

Lecture Notes in Control and Information Sciences 401

Editors: M. Thoma, F. Allgöwer, M. Morari

Graziano Chesi and Koichi Hashimoto (Eds.)

Visual Servoing via Advanced Numerical Methods

Series Advisory Board

P. Fleming, P. Kokotovic,
A.B. Kurzhanski, H. Kwakernaak,
A. Rantzer, J.N. Tsitsiklis

Editors

Prof. Graziano Chesi
University of Hong Kong
Department of Electrical
and Electronic Engineering
Pokfulam Road
Hong Kong
Chow Yei Ching Building
China, People's Republic
E-mail: chesi@eee.hku.hk

Prof. Koichi Hashimoto
Tohoku University
Dept. System Information Sciences
6-6-01 Aramaki-Aza Aoba
Sendai
Aoba-ku
980-8579 Japan
E-mail: koichi@ic.is.tohoku.ac.jp

ISBN 978-1-84996-088-5

e-ISBN 978-1-84996-089-2

DOI 10.1007/978-1-84996-089-2

Lecture Notes in Control and Information Sciences ISSN 0170-8643

Library of Congress Control Number: Applied for

© 2010 Springer-Verlag Berlin Heidelberg

MATLAB[®] and Simulink[®] are registered trademarks of The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098, USA. <http://www.mathworks.com>

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typeset & Cover Design: Scientific Publishing Services Pvt. Ltd., Chennai, India.

Printed on acid-free paper

5 4 3 2 1 0

springer.com

*To my family Shing Chee, Isabella and Sofia
(GC).*

*To my family Ritsuko, Riho, Daisuke, Kanta,
Teppei and Shogo (KH).*

*This book is dedicated in memory of Dr.
Ryosuke Mori (1972–2008).*

Preface

Robots able to imitate human beings have been at the core of stories of science fiction as well as dreams of inventors for a long time. Among the various skills that Mother Nature has provided us with and that often go forgotten, the ability of sight is certainly one of the most important. Perhaps inspired by tales of Isaac Asimov, comics and cartoons, and surely helped by the progress of electronics in recent decades, researchers have progressively made the dream of creating robots able to move and operate by exploiting artificial vision a concrete reality.

Technically speaking, we would say that these robots position themselves and their end-effectors by using the view provided by some artificial eyes as feedback information. Indeed, the artificial eyes are visual sensors such as cameras that have the function to acquire an image of the environment. Such an image describes if and how the robot is moving toward the goal and hence constitutes feedback information. This procedure is known in robotics with the term *visual servoing*, and it is nothing else than an imitation of the intrinsic mechanism that allows human beings to realize daily tasks such as reaching the door of the house or grasping a cup of coffee.

Hence, there is no need to say that visual servoing is one of the hottest areas of robotics. Indeed, visual servoing can be, and is, exploited in numerous and various applications, such as industry, surveillance, transportation, exploration, surgery, and the replacement of human beings in dangerous environments. This book aims to provide a collection of the latest advances in visual servoing, which have been achieved through the development of dedicated numerical methods that the recent progress in video devices, computer hardware, and optimization techniques, have made possible.

Organization of the Book

The book is organized in three main parts, reflecting three main classes of issues in visual servoing.

The first part, *Vision*, comprises contributions whose main focus is on vision issues that characterize visual servoing tasks. Specifically, Mariottini *et al.* introduce visual servoing via catadioptric stereo with planar mirrors. Swensen *et al.* analyze convergence properties of featureless visual servoing. Namiki *et al.* propose a high-speed vision system for grasping and manipulation. Hager considers human-machine cooperation via vision-based motion constraints. Collewet and Marchand propose luminance as a new feature for visual servoing. Bachtá *et al.* address vision issues in beating heart surgery.

The second part, *Estimation and Path-planning*, collects contributions whose main focus is on estimation issues and path-planning strategies. Specifically, Mezouar addresses trajectory planning via variational calculus. Malis *et al.* consider the estimation of homography dynamics. Chesi *et al.* investigate the effect of image measurement errors on the positioning error. Danes *et al.* analyze visual servoing through rational systems and linear matrix inequalities (LMIs). Kazemi *et al.* present a review of path-planning methods. Dani and Dixon consider structure and motion estimation with single camera. Tahri *et al.* address visual servoing and pose estimation with cameras obeying the unified model.

Lastly, the third part, *Control*, focuses on control issues of visual servoing tasks. Specifically, Ma and Hutchinson present gradient projection methods for taking into account constraints in image-based visual servoing (IBVS). Tarbouriech and Soueres address multi-constraint satisfaction in IBVS via LMIs. Hadj-Abdelkader *et al.* present a control scheme with central cameras. Lamiroux and Lefebvre describe deformation-based trajectory control for nonholonomic robots. Belo *et al.* consider eye-in-hand unicycle-like robots via position-based visual servoing and IBVS. Iwatani *et al.* address occlusion avoidance in unmanned helicopter control. Allibert *et al.* propose the use of nonlinear predictive control in visual servoing.

Acknowledgements

We thank the authors of the chapters for their precious contributions that have made possible to realize this great collection of advanced numerical methods for visual servoing. And we also thank the Springer Editors for their patience and suggestions that have helped us in the difficult task of editing a book.

This book was typeset by the authors using L^AT_EX.

Hong Kong
Sendai
September 2009

Graziano Chesi
Koichi Hashimoto

Contents

Part I: Vision

1	Catadioptric Stereo with Planar Mirrors: Multiple-view Geometry and Camera Localization	3
	<i>Gian Luca Mariottini, Stefano Scheggi, Fabio Morbidi, Domenico Prattichizzo</i>	
1.1	Introduction	3
1.1.1	Motivation and Related Works	3
1.1.2	Contributions	4
1.1.3	Organization	5
1.2	Planar Mirrors and Perspective Projection	5
1.2.1	The Virtual Point and the Reflection Transformation	5
1.2.2	The Virtual Camera and the Projection Equivalence	7
1.2.3	Reflective Epipolar Geometry	7
1.3	Single-View and Multiple-view Geometry for PCS Sensors	9
1.3.1	Single-View Geometry	9
1.3.2	Multiple-view Geometry	10
1.4	Mirror Calibration and Image-Based Camera Localization	12
1.4.1	Mirror Calibration	12
1.4.2	Image-Based Camera Localization	13
1.5	Simulation and Experimental Results	16
1.5.1	Simulations	16
1.5.2	Experiments	18
1.6	Conclusions and Future Work	20
	References	20

2	Empirical Characterization of Convergence Properties for Kernel-Based Visual Servoing	23
	<i>John P. Swensen, Vinutha Kallem, Noah J. Cowan</i>	
2.1	Featureless Visual Servoing	23
2.2	Kernel-Based Visual Servoing	25
2.3	Empirical Validation	29
	2.3.1 Analysis of the Domain of Attraction	30
	2.3.2 Experimental Results	32
	2.3.3 Final Error in Pixels	36
2.4	Conclusions	37
	References	37
3	High-Speed Visual Feedback Control for Grasping and Manipulation	39
	<i>Akio Namiki, Taku Senoo, Satoru Mizusawa, Masatoshi Ishikawa</i>	
3.1	Introduction	39
3.2	High-Speed Batting	40
	3.2.1 Hybrid Trajectory Generator	40
	3.2.2 System Configuration	41
	3.2.3 Batting Algorithm	43
	3.2.4 Experiment	45
3.3	Tool Manipulation by Visual Servoing	48
	3.3.1 Passive Joint in the Contact Point	49
	3.3.2 Visual Servo Control for Tool Manipulation	49
	3.3.3 Experiments	51
3.4	Conclusion	52
	References	52
4	Human-Machine Cooperative Manipulation with Vision-Based Motion Constraints	55
	<i>Gregory D. Hager</i>	
4.1	Introduction	55
4.2	Virtual Fixtures	56
	4.2.1 Virtual Fixtures as a Control Law	57
	4.2.2 Virtual Fixtures as Geometric Constraints	58
	4.2.3 Choosing the Preferred Direction	59
4.3	Vision-Based Virtual Fixtures	61
	4.3.1 Controlling the Viewer: Pure Translation	61
	4.3.2 Controlling the Viewer: General Case	64
	4.3.3 More General Camera Configurations	65
4.4	Examples of Use	66
4.5	Conclusion	68
	References	69

5	Luminance: A New Visual Feature for Visual Servoing . . .	71
	<i>Christophe Collewet, Eric Marchand</i>	
5.1	Introduction	71
5.2	Luminance as a Visual Feature	73
5.3	Visual Servoing Control Law	77
5.3.1	Visual Servoing as an Optimization Problem	77
5.3.2	Shape of the Cost Function	79
5.3.3	Control Law	80
5.4	Experimental Results	81
5.4.1	Positioning Tasks under Temporal Luminance Constancy	81
5.4.2	Positioning Tasks under Complex Illumination	86
5.5	Conclusion and Future Works	88
	References	88
6	Visual Servoing for Beating Heart Surgery	91
	<i>Wael Bachta, Pierre Renaud, Ezio Malis, Koichi Hashimoto, Jacques Gangloff</i>	
6.1	Introduction	91
6.2	Motion Compensation Approaches	93
6.2.1	Heart-Tool Synchronization	94
6.2.2	Heart Immobilization	95
6.3	Heart Motion Prediction	97
6.3.1	Linear Parameter Varying Method	97
6.3.2	Amplitude Modulation Method	98
6.4	Robust Real-Time Visual Measurement	100
6.4.1	Problem Formulation	101
6.4.2	Algorithm	102
6.4.3	High-Speed Implementation	103
6.4.4	Results	103
6.5	Control Strategies	105
6.5.1	Heart-Tool Synchronization	105
6.5.2	Heart Immobilization	108
6.6	Perspectives	111
	References	112

Part II: Estimation and Path-Planning

7	A Variational Approach to Trajectory Planning in Visual Servoing	117
	<i>Youssef Mezouar</i>	
7.1	Introduction	117
7.2	Preliminaries	119
7.2.1	Brief Review of $SO(3)$	119

7.2.2	Camera Model and Two Views Geometry	120
7.2.3	The Unconstrained Problem	121
7.3	The Constrained Problem	123
7.4	Solving the Variational Problem	125
7.5	Image Space Trajectories	126
7.6	Example	127
7.7	Conclusion	130
	References	131
8	Estimation of Homography Dynamics on the Special Linear Group	133
	<i>Ezio Malis, Tarek Hamel, Robert Mahony, Pascal Morin</i>	
8.1	Introduction	133
8.2	Theoretical Background	135
8.3	Nonlinear Observer on $SL(3)$	136
8.4	Simulations with Ground Truth	144
8.5	Experiments with Real Data	146
8.6	Conclusion	148
	References	149
9	Image Measurement Errors in Visual Servoing: Estimating the Induced Positioning Error	151
	<i>Graziano Chesi, Yeung Sam Hung, Ho Lam Yung</i>	
9.1	Introduction	151
9.2	Preliminaries	152
9.2.1	Notation and Problem Statement	153
9.2.2	Mathematical Formulation of the Problem	153
9.2.3	SMR of Polynomials	155
9.3	Computation of the Bounds	156
9.3.1	Upper Bounds	157
9.3.2	Lower Bounds	160
9.4	Examples	161
9.4.1	Example 1	161
9.4.2	Example 2	164
9.4.3	Example 3	164
9.5	Conclusion	165
	References	165
10	Multicriteria Analysis of Visual Servos through Rational Systems, Biquadratic Lyapunov Functions, and LMIs	169
	<i>Patrick Danès, Daniel F. Coutinho, Sylvain Durola</i>	
10.1	Introduction	169
10.2	The Rational Systems Framework to Visual Servos Multicriteria Analysis and Synthesis	170

10.2.1	State Space Formulation	171
10.2.2	The Rational Systems Framework	172
10.3	Theoretical Foundations of the Method	174
10.3.1	Elements of Lyapunov Theory	174
10.3.2	Matrix Inequalities and Related Important Lemmas	176
10.4	Multicriteria Analysis through Biquadratic Lyapunov Functions	177
10.4.1	Mathematical Background	177
10.4.2	LMI Conditions for Multicriteria Analysis Based on BQLFs	178
10.4.3	LMI Conditions for Multicriteria Analysis Based on PW-BQLFs	181
10.5	Case Study	184
10.6	Conclusion	186
	References	187
11	Path-Planning for Visual Servoing: A Review and Issues	189
	<i>Moslem Kazemi, Kamal Gupta, Mehran Mehrandezh</i>	
11.1	Introduction	189
11.2	Constraints in Visual Servoing	191
11.2.1	Image/Camera Constraints	191
11.2.2	Robot/Physical Constraints	192
11.3	Path-Planning for Visual Servoing	193
11.3.1	Image Space Path-Planning	193
11.3.2	Optimization-Based Path-Planning	196
11.3.3	Potential Field-Based Path-Planning	198
11.3.4	Global Path-Planning	200
11.4	Path-Planning under Uncertainty for Visual Servoing	201
11.5	Conclusions	203
	References	204
12	Single Camera Structure and Motion Estimation	209
	<i>Ashwin P. Dani, Warren E. Dixon</i>	
12.1	Introduction	209
12.2	Euclidean and Image Space Relationships	211
12.3	Perspective Camera Motion Model	214
12.4	Structure and Motion Estimation	215
12.4.1	Estimation with Known Angular and Linear Velocities	216
12.4.2	Estimation with a Known Linear Velocity	219
	References	227

13 Visual Servoing and Pose Estimation with Cameras	
Obeying the Unified Model	231
<i>Omar Tahri, Youcef Mezouar, François Chaumette, Helder Araujo</i>	
13.1 Introduction	231
13.2 Camera Model	234
13.3 Mathematical Background	234
13.3.1 Visual Servoing and Pose Estimation	234
13.3.2 Moments from the Projection of Points onto the Surface of Unit Sphere	236
13.4 Features Choice	238
13.4.1 Invariants to Rotational Motion	238
13.4.2 Variation of the Interaction Matrix with respect to the Camera Pose	238
13.4.3 Features Selection	241
13.5 Results	241
13.5.1 Variation of the Interaction Matrix with respect to Depth Distribution	242
13.5.2 Visual Servoing Results	242
13.5.3 Pose Estimation Results	244
13.6 Conclusion	248
References	248

Part III: Control

14 Gradient Projection Methods for Constrained	
Image-Based Visual Servo	253
<i>Wenzhuo Ma, Seth Hutchinson</i>	
14.1 Introduction	253
14.2 Exploiting Redundancy by Projecting onto Null Spaces	254
14.2.1 Task-Decomposition Approach	254
14.2.2 The Gradient Projection Method Applied to Robotic Control	256
14.3 Gradient Projection Method for Avoiding Joint Limits	259
14.3.1 Basic Algorithm Design	259
14.3.2 Simulation Results	265
14.4 Gradient Projection Method for Occlusion Avoidance	266
14.4.1 Basic Algorithm Design	266
14.4.2 Simulation Results	269
14.5 Gradient Projection Method for Keeping Target Features in the Field of View	270
14.5.1 Basic Algorithm Design	270
14.5.2 Simulation Results	271
14.6 Conclusions	273
References	274

15	Image-Based Visual Servo Control Design with Multi-Constraint Satisfaction	275
	<i>Sophie Tarbouriech, Philippe Souères</i>	
15.1	Introduction	275
15.2	Problem Statement	277
	15.2.1 System Description	277
	15.2.2 Problem Formulation	280
15.3	Preliminary Results	280
15.4	Control Design Results	282
	15.4.1 Theoretical Issues	283
	15.4.2 Optimization Issues	287
15.5	Application	287
15.6	Concluding Remarks and Perspectives	292
	References	293
16	Points-Based Visual Servoing with Central Cameras	295
	<i>Hicham Hadj-Abdelkader, Youcef Mezouar, Philippe Martinet</i>	
16.1	Introduction	295
16.2	Modeling	296
	16.2.1 Generic Projection Model	297
	16.2.2 Scaled Euclidean Reconstruction	298
16.3	Visual Servoing	300
	16.3.1 Task Function and Interaction Matrices	300
	16.3.2 Interaction Matrix for 2D Point	301
	16.3.3 Decoupled Visual Servoing	302
16.4	Results	305
16.5	Conclusion	311
	References	312
17	Sensor-Based Trajectory Deformation: Application to Reactive Navigation of Nonholonomic Robots	315
	<i>Florent Lamiraud, Olivier Lefebvre</i>	
17.1	Introduction	315
17.2	Nonholonomic Trajectory Deformation as a Dynamic Control System	317
	17.2.1 Admissible Trajectories	317
	17.2.2 Admissible Trajectory Deformation	317
	17.2.3 Potential Field and Inner Product	319
17.3	Nonholonomic Trajectory Deformation Algorithm	320
	17.3.1 Finite-Dimensional Subspace of Input Perturbations	321
	17.3.2 Boundary Conditions	322
	17.3.3 Direction of Deformation That Makes Trajectory Scalar Value Decrease	322
	17.3.4 Nonholonomic Constraint Deviation	324

17.4	Application to Mobile Robot Hilare 2 Towing a Trailer	327
17.4.1	Experimental Results	329
17.5	Extension to Docking	329
17.5.1	Docking Task	329
17.5.2	Computation of the Docking Configuration	330
17.6	Experimental Results	331
17.6.1	Bad Localization	332
17.6.2	The Unloading Platform Has Been Moved	333
	References	333
18	Unicycle-Like Robots with Eye-in-Hand Monocular Cameras: From PBVS towards IBVS	335
	<i>Daniele Fontanelli, Paolo Salaris, Felipe A.W. Belo, Antonio Bicchi</i>	
18.1	Introduction	336
18.2	Problem Definition	337
18.2.1	Position-Based Visual Servoing	339
18.2.2	Image-Based Visual Servoing	340
18.2.3	Optimal Trajectories	341
18.3	PBVS in the Large	341
18.3.1	Robot Localization	341
18.3.2	Visual Servoing with Omnidirectional Sight	343
18.3.3	Visual Servoing with FOV Constraint	344
18.3.4	Visual Servoing in the Large	344
18.3.5	Experimental Results	345
18.4	Optimal Trajectories	350
18.4.1	IBVS and Optimal Paths	352
18.4.2	Experimental Results	356
18.5	Conclusions	357
	References	358
19	Unmanned Helicopter Control via Visual Servoing with Occlusion Handling	361
	<i>Yasushi Iwatani, Kei Watanabe, Koichi Hashimoto</i>	
19.1	Introduction	361
19.2	Experimental Setup	362
19.3	Coordinate Frames	364
19.4	Image Jacobian Matrices	365
19.5	Image Feature Estimation and Selection	366
19.5.1	Image Feature Estimation	366
19.5.2	Image Feature Selection	367
19.6	Visual Servo Control with Occlusion Handling	367
19.7	Controller Design	369
19.8	Experimental Result	370
19.9	Conclusions	373
	References	373

20 Visual Servoing via Nonlinear Predictive Control	375
<i>Guillaume Allibert, Estelle Courtial, François Chaumette</i>	
20.1 Introduction	375
20.2 Predictive Control for Constrained IBVS	377
20.2.1 Visual Predictive Control	377
20.2.2 Internal Model Control Structure	378
20.2.3 Mathematical Formulation	378
20.3 Model of Image Prediction	380
20.3.1 Nonlinear Global Model	381
20.3.2 Local Model Based on the Interaction Matrix	382
20.4 Simulation Results	383
20.4.1 Case 1: Pure Rotation around the Optical Axis	384
20.4.2 Case 2: Large Displacement	389
20.5 Conclusions	392
References	392
Editors' Biographies	395
Index	397

List of Contributors

Guillaume Allibert

Institut PRISME, Polytech'Orleans,
8 rue Leonard de Vinci, 45072
Orleans, France,
guillaume.allibert@
univ-orleans.fr

Helder Araujo

Institute for Systems and Robotics,
Polo II 3030-290 Coimbra, Portugal,
helder@isr.uc.pt

Wael Bachta

LSIIT, University of
Strasbourg, Bd Sebastien
Brant, 67412 Illkirch, France,
bachta@lsiit.u-strasbg.fr

Felipe A.W. Belo

Department of Electrical Systems
and Automation, University of Pisa,
Via Diotisalvi 2, 56100 Pisa, Italy,
felipebelo@gmail.com

Antonio Bicchi

Department of Electrical Systems
and Automation, University of Pisa,
Via Diotisalvi 2, 56100 Pisa, Italy
bicchi@ing.unipi.it

François Chaumette

INRIA, Campus de Beaulieu, 35042
Rennes, France
francois.chaumette@irisa.fr

Graziano Chesi

Department of Electrical and
Electronic Engineering, University of
Hong Kong, Pokfulam Road,
Hong Kong
chesi@eee.hku.hk

Christophe Collewet

INRIA Rennes - Bretagne
Atlantique, IRISA,
Lagadic team, France
christophe.collewet@inria.fr

Estelle Courtial

Institut PRISME,
Polytech'Orleans, 8 rue Leonard de
Vinci, 45072 Orleans, France
estelle.courtial@univ-orleans.fr

Daniel F. Coutinho

Group of Automation and Control
Systems, PUC-RS, Av. Ipiranga
6681, Porto Alegre, RS 90619, Brazil
dcoutinho@pucrs.br

Noah J. Cowan

Department of Mechanical
Engineering, Johns Hopkins
University, 3400 North Charles
Street, Baltimore, MD 21218, USA
ncowan@jhu.edu

Patrick Danès

CNRS; LAAS; 7 avenue du colonel
Roche, F-31077 Toulouse, France;
and

Université de Toulouse; UPS,
INSA, INP, ISAE; LAAS; F-31077
Toulouse, France
patrick.danes@laas.fr

Ashwin P. Dani

Department of Mechanical and
Aerospace Engineering,
University of Florida, Gainesville,
FL 32608, USA
ashwin31@ufl.edu

Warren E. Dixon

Department of Mechanical and
Aerospace Engineering, University of
Florida, Gainesville, FL 32608, USA
wdixon@ufl.edu

Sylvain Durola

CNRS; LAAS; 7 avenue du colonel
Roche, F-31077 Toulouse, France
and

Université de Toulouse; UPS,
INSA, INP, ISAE; LAAS; F-31077
Toulouse, France
sylvain.durola@laas.fr

Daniele Fontanelli

Department of Information
Engineering and Computer Science,
University of Trento, Via Sommarive
14, 38123 Povo (TN), Italy
fontanelli@disi.unitn.it

Jacques Gangloff

LSIIT, University of Strasbourg,

Bd Sebastien Brant, 67412 Illkirch,
France

jacques.gangloff@
lsiit.u-strasbg.fr

Kamal Gupta

Simon Fraser University, Burnaby,
BC, V5A1S6, Canada
kamal@cs.sfu.ca

Hicham Hadj-Abdelkader

LASMEA, University Blaise Pascal,
Campus des Cezeaux,
63177 Aubiere, France
hadj@lasmea.univ-bpclermont.fr

Gregory D. Hager

Department of Computer Science,
Johns Hopkins University, 3400
North Charles Street, Baltimore,
MD 21218, USA
hager@cs.jhu.edu

Tarek Hamel

I3S-CNRS, 2000 Route des Lucioles,
06903 Sophia Antipolis, France
thamel@i3s.unice.fr

Koichi Hashimoto

Tohoku University, Aoba-ku
Aramaki
Aza Aoba 6-6-01, Sendai, Japan
koichi@ic.is.tohoku.ac.jp

Yeung Sam Hung

Department of Electrical and
Electronic Engineering,
University of Hong Kong,
Pokfulam Road,
Hong Kong
yshung@eee.hku.hk

Seth Hutchinson

Department of Electrical and
Computer Engineering,
University of Illinois, 405 North
Matthews Avenue, Urbana, IL

61801, USA
seth@illinois.edu

Masatoshi Ishikawa

Department of Information Physics
and Computing, University of Tokyo,
7-3-1 Hongo, Bunkyo, Tokyo, Japan
masatoshi_ishikawa@
ipc.i.u-tokyo.ac.jp

Yasushi Iwatani

Tohoku University, Aoba-ku
Aramaki Aza Aoba 6-6-01,
Sendai, Japan
iwatani@ic.is.tohoku.ac.jp

Vinutha Kallem

GRASP Laboratory, University of
Pennsylvania, 3330 Walnut Street,
Philadelphia, PA 19104, USA
vkallem@seas.upenn.edu

Moslem Kazemi

Simon Fraser University, Burnaby,
BC, V5A1S6, Canada
moslemk@cs.sfu.ca

Florent Lamiroux

LAAS-CNRS, 7 Avenue du Colonel
Roche, 31077 Toulouse, France
florent@laas.fr

Olivier Lefebvre

LAAS-CNRS, 7 Avenue du Colonel
Roche, 31077 Toulouse, France
olefebr@laas.fr

Wenzhou Ma

Department of Electrical and
Computer Engineering, University
of Illinois, 405 North Matthews
Avenue, Urbana, IL 61801, USA

Robert Mahony

Department of Engineering,

Australian National University,
North Road, Acton ACT 0200,
Australia

Robert.Mahony@anu.edu.au

Ezio Malis

INRIA, 2004 Route des Lucioles,
06902 Sophia Antipolis, France
ezio.malis@sophia.inria.fr

Eric Marchand

INRIA Rennes - Bretagne
Atlantique, IRISA,
Lagadic team, France
eric.marchand@inria.fr

Gian L. Mariottini

Department of Computer Science
and Engineering, University of
Minnesota, 200 Union Street SE,
Minneapolis, MN 55455, USA
gianluca@cs.umn.edu

Philippe Martinet

LASMEA, University Blaise Pascal,
Campus des Cezeaux,
63177 Aubiere, France
martinet@
lasmea.univ-bpclermont.fr

Mehran Mehrandezh

Faculty of Engineering and Applied
Science, University of Regina,
Regina, Saskatchewan S4S0A2
mehran.mehrandezh@uregina.ca

Youcef Mezouar

LASMEA, University Blaise Pascal,
Campus des Cezeaux,
63177 Aubiere, France
mezouar@univ-bpclermont.fr

Satoru Mizusawa

Department of Information Physics
and Computing, University of Tokyo,

7-3-1 Hongo, Bunkyo, Tokyo,
Japan
satoru_mizusawa@
ipc.i.u-tokyo.ac.jp

Fabio Morbidi

Department of Information
Engineering, University of Siena,
Via Roma 56, 53100 Siena,
Italy
morbidi@dii.unisi.it

Pascal Morin

INRIA, 2004 Route des Lucioles,
06902 Sophia Antipolis, France
pascal.morin@sophia.inria.fr

Akio Namiki

Department of Mechanical
Engineering, Chiba University, 1-33
Yayoi-cho, Inage, Chiba, Japan
namiki@faculty.chiba-u.jp

Domenico Prattichizzo

Department of Information
Engineering, University of Siena,
Via Roma 56, 53100 Siena, Italy
prattichizzo@dii.unisi.it

Pierre Renaud

LSIIT, University of Strasbourg,
Bd Sebastien Brant,
67412 Illkirch, France
pierre.renaud@
lsiit.u-strasbg.fr

Paolo Salaris

Department of Electrical Systems
and Automation, University of Pisa,
Via Diotisalvi 2, 56100 Pisa, Italy
salarispaolo@gmail.com

Stefano Scheggi

Department of Information
Engineering, University of Siena,

Via Roma 56, 53100 Siena, Italy
scheggi@dii.unisi.it

Taku Senoo

Department of Information Physics
and Computing, University of Tokyo,
7-3-1 Hongo, Bunkyo, Tokyo, Japan
taku_senoo@ipc.i.u-tokyo.ac.jp

Philippe Souères

LAAS-CNRS, Université de
Toulouse, 7 Avenue du Colonel
Roche, 31077 Toulouse cedex 4,
France
soueres@laas.fr

John P. Swensen

Department of Mechanical
Engineering, Johns Hopkins
University, 3400 North Charles
Street, Baltimore, MD 21218, USA
jpswensen@jhu.edu

Omar Tahri

Institute for Systems and Robotics,
Polo II 3030-290 Coimbra,
Portugal
omartahri@isr.uc.pt

Sophie Tarbouriech

LAAS-CNRS, Université de
Toulouse, 7 Avenue du Colonel
Roche, 31077 Toulouse cedex 4,
France
tarbour@laas.fr

Kei Watanabe

Tohoku University,
Aoba-ku Aramaki
Aza Aoba 6-6-01, Sendai, Japan
watanabe@ic.is.tohoku.ac.jp

Ho Lam Yung

Department of Electrical and
Electronic Engineering,
University of Hong Kong,
Pokfulam Road, Hong Kong
h0440266@eee.hku.hk

Abbreviations

AOI	Area of interest
ARIMAX	Autoregressive and integrated moving average with exogenous input
BQLF	Biquadratic Lyapunov function
CABG	Coronary artery bypass grafting
CCD	Charge-coupled device
CISST	Center for computer integrated surgical systems
CPV	Column-parallel high speed vision system
DA	Digital analog
DAR	Differential algebraic representation
DDR	Differential drive robot
DOF	Degrees of freedom
ECG	Electrocardiogram
EKF	Extended Kalman filter
ERSP	Evolution robotics software platform
ESM	Efficient second order minimization
FLC	Fourier linear combiner
FOV	Field of view
GN	Gauss–Newton
GPC	Generalized predictive controller
GPS	Global positioning system
IBO	Identifier-based observer
IBVS	Image-based visual servoing
IMC	Internal model control
IMU	Inertial measurement unit
JHU	Johns Hopkins University
MfS	Motion from structure
MIS	Minimally invasive surgery
MLM	Modified Levenberg–Marquardt
MRI	Magnetic resonance imaging
KBVS	Kernel-based visual servoing

KLT	Kanade–Lucas–Tomasi
LED	Light emitting diode
LMI	Linear matrix inequality
OECD	Organization for economic cooperation and development
OFCE	Optical flow constraint equation
PBVS	Position-based visual servoing
PC	Personal computer
PCI	Percutaneous coronary intervention
PCM	Perceptual control manifold
PCS	Planar catadioptric stereo
PD	Proportional derivative
PID	Proportional integral derivative
PW-BQLF	Piecewise-biquadratic Lyapunov function
RLS	Recursive least-squares
SaM	Structure and motion
SfM	Structure from motion
SHR	Steady hand robot
SDP	Semidefinite programming
SIFT	Scale-invariant feature transform
SLAM	Simultaneous localization and mapping
SMR	Square matricial representation
SOS	Sum of squares of polynomials
SQP	Sequential quadratic program
TECAB	Totally endoscopic coronary artery bypass
UUB	Uniformly ultimately bounded
VPC	Visual predictive control
VSLAM	Visual simultaneous localization and mapping
VVS	Virtual visual servoing