

Contents

1	Introduction and Motivation	1
1.1	How to Learn Motor Skills?	2
1.2	The Robotics Viewpoint	4
1.3	From the View of Cognitive Science	5
1.4	Requirements for Plausible and Feasible Models	6
1.5	Scope and Structure	7
I	Background	9
2	Introduction to Function Approximation and Regression	11
2.1	Problem Statement	11
2.2	Measuring Quality	12
2.3	Function Fitting or Parametric Regression	13
2.3.1	Linear Models with Ordinary Least Squares	13
2.3.2	Online Approximation with Recursive Least Squares	15
2.4	Non-Parametric Regression	17
2.4.1	Interpolation and Extrapolation	17
2.4.2	Gaussian Process Regression	19
2.4.3	Artificial Neural Networks	20
2.5	Local Learning Algorithms	24
2.5.1	Locally Weighted Projection Regression	25
2.5.2	XCSF – a Learning Classifier System	26
2.6	Discussion: Applicability and Plausibility	26
3	Elementary Features of Local Learning Algorithms	29
3.1	Clustering via Kernels	30
3.1.1	Spherical and Ellipsoidal Kernels	32
3.1.2	Alternative Shapes	34
3.2	Local Models	35
3.3	Inference as a Weighted Sum	36
3.4	Interaction of Kernel, Local Models, and Weighting Strategies	37

4	Algorithmic Description of XCSF	41
4.1	General Workflow	41
4.2	Matching, Covering, and Weighted Prediction	43
4.3	Local Model Adaptation	43
4.4	Global Structure Evolution	45
4.4.1	Uniform Crossover and Mutation	47
4.4.2	Adding new Receptive Fields and Deletion	48
4.4.3	Summary	48
4.5	Relevant Extensions to XCSF	50
4.5.1	Subsumption	50
4.5.2	Condensation and Compaction	52
II	Analysis and Enhancements of XCSF	55
5	How and Why XCSF works	57
5.1	XCSF's Objectives	57
5.2	Accuracy versus Generality	58
5.3	Coverage and Overlap	59
5.4	Three Phases to Meet the Objectives	60
6	Evolutionary Challenges for XCSF	63
6.1	Resource Management and Scalability	64
6.1.1	A Simple Scenario	64
6.1.2	Scalability Theory	66
6.1.3	Discussion	67
6.1.4	Empirical Validation	68
6.1.5	Structure Alignment Reduces Problem Complexity	69
6.1.6	Summary and Conclusion	71
6.2	Guided Mutation to Reduce Learning Time	72
6.2.1	Guiding the Mutation	73
6.2.2	Experimental Validation	77
6.2.3	Experiment 2: A 10D Sine Wave	79
6.2.4	What is the Optimal Guidance Probability?	81
6.2.5	Summary and Conclusion	82
III	Control Applications in Robotics	85
7	Basics of Kinematic Robot Control	87
7.1	Task Space and Forward Kinematics	88

7.2	Redundancy and Singularities	90
7.2.1	Singularities	91
7.3	Smooth Inverse Kinematics and the Nullspace	92
7.3.1	Singular Value Decomposition	93
7.3.2	Pseudoinverse and Damped Least Squares	94
7.3.3	Redundancy and the Jacobian's Nullspace	96
7.4	A Simple Directional Control Loop	98
8	Learning Directional Control of an Anthropomorphic Arm	101
8.1	Learning Velocity Kinematics	102
8.1.1	Learning on Trajectories	104
8.1.2	Joint Limits	105
8.2	Complete Learning and Control Framework	105
8.3	Simulation and Tasks	107
8.3.1	Target Generation	107
8.4	Evaluating Model Performance	108
8.5	Experiments	110
8.5.1	Linear Regression for Control	111
8.5.2	RBFN	114
8.5.3	XCSF	115
8.5.4	LWPR	117
8.5.5	Exploiting Redundancy: Secondary Constraints	118
8.5.6	Representational Independence	119
8.6	Summary and Conclusion	122
9	Visual Servoing for the iCub	125
9.1	Vision Defines the Task Space	125
9.1.1	Reprojection with Stereo Cameras	127
9.2	Learning to Control Arm and Head	130
9.3	Experimental Validation	131
10	Summary and Conclusion	137
10.1	Function Approximation in the Brain?	137
10.2	Computational Demand of Neural Network Approximation	138
10.3	Learning Motor Skills for Control	139
10.3.1	Retrospective: Is it Cognitive and Plausible?	141
10.3.2	On Optimization and Inverse Control	142
10.4	Outlook	142
	Bibliography	145
A	A one-dimensional Toy Problem for Regression	155