Contents

Agradecimientos	\mathbf{v}
Resum	vii
Resumen	ix
Abstract	xiii
1 Introduction	1
Motivations	2
Thesis Outline	3
2 State of the Art	5
2.1 Human Robot Interaction	5
2.1.1 Human Robot Cooperation	5
2.1.2 Assisted teleoperation	6
2.1.3 Augmented Reality-based Interfaces	8
2.2 Surface treatment	8
2.3 Bimanual robotics	9
2.4 Task optimization	10
2.5 Sliding Mode Control	11
2.5.1 Conventional SMC	11
2.5.2 Non-Conventional SMC	12
2.6 Computer vision	12
3 Theoretical Basis	15

xvi Contents

	3.1	Prelim	inaries	16
		3.1.1	Kinematics	16
		3.1.2	Task-priority based strategy	16
		3.1.3	Boundary model	17
	3.2	Sliding	g Mode Control	18
		3.2.1	Conventional SMC to satisfy equality constraints	18
		3.2.2	One-side SMC to satisfy inequality constraints	19
		3.2.3	Modified constraints	22
4			ssistance for industrial sanding with a smooth ap-	
			the surface and boundary constraints	23
	4.1		uction	23
		4.1.1		23
		4.1.2	State of the Art	24
			4.1.2.1 Robot tool	24
			4.1.2.2 Automatic mode of operation	24
			4.1.2.3 Human-robot Cooperation	25
			4.1.2.4 Computer vision	27
		4.1.3	Proposal	27
			4.1.3.1 Truly cooperative	27
			4.1.3.2 Camera network	29
			4.1.3.3 Smooth approach	30
			4.1.3.4 Boundary constraints	31
			4.1.3.5 Combination with automatic operation	31
	4.2	Propos	sed method	31
		4.2.1		31
		4.2.2	Level 1: Approach and boundary control	34
		4.2.3	Level 2: Orientation control	36
		4.2.4	Level 3: Modes of operation	37
			4.2.4.1 Manual operation	37
			4.2.4.2 Automatic operation	38
	4.3	Contro	ol algorithm	39
		4.3.1	Code of the control algorithm	39
		4.3.2	Design of the control algorithm parameters	41
	4.4	Experi	ments	42

CONTENTS xvii

		4.4.1	Experimental platform	42
		4.4.2	Values of the parameters	44
		4.4.3	Results	44
5			robot control using assisted teleoperation for sur-	
_			nent tasks	61
	5.1	Introd	uction	61
		5.1.1	Objective	61
		5.1.2	State of the Art.	62
			5.1.2.1 Assisted teleoperation in robotics	62
			5.1.2.2 Bimanual robotics	64
		5.1.3	Proposed approach	67
	5.2	Propos	sed approach	67
		5.2.1	System tasks	68
		5.2.2	Lie derivatives	71
		5.2.3	Boundary model	72
		5.2.4	Force model	72
		5.2.5	Control for the Workpiece robot	72
			5.2.5.1 Level 1: Boundary control	72
			5.2.5.2 Level 2: Orientation control	74
			5.2.5.3 Level 3: Teleoperation for the workpiece robot	75
			5.2.5.4 Level 4: Home configuration	75
		5.2.6	Control for the surface treatment robot	76
			5.2.6.1 Level 1: Boundary control	76
			5.2.6.2 Level 2: Treatment task constraints	78
			5.2.6.3 Level 3: Surface treatment tool teleoperation .	79
		5.2.7	Limitations of the proposed approach	80
	5.3	Contro	oller implementation	81
	5.4		xperimentation	83
		5.4.1	Setup	83
		5.4.2	Experiment conditions and parameter values	87
		5.4.3	Results	88
			5.4.3.1 Experiments for the WR control algorithm	89
			5.4.3.2 Experiments for the STR control algorithm	92
			5.4.3.3 Experiment for the bimanual application	106
			P	

xviii Contents

	5.5	Conclusions	118
6	AR-	-based interface for bimanual robot teleoperation	119
	6.1	Introduction	119
		6.1.1 Objective	119
		6.1.2 State of the Art	120
		6.1.2.1 Bimanual robotics	120
		6.1.2.2 Assisted robot teleoperation	120
		6.1.2.3 Augmented Reality-based Interfaces	121
		6.1.3 Proposed approach	122
	6.2	Previous work	123
		6.2.1 Description of the conventional PC-based interface	123
		6.2.2 Discussion of human-robots interaction using conven-	
		tional interfaces	126
	6.3	Proposed augmented reality-based user interface	126
	6.4	Results	132
	6.5	Conclusions	147
7	Con	clusions	149
	7.1	Main Results	149
	7.2	Contributions	151
	7.3	Further work	152
\mathbf{R}_{ℓ}	efere	nces	153

List of Figures

2.1	Graphical comparison between conventional SMC (left) and	
	one-side SMC (right).	11
3.1	Modified superellipse proposed in this work, which is composed	
	of a $2W \times 2(H-W)$ rectangle and two offseted halfs of an	T
	even-sided $2W \times 2W$ superellipse	18
4.1	Block diagram of the proposed method	32
4.1	Block diagram of the proposed method	32
4.2	Graphical illustration of the information obtained from the ma-	
	chine vision system.	33
4.0		
4.3	Experimental platform used for the real experimentation: a 6R	_
	robot arm, a F/T sensor, 3 RGB-D cameras , an industrial	
	sander and a car door.	43
4.4	Frames of the video of the first experiment.	45
4.5	Graphs for the approach constraint in the first experiment	47
1.0	Graphs for the approach constraint in the first experiment.	11
4.6	Tool orientation angles in the first experiment. From top to	
	bottom: roll, pitch and yaw angles. In the first two graphs: thin	
	line, reference values supplied by the machine vision system;	
	thick line, actual angle values.	48
-		
4.7	Trajectory followed by the robot end-effector in the first exper-	
	iment (triangle and circle symbols denote the initial and final	
	positions, respectively)	49

xx Figures

4.8 Control signals in the first experiment. From top to bottom:	
commanded accelerations computed by each control level; joint	
accelerations, velocities and positions to be sent to the robot	
controller. In the graphs, a different color is used for each robot	
joint, i.e., from the first to the sixth joint: blue, brown, yellow,	
magenta, green and cyan	51
4.9 Frames of the video of the second experiment	52
4.10 Boundary constraint in the second experiment: top graph, con-	
straint functions ϕ_b (dark-blue) and σ_b (light-cyan); bottom	
graph, activation of the boundary constraint.	53
4.11 Tool orientation angles in the second experiment: α , β and γ .	
In the first two graphs: thin line, reference values supplied by	
the machine vision system; thick line, actual angle values.	54
4.12 Tool guidance in the second experiment: tool velocities (mul-	
tiplied by \mathbf{C}_d) in light-cyan and forces of the human operator	
in dark-blue. From top to bottom: linear X , linear Y , linear Z	
and angular Z components of the vectors (all four components	
are relative to the tool coordinate system).	55
4.13 Trajectory of the tool position in the second experiment (tri-	
angle and circle symbols denote the initial and final positions,	
respectively) and mesh representing the boundary of the allowed	
area	57
4.14 Control signals in the second experiment. From top to bottom:	
commanded accelerations computed by each control level; joint	
accelerations, velocities and positions to be sent to the robot	
controller.	58
4.15 Frames of the third experiment recording.	59
5.1 Block diagram of the proposed control for the WR and STR.	70
5.2 Experimental setup. STR: a 6R serial manipulator with an F/T	
sensor, a tool consisting of a cylinder (blue) and a piece of cloth	
attached to it (black). WR: a 7R cobot serial manipulator with	
a methacrylate flat workpiece attached to its end-effector by	
means of a self developed adaptor (white).	86
5.3 Experiment 1. WR Level 1: Top, constraint functions σ_{w1}	
(thick dark-blue) and ϕ_{w1} (thin light-cyan) and constraint limit	
(dashed); and bottom, constraint activation.	90

FIGURES xxi

5.4	Experiment 1. 3D view (left) and top view (right) of the bound-	
	ary constraint of WR Level 1: allowed region (pink mesh);	
	actual position of the workpiece center (thick-blue line); and	
	reference position for the workpiece center (thin-red line)	91
5.5	Experiment 2. WR Level 2: Constraint functions $\sigma_{w2,i}$ (thick	
	dark-blue) and $\phi_{w2,i}$ (thin light-cyan) of the roll (α) , pitch	
	(β) and yaw (γ) angles of the workpiece and constraint limit	
	(dashed)	92
5.6	Experiment 2. Behavior of the restrictions of WR Level 2: an-	
	gular reference (thin-red), actual angular position (thick-blue)	
	of the workpiece and angular limits (dashed)	93
5.7	Experiment 3. STR Level 1: Top, constraint functions σ_{s1}	
	(thick dark-blue) and ϕ_{s1} (thin light-cyan) and constraint limit	
	(dashed); and bottom, constraint activation.	94
5.8	Experiment 3. Representation of the boundary constraint of	
	STR Level 1: allowed region (pink mesh); actual position of	
	the STR tool (thick-blue line); and reference position for the	
	STR tool (thin-red line). Coordinates relative to the workpiece	
	center.	95
5.9	Frames of the video of Experiment 3	97
5.10	Experiment 3. STR Level 2: constraint functions $\sigma_{s2,i}$ (thick	
	dark-blue) and $\phi_{s2,i}$ (light-cyan)	98
5.11	Frames of the video of Experiment 4	99
5.12	Experiment 4. STR Level 1: Top, constraint functions σ_{s1}	
-	(thick dark-blue) and ϕ_{s1} (thin light-cyan) and constraint limit	
	(dashed); and bottom, constraint activation.	100
5.13	Experiment 4. Representation of the boundary constraint of	
	STR Level 1: allowed region (pink mesh); and actual position	
	of the STR tool (thick-blue line). Note that there is no reference	
	position for the STR tool in this experiment, i.e., the STR tries	
	to keep the treatment tool still	101
		103
5.15	Experiment 5. Behavior of STR Level 2: measurements of the	
	F/T sensor in the linear Z-axis (top), angular X-axis (middle)	
	and angular Y -axis (bottom) of the STR end-effector frame.	
	The reference value for each signal is represented with a dashed	
	line	104

xxii Figures

5.16 Experiment 5. Behavior of the restrictions of STR Level 2: roll	
(top) and pitch (bottom) angles of the STR tool	104
5.17 Experiment 5. Representation of the boundary constraint of	
STR Level 1: allowed region (pink mesh); actual position of	
the STR tool (thick-blue line); and reference position for the	
STR tool (thin-red line). Coordinates relative to the workpiece	
center	105
5.18 Frames of the video of Experiment 6	107
5.19 Experiment 6. Behavior of STR Level 2: measurements of the	
F/T sensor in the linear Z-axis (top), angular X-axis (middle)	
and angular Y -axis (bottom) of the STR end-effector frame.	
The reference value for each signal is represented with a dashed	
line.	108
5.20 Experiment 6. Representation of the boundary constraint of	
STR Level 1: allowed region (pink mesh); actual position of	
the STR tool (thick-blue line); and reference position for the	
STR tool (thin-red line). Coordinates relative to the workpiece	
center	109
5.21 Frames of the video of Experiment 7	111
5.22 Experiment 7. Behavior of the restrictions of WR Level 2: an-	
gular reference (thin-red), actual angular position (thick-blue)	
of the workpiece and angular limits (dashed)	112
5.23 Experiment 7. Behavior of STR Level 2: measurements of the	
F/T sensor in the linear Z-axis (top), angular X-axis (middle)	
and angular Y -axis (bottom) of the STR end-effector frame.	
The reference value for each signal is represented with a dashed	
line.	113
5.24 Experiment 7. 3D view (left) and top view (right) of the bound-	
ary constraint of WR Level 1: allowed region (pink mesh);	
actual position of the workpiece center (thick-blue line); and	
reference position for the workpiece center (thin-red line)	114
5.25 Experiment 7. Representation of the boundary constraint of	
STR Level 1: allowed region (pink mesh); actual position of	
the STR tool (thick-blue line); and reference position for the	
STR tool (thin-red line). Coordinates relative to the workpiece	
center	115

FIGURES xxiii

5.26	Experiment 7. Commanded joint actions for the WR: contribu-	
	tion of each priority level to the commanded joint accelerations	
	in the first four plots, fifth plot represents commanded joint	
	accelerations, sixth plot represents commanded joint velocities	
	and seventh plot represents commanded joint positions	116
5.27	Experiment 7. Commanded joint actions for the STR: contribu-	
	tion of each priority level to the commanded joint accelerations	
	in the first three plots, fourth plot represents commanded joint	
	accelerations, fifth plot represents commanded joint velocities	
	and seventh plot represents commanded joint positions	117
6.1	Bimanual application setup and block diagram (for further de-	
	tails, refer to Chapter 5).	124
6.2	Conventional PC-based user interface: visual references and ef-	
	fects.	125
6.3	New setup used for the real experimentation.	127
6.4	Flowchart of the methodology proposed in this work for design-	
3.12	<u> </u>	128
6.5	Proposed holograms for the robot references.	131
6.6	Proposed holograms for the robot 3D and 2D boundaries	132
6.7	Material shader designed for controlling the visibility of the 3D	
	and 2D boundaries depending on the proximity of the WR end-	
	effector and STR tool, respectively.	133
6.8	First experiment: frames of the video showing the function-	
	alities of the proposed AR-based interface. See the video at	
		135
6.9	Second experiment: frames of the video showing the perfor-	
	mance of the 2D boundary and the STR reference hologram.	
	· · · · · · · · · · · · · · · · · · ·	136
6.10	The 2D trajectory performance for the second experiment, show-	
	ing the 2D boundary and the STR reference hologram (see the	
	video at (Video: Chapter 6, Experiment 2, 2022)): 2D allowed	
	workpiece region in green; trajectory followed by the user refer-	
	ence in thin red line; and trajectory followed by the STR tool	
	in thick blue line.	137

xxiv Figures

6.11 Performance of the STR position teleoperation for the second	ıd
experiment. First two graphs: user position references in the	
red line, actual position values of the STR tool on the work	
piece surface (coordinates relative to the surface) in thick blu	
line, and position limits given by the 2D boundary constrain	
in dashed lines. Bottom graph: activation of the 2D boundar	
constraint for the position of the STR tool on the workpiece su	
face.	
6.12 Third experiment: frames of the video showing the performance	
of the 3D boundary and the WR reference hologram. See the	
video at (Video: Chapter 6, Experiment 3, 2022)	
6.13 The 3D trajectory performance for the third experiment, show	
ing the 3D boundary and the WR reference hologram (see the	
video at (Video: Chapter 6, Experiment 3, 2022)): 3D allowe	
region in green; trajectory followed by the user reference in the	
red line; and trajectory followed by the WR end-effector in thic	
blue line.	141
6.14 Performance of the WR position teleoperation for the third ex	X-
periment. First three graphs: user position references in the	in
red line, actual position values of the workpiece in thick blu	ıе
line, and position limits given by the 3D boundary constrain	nt
in dashed lines. Bottom graph: activation of the 3D boundary	
constraint for the workpiece position	
6.15 Performance of the WR angle teleoperation for the third ex	X-
periment: user angular references in thin red line and actu	
angular values of the workpiece in thick blue line	143
6.16 <i>Cont.</i>	144
6.17 Fourth experiment: frames of the video showing the simultan	e-
ous teleoperation of both robots with the proposed AR-base	ed
interface. See the video at (Video: Chapter 6, Experiment	4,
2022).	144
6.18 The 2D trajectory performance for the fourth experiment, show	V-
ing the simultaneous teleoperation of both robots (see the vide	3 0
at (Video: Chapter 6, Experiment 4, 2022)): 2D allowed wor	
piece region in green; trajectory followed by the user reference	
in thin red line; and trajectory followed by the STR tool in thic	ck
blue line.	145

FIGURES xxv

6.19 The 3D trajectory performance for the fourth experiment, show-	
ing the simultaneous teleoperation of both robots (see the video	
at (Video: Chapter 6, Experiment 4, 2022)): 3D allowed region	
in green; trajectory followed by the user reference in thin red	
line; and trajectory followed by the WR end-effector in thick	
blue line.	146