

NONLINEAR TIME-SERIES ANALYSIS FOR
~~HUMAN-ROBOT~~ MOVEMENT VARIABILITY IN
HUMAN-ROBOT INTERACTION

by

MIGUEL P XOCHICALE

Chris Baber
comments on

21 August 2018

A thesis submitted to
The University of Birmingham
for the degree of
DOCTOR OF PHILOSOPHY

School of Engineering
College of Engineering and Physical Sciences
The University of Birmingham
July 2018

Table of contents

1	Introduction	1
1.1	Background	1
1.2	Research questions and contributions	3
1.3	Structure of this thesis	3
1.4	Publications	4
2	Literature Reviews	7
2.1	Movement Variability	7
2.2	Human Movement Variability	9
2.2.1	Measures of Variability	11
2.3	Human-Robot Movement Variability (HRMV)	13
2.3.1	HRMV in rehabilitation	13
2.3.2	HRMV in robotic dance	14
2.4	Gaps in ^{the study of} Movement Variability in the context of Human-Humanoid Interaction	14
3	Quantifying Movement Variability	15
3.1	Introduction	15
3.2	Fundamental concepts of time-series analysis	16
3.2.1	Stochastic vs deterministic	16

Table of contents

3.2.2	Nonstationary vs stationary	16
3.3	Quantifying Movement Variability with traditional approaches	16
3.3.1	Time-domain	16
3.3.2	Frequency-domain	16
3.3.3	Shortcomings of linear methods	17
3.4	Quantifying Movement Variability with Nonlinear Dynamics	17
3.4.1	RSS	17
3.4.2	RP and RQA	17
3.4.3	Others: Entropy, LyE, Poincare Maps	17
3.4.4	Shortcoming of nonlinear dynamics tools	18
4	Nonlinear Dynamics Tools	21
4.1	Introduction	21
4.2	State Space Reconstruction Theorem	22
4.3	Uniform Time-Delay Embedding (UTDE)	23
4.4	Estimation of Embedding Parameters	25
4.4.1	False Nearest Neighbours	25
4.4.2	Average Mutual Information	30
4.4.3	Other methodologies for state space reconstruction.	32
4.5	Recurrence Plots	33
4.6	Structures of Recurrence Plots	34
4.7	Recurrence Quantifications Analysis (RQA)	36
4.7.1	Measures based on the recurrence density	37
4.7.2	Measures based on diagonal lines	37
4.7.3	Measures based on vertical lines	39
4.7.4	Advanced quantifications	40
4.7.5	Sensitivity and robustness of RPs and RQA.	40

5	Time-series Dataset	43
5.1	Arm movements following an image while not hearing a beat	44
5.2	Arm movements following an image while hearing a beat	44
5.3	Arm movements following a humanoid robot while hearing beat rate . .	45
6	Quantifying Human Imitation Activities	47
7	Quantifying Human-Humanoid Imitation Activities	49
7.1	Human-Humanoid Imitation Experiment	49
7.1.1	Experiment of HHI activities	50
7.1.2	Time-series from Inertial Measurement Units	52
7.1.3	Postprocessing data	53
7.2	Human-Humanoid Imitation Activities	55
7.2.1	Time series	55
7.2.2	UTDE for time series in the context of human-robot interaction	56
7.2.3	RPs and RQA for time series in the context of human-robot interaction	60
7.2.4	RQA metrics with different embedding parameters, recurrence thresholds, window lengths, levels of smoothness, and time series structures.	68
8	Conclusion	75
8.1	Discussion	75
8.1.1	RQA metrics with fixed parameters	76
8.1.2	RQA metrics with different parameters	77
8.2	Conclusions	77
8.3	Future Work	78
8.3.1	Inertial Sensors	78

Table of contents

8.3.2 RQA	79
Appendix A Examples of Uniform Time-Delay Embedding	81
A.1 20 sample length vector.	81
A.2 Time series from an horizontal movement of a triaxial accelerometer. .	83
Appendix B Inertial Sensors	87
B.1 NeMEMsi IMU sensors	87
B.2 Time-series preprocessing	90
B.2.1 Organising Data in Multidimensional Arrays	90
B.2.2 Data Synchronisation	90
B.2.3 Time Alignment	91
References	93