

Studies in Systems, Decision and Control

Volume 160

Series editor

Janusz Kacprzyk, Polish Academy of Sciences, Warsaw, Poland
e-mail: kacprzyk@ibspan.waw.pl

The series “Studies in Systems, Decision and Control” (SSDC) covers both new developments and advances, as well as the state of the art, in the various areas of broadly perceived systems, decision making and control-quickly, up to date and with a high quality. The intent is to cover the theory, applications, and perspectives on the state of the art and future developments relevant to systems, decision making, control, complex processes and related areas, as embedded in the fields of engineering, computer science, physics, economics, social and life sciences, as well as the paradigms and methodologies behind them. The series contains monographs, textbooks, lecture notes and edited volumes in systems, decision making and control spanning the areas of Cyber-Physical Systems, Autonomous Systems, Sensor Networks, Control Systems, Energy Systems, Automotive Systems, Biological Systems, Vehicular Networking and Connected Vehicles, Aerospace Systems, Automation, Manufacturing, Smart Grids, Nonlinear Systems, Power Systems, Robotics, Social Systems, Economic Systems and other. Of particular value to both the contributors and the readership are the short publication timeframe and the world-wide distribution and exposure which enable both a wide and rapid dissemination of research output.

More information about this series at <http://www.springer.com/series/13304>

Michał Piórek

Analysis of Chaotic Behavior in Non-linear Dynamical Systems

Models and Algorithms for Quaternions

 Springer

Michał Piórek
Department of Computer Engineering
Wrocław University of Science
and Technology
Wrocław, Poland

ISSN 2198-4182 ISSN 2198-4190 (electronic)
Studies in Systems, Decision and Control
ISBN 978-3-319-94886-7 ISBN 978-3-319-94887-4 (eBook)
<https://doi.org/10.1007/978-3-319-94887-4>

Library of Congress Control Number: 2018946568

© Springer International Publishing AG, part of Springer Nature 2019

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 the registered company Springer International Publishing AG part of Springer Nature
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To my Wife and my Family

Acknowledgements

Many people have contributed to this work. At first, I would like to express my deepest gratitude to Prof. Ewa Skubalska-Rafajłowicz and Dr. Bartosz Jabłoński for the countless support during the study on chaotic systems and quaternions. Their guidance helped me in all the time of research and writing of this book.

I would like to express my appreciation to Prof. Józef Korbicz and Prof. Andrzej Polański for the comments, which helped me to increase the value of this work.

I would also like to thank Prof. Ewaryst Rafajłowicz, Prof. Tyll Krueger, and Dr. Łukasz Korus for very important advice and help during the research.

My sincere thanks also go to Prof. Konrad Wojciechowski, Dr. Henryk Josiński, Dr. Adam Świtoński, and colleagues from Silesian University of Technology, who provided me an opportunity to work with their team, and who gave access to the great gait recordings data set. Without their precious support, it would not be possible to conduct this research. Human motion data used in the experiments presented in this book was obtained from the Centre for Research and Development of Polish-Japanese Academy of Information Technology (www.bytom.pja.edu.pl).

A special thanks to my family, my wife for her patience and indulgence, my parents, siblings, and friends for supporting me spiritually. I hope we will have more time for each other now.

Contents

1	Introduction	1
1.1	Problem Characteristics	3
1.2	Proposed Methods and Algorithms, Carried Out Numerical Experiments	3
1.3	Novelties Presented in This Work	4
1.4	Motivations	4
1.5	Book Structure	5
2	Processes Described by Quaternion Models	7
2.1	Definition of the Processes Described by Quaternion Models	7
2.2	Elements of Quaternion's Algebra	8
2.3	Quaternions Visualization	11
2.4	Quaternions Averaging	12
2.5	Quaternions Random Generation	14
2.6	Advantages and Disadvantages of Using Quaternions Parametrization of Rotation	16
3	Deterministic Chaos Properties	19
3.1	Dynamical Systems	19
3.2	Chaos Properties	22
3.2.1	Positive Entropies	22
3.2.2	Strong Sensitivity to Initial Conditions	26
3.2.3	Strange Attractor	28
3.2.4	Non-integer Fractal Dimension of the Attractor	29
3.3	Analysis of Chaos Basing on a Time Series	30
3.4	Time Delay Embedding	32
4	Analysis of Chaos from Time Series - Existing Methods Survey	35
4.1	Time Delay	35
4.2	Embedding Dimension	37
4.3	Reconstruction of the Phase Space	38

4.4	The Largest Lyapunov's Exponent	40
4.5	Entropies	41
4.6	Fractal Dimension	43
5	Analysis of Chaos from Quaternion Time Series - Proposed Methods	45
5.1	Quaternion's Angle Method	45
5.2	Time Delay Embedding for Quaternion Time Series	47
5.3	Mutual Information for Quaternions	48
5.4	Quaternions Clustering	50
5.5	Quaternions Clustering Validity Measures	53
	5.5.1 Quaternion Davies–Bouldin Index (QDB)	54
	5.5.2 Quaternion Dunn's Index (QDI)	54
	5.5.3 Quaternion Calinski–Harabasz Index (QCH)	56
5.6	False Nearest Neighbours	58
5.7	The Largest Lyapunov's Exponent	60
5.8	Correlation Dimension	62
6	Numerical Experiments	65
6.1	Experiments Description	65
6.2	Investigated Time Series	66
6.3	Gait Quaternion Time Series	66
6.4	Random Quaternion Time Series	70
6.5	Periodic Quaternion Time Series	70
6.6	The Aim of Experiments	70
7	Analysis of Chaos for Quaternion Time Series	73
7.1	Analysis of Chaos - Gait Time Series	73
	7.1.1 Clusters Number Estimation	73
	7.1.2 Time Delay Estimation	75
	7.1.3 Embedding Dimension Estimation	75
	7.1.4 Phase Space Reconstruction	76
	7.1.5 The Largest Lyapunov's Exponent Estimation	76
	7.1.6 Correlation Dimension Estimation	77
7.2	Analysis of Chaos - Periodic Time Series	78
	7.2.1 Clusters Number Estimation	78
	7.2.2 Time Delay Estimation	79
	7.2.3 Embedding Dimension Estimation	80
	7.2.4 Phase Space Reconstruction	80
	7.2.5 The Largest Lyapunov Exponent Estimation	81
	7.2.6 Correlation Dimension Estimation	81
7.3	Analysis of Chaos - Random Time Series	82
	7.3.1 Clusters Number Estimation	82
	7.3.2 Time Delay Estimation	83

- 7.3.3 Embedding Dimension Estimation 84
- 7.3.4 Phase Space Reconstruction 84
- 7.3.5 The Largest Lyapunov Exponent Estimation 85
- 7.3.6 Correlation Dimension Estimation 86
- 7.4 Experiments Conclusions 87
- 8 Comparison Against Existing Approaches 89**
 - 8.1 Compared Approaches 89
 - 8.2 Medical Angles Analysis 91
 - 8.2.1 Medical Angles Analysis Procedure 91
 - 8.2.2 Model Parameters 93
 - 8.2.3 LLE Values 94
 - 8.3 Quaternion Angles Analysis 96
 - 8.3.1 Quaternion Angles Embedding Procedure 96
 - 8.3.2 Model Parameters 97
 - 8.3.3 LLE Values 98
 - 8.4 Quaternions Analysis 100
 - 8.4.1 Quaternions Analysis Procedure 100
 - 8.4.2 Clusters Numbers 104
 - 8.4.3 Model Parameters 107
 - 8.4.4 LLE Values 107
 - 8.5 Experiments Conclusions 109
- 9 Quaternions Clustering 111**
 - 9.1 Optimal Clusters Number Selection - Data Sets Generated
Around Known Number of Clusters. 111
 - 9.2 Optimal Clusters Number Selection - Data with Varied
Overlapping Degree 115
 - 9.3 Optimal Clusters Number Selection - Data with Different
Variance. 117
 - 9.4 Experiments Conclusions 118
- 10 Summary 123**
- References 127**