

# Contents

<b>Introduction</b>	<b>1</b>
Motivation . . . . .	1
Ansatz/Model (brief) . . . . .	3
Related Work . . . . .	3
Outline . . . . .	3
 <b>I   A baseline behavior library of evolved gait controllers</b>	 <b>4</b>
<b>1   Control Architecture</b>	<b>5</b>
1.1   Dynamical Systems . . . . .	6
1.2   Control Basics . . . . .	9
1.2.1   Proportional-Integral-Derivative Controller . . . . .	11
1.2.2   Non-linear extensions to PID control . . . . .	13
1.3   Cognitive Sensorimotor Loops . . . . .	14
1.4   Advanced Non-linear Controllers for Multi-Joint Robots . . . . .	21
1.4.1   Sensor and Motor Space Definition . . . . .	22
1.4.2   Generalized Non-linear Controller . . . . .	24
1.4.3   A simple bipedal gait pattern . . . . .	29
1.4.4   Reducing the number of weights . . . . .	31
 <b>2   Simulated Environment and Robots</b>	 <b>35</b>
2.1   Simloid . . . . .	35
2.2   Robot model . . . . .	37
2.2.1   Body Model . . . . .	37
2.2.2   Joint Model . . . . .	38
2.2.3   Angle and Velocity Sensor Models . . . . .	38
2.2.4   Acceleration Sensor Model . . . . .	38
2.2.5   Electromechanical Motor Model . . . . .	39
2.3   Joint Friction Model . . . . .	41
2.3.1   Friction Models . . . . .	42
2.3.2   The BRUSH Friction Model . . . . .	44
2.4   Simulated Robots . . . . .	47
2.4.1   Pendulum . . . . .	50
2.4.2   Crawler . . . . .	51
2.4.3   Tadpole . . . . .	51
2.4.4   Quadruped . . . . .	52

## Contents

2.4.5	Humanoid . . . . .	53
2.4.6	How to handle undesired terminal states . . . . .	55
2.5	Scenarios for increasing the robustness of walking . . . . .	55
<b>3</b>	<b>A Baseline Behavior Library</b>	<b>59</b>
3.1	Artificial Evolution—Terms and Principles . . . . .	59
3.2	The gait controller as subject to evolution . . . . .	64
3.2.1	Initial Values for starting Populations . . . . .	64
3.2.2	Symmetry Assumption . . . . .	65
3.3	Fitness Functions for Legged Robots . . . . .	66
3.3.1	Running fast . . . . .	66
3.3.2	Constraints . . . . .	67
3.3.3	Walking efficiently . . . . .	68
3.3.4	Slowing Down and Stopping . . . . .	68
3.3.5	Seeds . . . . .	69
3.4	Proposal for a simple Generation-free Algorithm . . . . .	70
3.5	Experiments and Results . . . . .	71
3.5.1	Crawling . . . . .	72
3.5.2	Walking . . . . .	72
3.5.3	Running . . . . .	73
3.5.4	Starting and Stopping . . . . .	73
3.5.5	Directional Locomotion . . . . .	74
3.5.6	Walking under Disturbances . . . . .	75
3.5.7	Operators and Hyper-Parameters . . . . .	76
3.6	Behavior Library Overview . . . . .	77
	<b>Summary of Part One</b>	<b>82</b>
<b>II</b>	<b>Hannah—An open-source fourlegged robotic platform for research and development</b>	<b>84</b>
<b>4</b>	<b>Mechanical Design</b>	<b>86</b>
4.1	Introducing Hannah . . . . .	86
4.2	Free/Libre Open-Source Hardware Designs . . . . .	88
4.3	Low-cost, Lightweight, and Highly Available Parts . . . . .	90
4.4	Reusability and Generalization . . . . .	91
4.5	Fast-Prototyping, Manufacturing, and Materials . . . . .	92
4.6	Legs and Drives . . . . .	94
4.6.1	Tooth Belt Transmission . . . . .	94
4.6.2	Leg Assembly Concept . . . . .	96
4.6.3	Knee Joints, Lower Legs, and Feet . . . . .	98
4.7	Torso base structure . . . . .	98
4.8	Shells . . . . .	100

<b>5</b>	<b>Electronics, Communication and Control</b>	<b>103</b>
5.1	Architecture Summary . . . . .	103
5.2	Requirements for Robotic Drives . . . . .	104
5.3	Sensorimotor . . . . .	106
5.3.1	Overvoltage and Constant Voltage Operation . . . . .	107
5.3.2	Additional Sensors . . . . .	108
5.4	Limb Controller . . . . .	111
5.4.1	Bus System . . . . .	111
5.4.2	Spinal Cord Communication . . . . .	113
5.4.3	Motor Cord Communication . . . . .	114
5.4.4	Power Supply Management . . . . .	114
5.4.5	Application Interface . . . . .	115
5.4.6	Diagnostics Interface . . . . .	117
<b>6</b>	<b>Bridging the Reality Gap</b>	<b>118</b>
6.1	A Simulation Model for the Hannah Robot . . . . .	120
6.1.1	Sensor Model Parameters . . . . .	120
6.1.2	Motor Model Parameters . . . . .	121
6.2	Evolving Gaits for Hannah . . . . .	122
6.3	Domain Randomization . . . . .	122
6.4	Testing Simulation Results on Hardware . . . . .	124
<b>III</b>	<b>Proposal of an architecture for unsupervised robot locomotion learning</b>	<b>126</b>
<b>7</b>	<b>Model and Hypotheses</b>	<b>127</b>
7.1	A General View on Sensorimotor Flow . . . . .	127
7.2	A Model for Self-Supervised Sensorimotor Learning . . . . .	129
7.3	Hypotheses . . . . .	129
<b>8</b>	<b>Methods</b>	<b>130</b>
8.1	Supervised Learning . . . . .	130
8.1.1	Stochastic Gradient Descent . . . . .	131
8.1.2	Backpropagation . . . . .	131
8.1.3	Adam . . . . .	133
8.2	Unsupervised Learning . . . . .	134
8.2.1	Autoencoder Neural Networks . . . . .	136
8.2.2	Self-Organizing and Growing Networks . . . . .	138
8.2.3	Growing Neural Gas . . . . .	139
8.2.4	Homeokinesis . . . . .	140
8.3	Reinforcement Learning . . . . .	144
8.3.1	State-Action Value Function Learning . . . . .	147
8.3.2	Boltzmann-Softargmax Action Selection . . . . .	149
8.3.3	Episodic vs. Continuous Learning . . . . .	152

## Contents

8.3.4	Reward Functions for Walking Robots . . . . .	153
8.3.5	Learning Everything Simultaneously . . . . .	155
8.4	Intrinsic Motivation . . . . .	156
<b>9</b>	<b>Implementation of a Self-Supervised Sensorimotor Learning Agent</b>	<b>161</b>
9.1	A Growing Multi-Expert Structure . . . . .	161
9.1.1	GMES Algorithm . . . . .	163
9.2	Implementation of the Model . . . . .	170
9.2.1	Self-Organizing State and Behavior Spaces . . . . .	170
9.2.2	The intrinsically motivated learner . . . . .	170
<b>10</b>	<b>Experiments and Results</b>	<b>173</b>
10.1	Tadpole all directions . . . . .	173
10.2	Hannah forwards . . . . .	173
10.3	Summary, Conclusions, and Outlook . . . . .	173
	<b>Bibliography</b>	<b>174</b>