Contents

Agraïments v

Resum vii

Resumen ix

Abstract xi

1 Introduction 1
Motivations . . . 2
Thesis Outline . . . 2

2 State of the Art 7
2.1 Robot visual servoing . . . 8
2.1.1 Basic notation . . . 8
2.1.2 Kinematics . . . 8
2.1.3 Classical continuous control laws . . . 9
2.1.4 Robot-camera configurations . . . 10
2.1.5 Visual servoing schemes . . . 12
2.1.5.1 Position Based Visual Servoing . . . 13
2.1.5.2 Image Based Visual Servoing . . . 15
2.1.5.3 PBVS-IBVS comparison . . . 15
2.1.5.4 VS schemes combining PBVS and IBVS . . . 17
2.1.6 Constraints in visual servoing . . . 17
2.1.7 Robot control . . . 17
2.1.8 Computer vision algorithm . . . 18

2.2 Sliding mode control 18
2.3 Task-priority based redundancy resolution 19
2.3.1 Regularization 21

3 Geometric invariance using sliding mode control 23
3.1 Conventional sliding mode 25
3.1.1 Using matrix inversion 26
3.1.2 Higher-order invariance 26
3.1.3 Order of the control action 27
3.1.4 Proof of condition Eq. (3.5) 28
3.2 One-side sliding mode 29
3.2.1 Proof of condition Eq. (3.20) 31

4 Fulfillment of constraints in VS using SM control 33
4.1 Introduction 33
4.2 Preliminaries 39
4.3 Proposed approach 40
4.3.1 System tasks 40
4.3.2 Lie derivatives 41
4.3.3 Level 1: robot constraints 42
4.3.3.1 Visibility constraints 42
4.3.3.2 Constraints for the joint range limits 45
4.3.3.3 Constraints for the maximum joint speeds . . . 45
4.3.3.4 Workspace constraints: object collision avoidance, task space limits and robot workspace limits 46
4.3.3.5 Acceleration equality for Level 1 47
4.3.3.6 Gradient vectors for Level 1 48
4.3.4 Level 2: reference tracking 49
4.3.4.1 Adaptive gain for the kinematic controller . . . 50
4.3.4.2 Visual features and Jacobian matrix for PBVS 50
4.3.4.3 Visual features and Jacobian matrix for IBVS 50
4.3.5 Chattering 51
4.3.6 Additional remarks 51
4.3.6.1 Guidelines for the paramaters design 51
4.3.6.2 Moving constraints 52

4.3.6.3 Time derivatives 53
4.3.7 Computer Implementation 53
4.4 Simulation 2D PBVS: first example 55
4.4.1 Potential Field-Based Method 56
4.4.2 Simulation conditions and parameter values 57
4.4.3 Simulation results 58
4.5 Simulation 3D PBVS: case study 61
4.5.1 Simulation conditions and parameter values 62
4.5.2 Simulation results 64
4.6 Simulation 3D IBVS: case study 69
4.6.1 Simulation conditions and parameter values 70
4.6.2 Simulation results 72
4.7 Experiments: visibility constraints in PBVS and IBVS 73
4.7.1 Experimental conditions and parameter values 78
4.7.2 Experimental results 80
4.8 Experiment: workspace constraints in IBVS 86
4.8.1 Experiment conditions and parameter values 86
4.8.2 Experimental results 88
4.9 Conclusions 92

5 High-Order SM Control for Reference Tracking in VS 95
5.1 Introduction 95
5.2 Preliminaries 98
5.3 Proposed approach 99
5.3.1 Sliding mode control for reference tracking 99
5.3.1.1 Procedure to use sliding mode control 99
5.3.1.2 Sliding mode control using joint velocities . . . 100
5.3.1.3 Sliding mode control using joint accelarations . 100
5.3.1.4 Sliding mode control using joint jerks 101
5.3.1.5 Additional remarks 102
5.3.2 Comparison with classical continuous control 103
5.3.2.1 Classical continuous control using joint velocities 103
5.3.2.2 Classical continuous control using joint accelarations 103

5.3.2.3 Equivalences between sliding mode control and classical continuous control 104
5.4 Conditions for the simulations and experiments 104
5.5 Simulation: positioning task 105
5.5.1 Conditions for the simulated positioining task 105
5.5.2 Simulation results for the positining task 107
5.6 Simulation: tracking task 112
5.6.1 Conditions for the simulated tracking task 112
5.6.2 Simulation results for the tracking task 113
5.6.3 Robustness against errors 118
5.7 Experiments: positioning and tracking tasks 123
5.7.1 Experiment conditions and parameter values 124
5.7.2 Experimental results with no errors 125
5.7.3 Experimental robustness against errors 132
5.8 Conclusions 134

6 PWM and PFM for VS in fully decoupled approaches 137
6.1 Introduction 137
6.2 Preliminaries: Decoupling DOFs in Visual Servoing Approaches 140
6.2.1 Partitioned approach to IBVS control 140
6.2.2 Image moments for partially decoupled IBVS 141
6.2.3 Homography and epipolar geometry to decouple rotation from translation in IBVS 141
6.2.4 Hybrid visual servoing 142
6.2.5 Position Based Visual Servoing 143
6.3 Proposed approach 143
6.3.1 Errors weighting and gain tuning 144
6.3.2 PWM and PFM visual servoing 145
6.4 Results 147
6.5 Practical issues 154
6.6 Conclusions 155

7 Other results in VS applications 157
7.1 DR-NLHOH for VS Applications 158
7.2 On Improving Robot IBVS Based on DR-RFCS 161
7.3 The Complete Design of the ORCA300-AUV 164

8 Conclusions **169**
8.1 Main Results 171
8.2 Contributions 173
8.2.1 Articles published in journals 173
8.2.2 Articles submitted to journals 173
8.2.3 Articles published in conferences 174
8.3 Further work 175

A Experimental Platform **177**

References **185**