QUARTERLY

OF

APPLIED MATHEMATICS

EDITED BY

S. S. ANTMAN Z. ARTSTEIN H. T. BANKS J. A. CARRILLO H. COHEN A. CONSTANTIN J. D. COWAN G. DASSIOS S. GEMAN J. HUNTER G. IOOSS I. KIM I. KONTOYIANNIS P. D. MILLER

D. MUMFORD J. R. RICE B. SANDSTEDE L. SIROVICH M. SLEMROD J. WILKENING

CONSTANTINE DAFERMOS Managing Editor

GOVIND MENON Associate Managing Editor

MANAGING EDITOR 1965–2014 WALTER FREIBERGER

FOUNDER, AND MANAGING EDITOR 1943–1965

W. PRAGER

VOLUME LXXVII

JUNE · 2019

NUMBER 2

Quarterly of Applied Mathematics

This journal is devoted to original papers in applied mathematics which have an intimate connection with applications. It is expected that each paper will be of a high scientific standard; that the presentation will be of such character that the paper can be easily read by those to whom it would be of interest; and that the mathematical argument, judged by the standard of the field of application, will be of an advanced character.

In accordance with their general policy, the Editors welcome particularly contributions which will be of interest both to mathematicians and to scientists or engineers. Authors will receive galley proof, and offprints will be provided in electronic form free of charge. A downloadable and printable PDF of each published article will be available to authors immediately after publication. Detailed instructions will be sent with galley proofs.

Submission information. The Quarterly of Applied Mathematics uses Centralized Manuscript Processing for initial submission. Authors should submit a PDF file using the Initial Manuscript Submission form found at www.ams.org/submission/qam. The final decision on acceptance of a manuscript for publication is made by the Managing Editor. Simultaneous submissions (i.e., concurrent submissions to another journal) are not accepted. See Suggestions Concerning the Preparation of Manuscripts for the Quarterly of Applied Mathematics at the end of this issue.

Publication on the AMS website. Articles are published on the AMS website individually after proof is returned from authors and before appearing in an issue.

Copying and reprinting. Material in this journal may be reproduced by any means for educational and scientific purposes without fee or permission with the exception of reproduction by services that collect fees for delivery of documents and provided that the customary acknowledgment of the source is given. This consent does not extend to other kinds of copying for general distribution, for advertising or promotional purposes, or for resale. Requests for permission for commercial use of material should be addressed to the Division of Applied Mathematics, Brown University, 182 George Street, Box F, Providence, RI 02912.

Excluded from these provisions is material in articles for which the author holds copyright. In such cases, requests for permission to use or reprint should be addressed directly to the author(s). (Copyright ownership is indicated in the notice in the lower right-hand corner of the first page of each article.)

Subscription information. Beginning March 2005 the Quarterly of Applied Mathematics is accessible from www.ams.org/journals/. Subscription prices for Volume 77 (2019) are as follows: for paper delivery, US\$200; for electronic delivery, US\$175. Subscription renewals are subject to late fees. See www.ams.org/journals-faq for more journal subscription information. Upon request, subscribers to paper delivery of this journal are also entitled to receive electronic delivery. For back volume/back issue prices and availability, go to www.ams.org/bookstore/backvols/. For paper delivery, subscribers inside the United States must pay a postage surcharge of US\$5.25; subscribers outside the United States must pay a postage surcharge of US\$15. Subscriptions and orders for back volumes must be addressed to the American Mathematical Society, P.O. Box 845904, Boston, MA 02284-5904, USA. All orders must be accompanied by payment. Other subscription correspondence should be addressed to the American Mathematical Society, 201 Charles St., Providence, RI 02904-2213, USA.

© 2019 Brown University

This journal is indexed in Mathematical Reviews, Zentralblatt MATH, Science Citation Index[®], Science Citation IndexTM-Expanded, ISI Alerting ServicesSM, CompuMath Citation Index[®], Current Contents[®]/Engineering, Computing & Technology. It is also indexed by Applied Science & Technology Index and abstracted by Applied Science & Technology Abstracts. Periodicals postage paid at Providence, RI and additional mailing offices. POSTMASTER: Send address changes to Quarterly of Applied Mathematics, Membership and Customer Services Department, American Mathematical Society, 201 Charles St., Providence, RI 02904-2213, USA. Publication number 808680. Quarterly of Applied Mathematics (ISSN 0033-569X (print); ISSN 1552-4485 (online)) is published four times per year (March, June, September, and December) by Brown University, Division of Applied Mathematics, 182 George St., Providence, RI 02912, USA. Printed in the United States of America. The paper used in this journal is acid-free and falls within the guidelines established to ensure permanence and durability.

FOREWORD

This issue of the Quarterly of Applied Mathematics is dedicated to the memory of our distinguished colleague Ulf Grenander. In a career spanning more than four decades, Ulf pioneered a holistic foundation for the analysis of high-dimensional signals that he termed *pattern theory*. A personal introduction to these ideas and a brief testament to Ulf as a person are contained in the article by our colleague David Mumford. The remaining articles in this issue are scientific papers that discuss many current aspects of pattern theory.

I express my gratitude to Michael Miller, Anuj Srivastava, and Song-Chun Zhu for their enthusiastic appreciation for Ulf's work, their assistance in editing this issue, and their persistent efforts to bring it to completion.

> Govind Menon Associate Managing Editor

SUGGESTIONS CONCERNING THE PREPARATION OF MANUSCRIPTS FOR THE QUARTERLY OF APPLIED MATHEMATICS

The editors will appreciate the authors' cooperation in taking note of the following directions for the preparation of manuscripts. These directions have been drawn up with a view toward eliminating unnecessary correspondence, avoiding the return of papers for changes, and reducing the charges made for "author's corrections."

Submission of Accepted Manuscripts:

Submission of manuscripts electronically-prepared in IATEX is required, with a strong preference for $\mathcal{A}_{\mathcal{M}}S$ -IATEX. To assist authors in preparing electronic manuscripts, the AMS has prepared author packages. The author package includes instructions for preparing electronic manuscripts, the AMS Author Handbook, samples, graphic creation instructions, and a style file. When choosing a style file for the Quarterly of Applied Mathematics, choose the QAM-specific journal package, made available by the American Mathematical Society at www.ams.org/distribution/qam/qamauthorpac.html. For more technical information, please visit www.ams.org/authors/author-faq.html.

Contributions to the *Quarterly of Applied Mathematics* should be submitted in final form. Only typographical errors should be corrected in proof; composition charges for any major deviations from the manuscript will be passed on to the *Quarterly of Applied Mathematics*. An abstract is required for all QAM manuscripts.

After the contribution has been accepted for publication, electronic files (.tex files along with .eps (or .tiff) files for figures) should be submitted via the web at www.ams.org/submit-book-journal, or sent via email to pub-submit@ams.org, or sent on CD to the Electronic Prepress Department, American Mathematical Society, 201 Charles St., Providence, RI 02904-2294 USA. When submitting electronic manuscripts via email or CD, please include a message indicating that the paper has been accepted for publication in the *Quarterly of Applied Mathematics*.

Electronic Graphics:

Comprehensive instructions on preparing graphics are included in PDF format in the author package. Submit files for graphics as EPS (Encapsulated PostScript) files. This includes graphics originating via a graphics application as well as scanned photographs or other computer-generated images. If this is not possible, TIFF files are acceptable as long as they can be opened in Adobe Photoshop or Illustrator.

Authors using graphics packages for the creation of electronic art should avoid the use of any lines thinner than 0.5 points in width at 100%. Many graphics packages allow the user to specify a "hairline" for a very thin line. Hairlines often look acceptable when proofed on a typical laser printer. However, when produced on a high-resolution laser imagesetter, hairlines become nearly invisible and will be lost entirely in the final printing process.

Screens should be set to values between 15% and 85%. Screens that fall outside of this range are too light or too dark to print correctly. Variations of screens within a graphic should be no less than 10%.

Any graphics created in color will be rendered in grayscale for the printed QAM issue unless color printing is authorized by the Managing Editor and paid for by the authors. In general, color graphics will appear in color in the online QAM issue.

CONTENTS

Vol. LXXVII, No. 2 June	2019
DAVID MUMFORD, A tribute to Ulf Grenander	201
JIAJUN SHEN AND YALI AMIT, Deformable classifiers	207
IRÈNE KALTENMARK AND ALAIN TROUVÉ, Estimation of a growth development with partial diffeomorphic mappings	227
MITCH HILL, ERIK NIJKAMP, AND SONG-CHUN ZHU, Building a telescope to look into high-dimensional image spaces	269
SATHYANARAYANAN N. AAKUR, FILLIPE DM DE SOUZA, AND SUDEEP SARKAR, Generating open world descriptions of video using common sense knowledge in a pattern theory framework	
RONAK MEHTA, HYUNWOO J. KIM, SHULEI WANG, STERLING C. JOHNSON, MING YUAN, AND VIKAS SINGH, Localizing differentially evolving covariance structures via scan statistics	357
SUTANOY DASGUPTA, DEBDEEP PATI, AND ANUJ SRIVASTAVA, Bayesian shape- constrained density estimation	399
YING NIAN WU, RUIQI GAO, TIAN HAN, AND SONG-CHUN ZHU, A tale of three probabilistic families: Discriminative, descriptive, and generative models	423
DANIEL J. TWARD, PARTHA P. MITRA, AND MICHAEL I. MILLER, Estimating diffeomorphic mappings between templates and noisy data: Variance bounds on the estimated canonical volume form	

