

*Commenced Publication in 1973*

Founding and Former Series Editors:

Gerhard Goos, Juris Hartmanis, and Jan van Leeuwen

## Editorial Board

David Hutchison

*Lancaster University, Lancaster, UK*

Takeo Kanade

*Carnegie Mellon University, Pittsburgh, PA, USA*

Josef Kittler

*University of Surrey, Guildford, UK*

Jon M. Kleinberg

*Cornell University, Ithaca, NY, USA*

Friedemann Mattern

*ETH Zurich, Zurich, Switzerland*

John C. Mitchell

*Stanford University, Stanford, CA, USA*

Moni Naor

*Weizmann Institute of Science, Rehovot, Israel*

C. Pandu Rangan

*Indian Institute of Technology, Madras, India*

Bernhard Steffen

*TU Dortmund University, Dortmund, Germany*

Demetri Terzopoulos

*University of California, Los Angeles, CA, USA*

Doug Tygar

*University of California, Berkeley, CA, USA*

Gerhard Weikum

*Max Planck Institute for Informatics, Saarbrücken, Germany*

More information about this series at <http://www.springer.com/series/7412>

Maria A. Zuluaga · Kanwal Bhatia  
Bernhard Kainz · Mehdi H. Moghari  
Danielle F. Pace (Eds.)

# Reconstruction, Segmentation, and Analysis of Medical Images

First International Workshops, RAMBO 2016 and HVSMR 2016  
Held in Conjunction with MICCAI 2016  
Athens, Greece, October 17, 2016  
Revised Selected Papers

*Editors*

Maria A. Zuluaga  
University College London  
London  
UK

Kanwal Bhatia  
King's College London  
London  
UK

Bernhard Kainz  
Imperial College London  
London  
UK

Mehdi H. Moghari  
Harvard Medical School and Boston  
Children's Hospital  
Boston, MA  
USA

Danielle F. Pace  
MIT  
Cambridge, MA  
USA

ISSN 0302-9743

ISSN 1611-3349 (electronic)

Lecture Notes in Computer Science

ISBN 978-3-319-52279-1

ISBN 978-3-319-52280-7 (eBook)

DOI 10.1007/978-3-319-52280-7

Library of Congress Control Number: 2016963670

LNCS Sublibrary: SL6 – Image Processing, Computer Vision, Pattern Recognition, and Graphics

© Springer International Publishing AG 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, 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.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature

The registered company is Springer International Publishing AG

The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# Preface

This book gathers the works presented at the Workshop on Reconstruction and Analysis of Moving Body Organs (RAMBO) and the Workshop on Whole-Heart and Great Vessel Segmentation from 3D Cardiovascular MRI in Congenital Heart Disease (HVSMD), which were held in conjunction with MICCAI on October 17, 2016.

## RAMBO

Physiological motion is an important factor in several medical imaging applications. For instance, the speed of motion may inhibit the acquisition of high-resolution images needed for effective visualization and analysis, for example, in cardiac or respiratory imaging or in functional magnetic resonance imaging (fMRI) and perfusion applications. Additionally, in cardiac and fetal imaging, the variation in frame of reference may confound automated analysis pipelines. The underlying motion may also need to be characterized either to enhance images or for clinical assessment. Techniques are therefore needed for faster or more accurate reconstruction or for analysis of time-dependent images. Despite the related concerns, few meetings have addressed the issues caused by motion in medical imaging, without restriction on the clinical application area or methodology used. RAMBO 2016 was set up to provide a discussion forum for researchers for whom motion and its effects are critical in image analysis or visualization. By inviting contributions across all application areas, the workshop aimed to bring together ideas from different areas of specialization, without being confined to a particular methodology. In particular, the recent trend to move from model-based to learning-based methods of analysis has resulted in increased transferability between application domains. A further goal of this workshop was to enhance the links between image analysis (including computer vision and machine learning techniques) and image acquisition and reconstruction, which generally tends to be addressed in separate meetings. The presented contributions can be broadly categorized into segmentation, registration, and reconstruction, while application areas include cardiac, abdominal, fetal, and brain perfusion, showing the breadth of interest in the topic. Research from both academia and industry is presented. We hope that this workshop enables the cross-fertilization of ideas across application domains with the aim of tackling and taking advantage of the problems and opportunities arising from motion in medical imaging.

October 2016

Bernhard Kainz  
Kanwal Bhatia  
Ghislain Vaillant  
Maria A. Zuluaga

## HVSMR

Congenital heart disease (CHD) affects approximately 1.2% of children and is the leading cause of birth defect-related deaths. About 6 to 19 per 1,000 cause moderate to severe problems requiring immediate surgical repair. Clinicians currently rely on two-dimensional imaging (2D) for monitoring and procedural planning. However, 2D images cannot depict the 3D spatial relationships of intracardiac anatomy, and reliance on them limits efficient decision-making.

Compared with conventional 2D imaging techniques, it has been recently shown that 3D virtual and physical heart models convey several benefits when visualizing intracardiac anatomy in 3D and in producing consensus around a surgical plan.

Three-dimensional images can be generated by segmenting the cardiac muscle and blood in 3D images acquired from echocardiography, X-ray, or magnetic resonance imaging (MRI). MRI has many advantages including better image quality compared with echocardiography, and unlike X-ray is not associated with ionizing radiation. However, segmentation of cardiac MR images is challenging owing to intensity inhomogeneities (due to the motion of the heart and blood), poor contrast, the presence of thin walls separating cardiac chambers, and the wide anatomical variability in congenital heart disease patients.

Manual segmentation has been the most robust technique for delineating the cardiac muscle and blood in cardiac MR datasets. This technique, however, is time intensive (4–8 h of work), prone to error, and subject to intra- and inter-observer variability. As of yet, there is no robust automatic segmentation algorithm developed for cardiac MR segmentation for congenital heart disease.

The HVSMR workshop gathered researchers from around the world to tackle this challenging problem, sharing a newly released open dataset of cardiac MR images from patients with various forms of congenital heart disease. The ultimate goal is to improve surgical planning for patients with complex congenital heart disease. We believe this workshop provided a snapshot of the current progress in the field of cardiac MR segmentation for this patient cohort.

October 2016

Mehdi H. Moghari  
Danielle F. Pace  
Alireza Akhondi-Asl  
Andrew J. Powell

# Organization

## RAMBO: Conference Chairs

Bernhard Kainz	Imperial College London, UK
Kanwal Bhatia	King's College London, UK
Maria A. Zuluaga	University College London, UK
Ghislain Vaillant	Imperial College London, UK

## HVSMR: Conference Chairs

Mehdi Hedjazi Moghari	Boston Children's Hospital and Harvard Medical School, USA
Danielle F. Pace	Massachusetts Institute of Technology, USA
Alireza Akhondi-Asl	Boston Children's Hospital and Harvard Medical School, USA
Andrew Powell	Boston Children's Hospital and Harvard Medical School, USA

## RAMBO: Program Committee

Wenjia Bai	Imperial College London, UK
Olivier Bernard	CREATIS, France
Wolfgang Birkfellner	Medical University Vienna, Austria
Lucilio Cordero-Grande	King's College London, UK
Ali Gholipour	Boston Children's Hospital, USA
Alberto Gomez	King's College London, UK
Matthias Heinrich	Universität zu Lübeck, Germany
Karim Lekadir	Stanford University, USA
Herve Lombaert	Inria, France
Bartlomiej Papiez	University of Oxford, UK
Francois Rousseau	Telecom Bretagne, France
Martin Urschler	Graz University of Technology, Austria
Wolfgang Wein	ImFusion GmbH, Germany

## HVSMR: Program Committee

Polina Golland	Massachusetts Institute of Technology, USA
Terry Peters	Western University, Canada
Caroline Petitjean	University of Rouen, France
Martin Rajchl	Imperial College London, UK
Daniel Rueckert	Imperial College London, UK

Alistair Young	The University of Auckland, New Zealand
Xiahai Zhuang	Shanghai Jiao Tong University, China

**Additional Reviewers**

Jan Egger	Graz University of Technology, Austria
Vikash Gupta	University of Southern California, USA
Matthew Chung Hai Lee	Imperial College London, UK
Steven McDonagh	University of Edinburgh, UK



# Contents

## RAMBO: Registration

Point-Spread-Function-Aware Slice-to-Volume Registration: Application to Upper Abdominal MRI Super-Resolution . . . . .	3
<i>Michael Ebner, Manil Chouhan, Premal A. Patel, David Atkinson, Zahir Amin, Samantha Read, Shonit Punwani, Stuart Taylor, Tom Vercauteren, and Sébastien Ourselin</i>	
Motion Correction Using Subpixel Image Registration . . . . .	14
<i>Amir HajiRassouliha, Andrew J. Taberner, Martyn P. Nash, and Poul M.F. Nielsen</i>	
Incompressible Phase Registration for Motion Estimation from Tagged Magnetic Resonance Images . . . . .	24
<i>Fangxu Xing, Jonghye Woo, Arnold D. Gomez, Dzung L. Pham, Philip V. Bayly, Maureen Stone, and Jerry L. Prince</i>	

## RAMBO: Reconstruction

Robust Reconstruction of Accelerated Perfusion MRI Using Local and Nonlocal Constraints . . . . .	37
<i>Cagdas Ulas, Pedro A. Gómez, Felix Krahmer, Jonathan I. Sperl, Marion I. Menzel, and Bjoern H. Menze</i>	
Graph-Based 3D-Ultrasound Reconstruction of the Liver in the Presence of Respiratory Motion . . . . .	48
<i>Houssem-Eddine Gueziri, Sebastien Tremblay, Catherine Laporte, and Rupert Brooks</i>	
Whole-Heart Single Breath-Hold Cardiac Cine: A Robust Motion-Compensated Compressed Sensing Reconstruction Method . . . . .	58
<i>Javier Royuela-del-Val, Muhammad Usman, Lucilio Cordero-Grande, Marcos Martin-Fernandez, Federico Simmross-Wattenberg, Claudia Prieto, and Carlos Alberola-López</i>	
Motion Estimated-Compensated Reconstruction with Preserved-Features in Free-Breathing Cardiac MRI . . . . .	70
<i>Aurélien Bustin, Anne Menini, Martin A. Janich, Darius Burschka, Jacques Felblinger, Anja C.S. Brau, and Freddy Odille</i>	

## **RAMBO and HVSMR: Deep Learning for Heart Segmentation**

Recurrent Fully Convolutional Neural Networks for Multi-slice MRI Cardiac Segmentation . . . . .	83
<i>Rudra P.K. Poudel, Pablo Lamata, and Giovanni Montana</i>	
Dilated Convolutional Neural Networks for Cardiovascular MR Segmentation in Congenital Heart Disease . . . . .	95
<i>Jelmer M. Wolterink, Tim Leiner, Max A. Viergever, and Ivana Išgum</i>	
3D FractalNet: Dense Volumetric Segmentation for Cardiovascular MRI Volumes. . . . .	103
<i>Lequan Yu, Xin Yang, Jing Qin, and Pheng-Ann Heng</i>	
Automatic Whole-Heart Segmentation in Congenital Heart Disease Using Deeply-Supervised 3D FCN . . . . .	111
<i>Jinpeng Li, Rongzhao Zhang, Lin Shi, and Defeng Wang</i>	

## **RAMBO and HVSMR: Discrete Optimization and Probabilistic Intensity Modeling**

A GPU Based Diffusion Method for Whole-Heart and Great Vessel Segmentation . . . . .	121
<i>Philipp Lösel and Vincent Heuveline</i>	
Fully-Automatic Segmentation of Cardiac Images Using 3-D MRF Model Optimization and Substructures Tracking . . . . .	129
<i>Georgios Tziritas</i>	

## **HSVMR: Atlas-Based Strategies**

Strengths and Pitfalls of Whole-Heart Atlas-Based Segmentation in Congenital Heart Disease Patients . . . . .	139
<i>Maria A. Zuluaga, Benedetta Biffi, Andrew M. Taylor, Silvia Schievano, Tom Vercauteren, and Sébastien Ourselin</i>	
Automated Cardiovascular Segmentation in Patients with Congenital Heart Disease from 3D CMR Scans: Combining Multi-atlases and Level-Sets . . . . .	147
<i>Rahil Shahzad, Shan Gao, Qian Tao, Oleh Dzyubachyk, and Rob van der Geest</i>	

## **HSVMR: Random Forests**

Automatic Heart and Vessel Segmentation Using Random Forests and a Local Phase Guided Level Set Method . . . . .	159
<i>Chunliang Wang, Qian Wang, and Örjan Smedby</i>	

Total Variation Random Forest: Fully Automatic MRI Segmentation in Congenital Heart Diseases . . . . .	165
<i>Anirban Mukhopadhyay</i>	
<b>Author Index</b> . . . . .	173