3 introduces the general model and this is its main contribution. It also contains a unique definition of redundancy and redundancy types from a functional point of view and a special perspective on learning and adaptation. Parts of this chapter appear in Karniel and Inbar (2000) and in Karniel et al. (1999)

Chapter 4 describes two simulations. The models were already presented in the literature. The novelty in this chapter is in demonstrating that these biologically plausible models can explain some well-observed properties of rapid human movements with a simple control scheme. The first simulation work was presented in my M.Sc. thesis, see Karniel (1996) and Karniel and Inbar (1997); it is brought here as an additional example. It is the first time that the stereotypical relationships between the parameters of rapid movements are shown to be reproducible by a simple biologically plausible mechanical model, the one-fifth-power law. Parts of this chapter appear in Karniel and Inbar (1999a)

Chapter 5 introduces a new architecture and algorithms for many-to-one function approximation and inversion. There are some minor improvements in the description and implementation of the hinging hyperplanes algorithm of Breiman (1993). An algorithm is developed to transform the parameters of the hinging hyperplanes to the PMLE parameters. The main contribution of this chapter is in the PMLE architecture and in the description and proof of its properties. Parts of this chapter appear in Karniel et al. (1998), and in Karniel et al. (1999).

Chapter 6 contributes in two directions. It provides some extensions to the field of learning theory by defining an error measure for one-to-many “function” approximation and by showing some basic bounds. It also rigorously shows the difference between two methods for learning inverse model for control. This observation is important in order to use the best method for control purposes and avoid errors in the estimation. Parts of this chapter appear in Karniel et al. (1999).

Chapter 7 discusses the issues of this dissertation with many references to related work and suggestions of some prospective direction for future research.

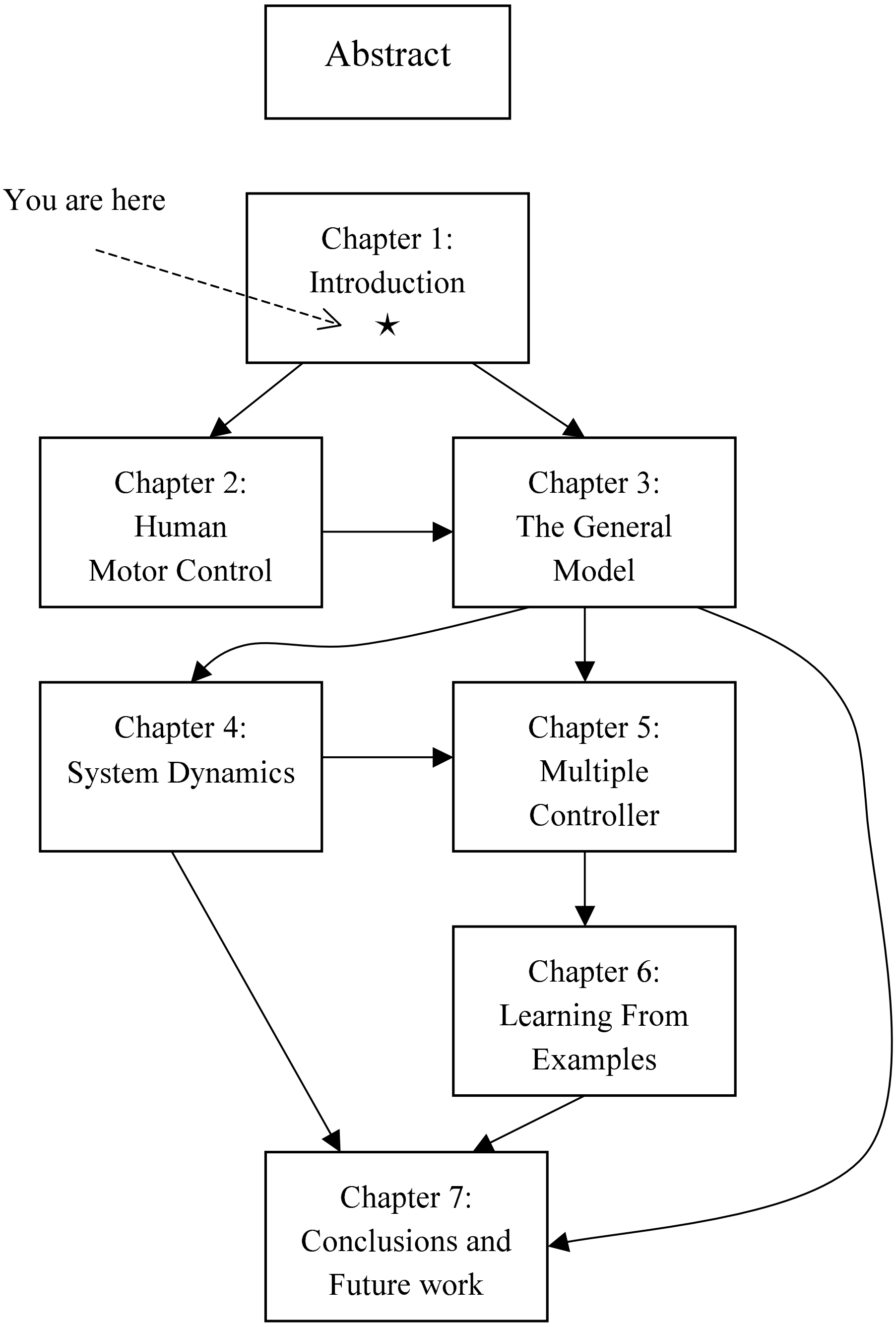

Figure 1: The Structure of this dissertation. The arrows represent possible sequences of reading.