

Contents

1	Introduction	1
1.1	Behavior-Based Robotics	2
1.2	Meaningful Feedback	3
1.3	Immediate Connection and Meaningful Feedback: Live Programming	3
1.4	Problem Statement	4
1.5	Goals & Hypotheses	6
1.6	Results	8
1.6.1	Research Question 1: VizRob	8
1.6.2	Research Question 2 & Testing Hypothesis 1: Live RobotProgramming	8
1.6.3	Research Question 3 & Testing Hypothesis 2: Controlled Experiments	8
1.7	Contributions	9
1.8	Associated Publications	9
1.9	Dissertation Outline	10
2	Behavior-Based Robotics	11
2.1	Introduction to Robotics: Sense, Plan, Act	11
2.2	What is Behavior-Based Robotics?	13
2.3	Expressing Behaviors: Nested State Machines	14
2.3.1	General State Machine Concepts	15
2.3.2	Nested Machines	16
2.3.3	Concurrency	17
2.3.4	State Machines vs Statecharts	18
2.4	Conclusions	19
3	Programming Robotic Behaviors	20
3.1	Programming Robots using ROS	20
3.1.1	Programs in ROS: Nodes & Topics	21
3.1.2	Systems in ROS: Packages	22
3.1.3	Services and Parameters	22
3.2	Programming Behaviors in ROS: SMACH	22
3.2.1	SMACH Core	23
3.2.2	SMACH and ROS	24
3.2.3	Visualization	24
3.3	More Behavior-Based Tools	25
4	Meaningful Feedback: VizRob	28

4.1	Current Debugging Practices and Research Questions	29
4.1.1	Looking at common logging and debugging problems	29
4.1.2	Research Questions	30
4.2	Current Tools to Debug Robotic Programs	31
4.2.1	Log Listings	31
4.2.2	Nested State Machine Visualizations	31
4.2.3	Augmented Reality	32
4.3	VizRob	32
4.3.1	Common Features	32
4.3.2	Types of Logs	33
4.3.3	Error Logs	34
4.3.4	Frequency	34
4.3.5	Logs Listing	35
4.3.6	Navigation	36
4.4	VizRob Design Notes	37
4.5	Initial Feedback: Case Study	38
4.5.1	Robotic Behaviors	38
4.5.2	Problems found	39
4.5.3	VizRob vs participants' debugging tool	40
4.5.4	Use of VizRob	41
4.6	Answering our Research Questions	41
4.7	Threats to Validity	42
4.8	Conclusions	43
5	Live Programming	44
5.1	Overview	44
5.2	Characterization	46
5.2.1	Level of Liveness	46
5.2.2	Immediate and Meaningful Feedback	47
5.2.3	Related Concepts	48
5.3	Live Programming in Robotics	48
5.3.1	Immediate Connection	49
5.3.2	Meaningful Feedback	49
5.4	Live Programming Languages	50
5.4.1	General Live Programming Languages	50
5.4.2	Robotics and State Machines Live Programming Languages	51
5.5	Conclusions	52
6	Live Programming in Robotic Behaviors: LRP	53
6.1	The LRP Language	54
6.1.1	Language Design	56
6.1.2	LRP By Example	59
6.2	Using LRP: Live Programming of the Looking Behavior	63
6.3	The LRP Interpreter	64
6.3.1	Executing a Program: The Main Loop	64
6.3.2	Variables, Scope and Blocks of Code	66
6.3.3	Concurrence	68

6.3.4	A Note on Performance	68
6.4	How the LRP Interpreter Enables Live Programming	69
6.4.1	Dealing with Program Changes	70
6.4.2	Dealing with Program Errors	71
6.4.3	Pausing the Interpreter	72
6.4.4	Forcing States	72
6.4.5	Live Programming and the UI	73
6.5	Bridging LRP To Robot APIs	74
6.5.1	Bridging LRP to PhaROS	74
6.5.2	Bridging LRP to JetStorm	77
6.5.3	Building a Custom Bridge	79
6.6	Conclusions	79
7	LRP in Practice: a Controlled Experiment	81
7.1	Overall Experimental Design	82
7.1.1	Goals	82
7.1.2	Dependent and Independent Variables	83
7.1.3	Baseline	83
7.1.4	Experiment Design	83
7.1.5	Participants	84
7.1.6	Task Setup	84
7.1.7	Work Session	84
7.2	Controlled Experiment: Program Comprehension	85
7.2.1	Goal	85
7.2.2	Experiment Design	86
7.2.3	Pilot Study	88
7.2.4	On Reducing Biases	88
7.2.5	Work Sessions	89
7.2.6	Warm-up Phase	89
7.2.7	Evaluation phase	90
7.2.8	Results	91
7.2.9	Observations on Subject Behavior	94
7.2.10	Conclusions on Program Comprehension	95
7.3	Controlled Experiment: Program Writing	95
7.3.1	Goal	95
7.3.2	Tasks to Evaluate	96
7.3.3	Pilot Study	96
7.3.4	On Reducing Bias	97
7.3.5	Work Sessions	98
7.3.6	Warm-up phase	99
7.3.7	Evaluation phase	99
7.3.8	Results	100
7.3.9	Observations on Subject Behavior	104
7.3.10	Conclusions on Program Writing	105
7.4	Discussion	105
7.4.1	Why should LRP perform better?	106
7.4.2	Why does LRP NOT perform better?	106

7.4.3	How to improve our experiments?	108
7.5	Threats to Validity	108
7.6	Related Work: Live Programming Experiments	110
7.7	Conclusions	111
8	Conclusions	113
8.1	Contributions	113
8.1.1	VizRob	114
8.1.2	LRP	114
8.1.3	Research Questions & Hypotheses	115
8.2	Why Meaningful Feedback Matters When Building Robotic Behaviors	116
8.3	Why Live Programming Matters in Robotic Behaviors	117
8.4	Why LRP Does Not Improve Robotic Behavior Development	117
8.5	Future Work	118
8.5.1	VizRob	118
8.5.2	LRP	119
8.5.3	LRP Validation	119
8.6	Final Remarks	120
	Bibliography	121