

ACSP · Analog Circuits And Signal Processing

Hani Saleh
Nourhan Bayasi
Baker Mohammad
Mohammed Ismail

Self-powered SoC Platform for Analysis and Prediction of Cardiac Arrhythmias

Analog Circuits and Signal Processing

Series editors

Mohammed Ismail, Dublin, USA

Mohamad Sawan, Montreal, Canada

The Analog Circuits and Signal Processing book series, formerly known as the Kluwer International Series in Engineering and Computer Science, is a high level academic and professional series publishing research on the design and applications of analog integrated circuits and signal processing circuits and systems. Typically per year we publish between 5-15 research monographs, professional books, handbooks, edited volumes and textbooks with worldwide distribution to engineers, researchers, educators, and libraries.

The book series promotes and expedites the dissemination of new research results and tutorial views in the analog field. There is an exciting and large volume of research activity in the field worldwide. Researchers are striving to bridge the gap between classical analog work and recent advances in very large scale integration (VLSI) technologies with improved analog capabilities. Analog VLSI has been recognized as a major technology for future information processing. Analog work is showing signs of dramatic changes with emphasis on interdisciplinary research efforts combining device/circuit/technology issues. Consequently, new design concepts, strategies and design tools are being unveiled.

Topics of interest include:

Analog Interface Circuits and Systems;
Data converters;
Active-RC, switched-capacitor and continuous-time integrated filters;
Mixed analog/digital VLSI;
Simulation and modeling, mixed-mode simulation;
Analog nonlinear and computational circuits and signal processing;
Analog Artificial Neural Networks/Artificial Intelligence;
Current-mode Signal Processing; Computer-Aided Design (CAD) tools;
Analog Design in emerging technologies (Scalable CMOS, BiCMOS, GaAs, heterojunction and floating gate technologies, etc.);
Analog Design for Test;
Integrated sensors and actuators; Analog Design Automation/Knowledge-based Systems; Analog VLSI cell libraries; Analog product development; RF Front ends, Wireless communications and Microwave Circuits;
Analog behavioral modeling, Analog HDL.

More information about this series at <http://www.springer.com/series/7381>

Hani Saleh • Nourhan Bayasi
Baker Mohammad • Mohammed Ismail

Self-powered SoC Platform for Analysis and Prediction of Cardiac Arrhythmias

Hani Saleh
Department of Electronic Engineering
Khalifa University of Science, Technology
and Research
Abu Dhabi, United Arab Emirates

Baker Mohammad
Department of Electronic Engineering
Khalifa University of Science, Technology
and Research
Abu Dhabi, United Arab Emirates

Nourhan Bayasi
Department of Electrical and Computer
Engineering
Khalifa University of Science, Technology
and Research
Abu Dhabi, United Arab Emirates

Mohammed Ismail
Department of Electrical and Computer
Engineering Department
Khalifa University of Science, Technology
and Research
Abu Dhabi, United Arab Emirates

ISSN 1872-082X ISSN 2197-1854 (electronic)
Analog Circuits and Signal Processing
ISBN 978-3-319-63972-7 ISBN 978-3-319-63973-4 (eBook)
DOI 10.1007/978-3-319-63973-4

Library of Congress Control Number: 2017953939

© Springer International Publishing AG 2018

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

During the last decades, medical wearable devices have gain lots of interest due to their potential influence in providing remote and ambulatory monitoring to support patients. Many devices have been developed, improved, and implemented for the long-term and continuous monitoring of the healthcare practices in general and cardiovascular diseases in particular. Due to its efficiency, simplicity, and noninvasiveness, the electrocardiogram (ECG) signal has been widely used for monitoring cardiac functions despite the development of newer techniques or technologies. The information contained in the morphological features of the ECG signal has been broadly employed to build a full classification system capable of distinguishing between normal and abnormal conditions.

This book presents the first ASIC implementation of an ECG-based signal processor (ESP) that is capable of predicting ventricular arrhythmia up to 3 h before the onset. The ESP is composed of three stages which include ECG signal processing, feature extraction, and classification, and it utilizes adaptive and novel techniques that are highly effective and suitable for real-time implementation. The extracted ECG features, individually and in combinations, showed good potential in the prediction of ventricular arrhythmia with significant statistical results, and the combination of these features has never been used in any previous detection or prediction system. Two databases of heart signal recordings from MIT PhysioNet and the American Heart Association (AHA) were used as training, test, and validation sets to evaluate the performance of the proposed system. Based on MATLAB testing results, the proposed system achieved a prediction accuracy (ACC) of 99.98% on the out-of-sample validation data by tenfold cross validation with 3-s window size.

Furthermore, the proposed ESP was developed using Verilog RTL and implemented using ASIC implementation flow based on 65-nm GlobalFoundries

low-power CMOS process. Based on the design constraints, the ESP occupied a state-of-the-art total cell area of 0.112 mm^2 and consumed a total power of $2.78 \text{ } \mu\text{W}$ at an operating frequency of 10 kHz and operating voltage of 1.2 V.

Abu Dhabi, United Arab Emirates

Hani Saleh
Nourhan Bayasi
Baker Mohammad
Mohammed Ismail

Acknowledgments

The work in this book has its roots in the MSc thesis of the second author. We would like to thank and acknowledge all those who assisted us with the different phases of developing the material that lead to this book. We would like to specifically acknowledge our colleagues at the Khalifa Semiconductor Research Center (KSRC) for their help, encouragement, and support; our thanks go to Temesghen, Yonatan, Dima, Maisam, Lama, and Mohammad. Special thanks to Dr. Ahsan Khandoker from the Biomedical Department at Khalifa University for his insightful input at the start of this project for tackling the VT/VF problem and for his continued support for Bayasi during the development of the VT/VF predictor.

We also like to acknowledge the support of Mubadala for the funding and the US Semiconductor Research Corporation (SRC) for overseeing the projects of the ACE4S Mubadala-SRC Center of Excellence under which this project was completed. We must also acknowledge our industrial liaisons for their suggestions and insights, John Pigott, Mark Schlarman from NXP, Muhammad Khellah, and Lilly Huang from Intel.

The work in this book was part of a complete system on chip targeting a platform for wearable healthcare. We would like to thank our colleagues responsible for other parts of such a system and acknowledge their unmatched spirit of teamwork. Finally we would like to acknowledge the help and support of our families and friends and thank them for their patience and understanding.

This work was supported by the Mubadala-SRC Center of Excellence for Energy-Efficient Electronic Systems research contract 2013-HJ2440.

Contents

1	Introduction.....	1
1.1	Remote Monitoring System (RMS).....	2
1.1.1	Key Enabling Technologies	3
1.1.2	Economical Impact	4
1.2	Electrocardiographic Signal.....	4
1.3	Cardiac Arrhythmias	6
1.4	The Problem with Existing Cardiac Arrhythmia Automatic Diagnostic Solutions	7
1.5	Proposed Solutions and Book Contribution.....	7
1.6	Goal of the Work.....	8
1.7	Book Outline.....	9
2	Literature Review	11
2.1	Cardiovascular Diseases	12
2.1.1	Mortality	12
2.1.2	Prevalence	13
2.2	ECG Filtering: A Review	13
2.3	ECG Feature Extraction Techniques: A Review	15
2.4	ECG Classification Techniques: A Review	15
2.4.1	Support Vector Machine (SVM)	16
2.4.2	Artificial Neural Network (ANN).....	17
2.4.3	Hidden Markov Model (HMM).....	18
2.4.4	Linear Discriminant Analysis (LDA).....	18
2.4.5	Naive Bayes	19
2.4.6	Hybrid Methods	19
2.5	Hardware Implementation of ECG Signal Processing Systems: A Review	20
2.5.1	State-of-the-Art.....	20
3	System Design and Development.....	23
3.1	ECG Databases	26
3.2	Analytical Methods for ECG Preprocessing.....	27