

CONTENTS

1	INTRODUCTION	1
2	RELATED WORK	5
2.1	Analytic Bipedal Walking	5
2.2	Learned Bipedal Walking	8
3	THE ROBOTS	11
4	OVERVIEW	17
5	PRINCIPLES OF BIPEDAL WALKING	19
6	STEP MOTION GENERATOR	23
6.1	The Layers of the Motion Generator	25
6.2	Abstract Kinematic Interface	26
6.3	Motion Pattern	29
6.3.1	Halt Position	30
6.3.2	Leg Lifting	31
6.3.3	Leg Swing	31
6.3.4	Lateral Hip Swing	33
6.3.5	Leaning	33
6.3.6	Complete Leg Pattern	34
6.3.7	Arm Motion	35
6.3.8	Compliant Actuation	35
6.4	Control Interface	38
6.4.1	Step Size Conversion	38
6.4.2	Step Timing	42
6.5	Experiments	43
6.5.1	Video Demonstration	43
6.5.2	Center of Mass and Compliant Actuation	44
6.5.3	Stability Analysis	44
6.6	Discussion	48
7	STATE ESTIMATION	51
7.1	Trunk Attitude Estimation	52
7.2	Tilted Whole-Body Pose Reconstruction	53
7.3	Center of Mass State Estimation	55
7.4	Support Foot Estimation	55
7.5	Experiments	56
7.5.1	Trunk Attitude Estimation	56
7.5.2	Center of Mass State Estimation	57
7.6	Discussion	59

8	ANALYTIC FOOTSTEP CONTROL	61
8.1	The Linear Inverted Pendulum Model	63
8.1.1	One-dimensional Model	63
8.1.2	Two-dimensional Model	65
8.2	Predictive Filter	66
8.3	Reference Trajectory Generation	71
8.4	Balance Control	74
8.4.1	Lateral Zero Moment Point Offset	75
8.4.2	Step Time	76
8.4.3	Sagittal Zero Moment Point Offset	78
8.4.4	Footstep Location	79
8.5	Experiments	82
8.5.1	Walk and Push	82
8.5.2	Technology Demonstration	83
8.5.3	Push Recovery	84
8.6	Discussion	87
9	LEARNED FOOTSTEP CONTROL	89
9.1	Machine Learning Framework	91
9.2	Learning the Sagittal Step Size	93
9.3	Experiments	95
9.3.1	Evaluation of Reference Tracking	96
9.3.2	Evaluation of Disturbance Rejection	97
9.3.3	Evaluation of Stability	98
9.3.4	Push Recovery Learning with a real Robot	99
9.4	Discussion	102
10	CONCLUSION	105
	BIBLIOGRAPHY	109