

Contents

1	An Introduction to the 6th Edition of the International Workshop on Functional and Operatorial Statistics	1
	Germán Aneiros, Enea G. Bongiorno, Aldo Goia and Marie Hušková	
1.1	IWFOS Contribution to Functional Data Analysis	1
1.2	Methodological Contribution for Statistics with Functional Data	2
1.3	Applied Functional Data Analysis Contributions	3
1.4	Contributions on AI	4
1.5	Concluding Comments	4
	References	4
2	Local Constant Likelihood Estimation for Beta Distribution with Time Varying Parameters	7
	Nihan Acar-Denizli and Pedro Delicado	
2.1	Introduction	7
2.2	Local Constant Log-likelihood in Two Parameter Models	8
2.3	Case Study: Effect of Quinoa Diet on Glucose Concentrations	9
	References	14
3	An Expansion of the Functional Projection Pursuit Regression to Generalized Partially Linear Single Index Models	15
	Mohamed Alahiane, Mustapha Rachdi, Idir Ouassou and Philippe Vieu	
3.1	Introduction	16
3.2	Estimation Methodology	17
3.3	Assumptions	20
3.4	Some Asymptotics	21
	References	22
4	On the Estimation of Invertible Functional Time Series	25
	Alexander Aue, Sebastian Kühnert and Gregory Rice	
4.1	Introduction	25
4.2	Estimation in the inverted representation	26
	References	31

5	Uniform Confidence Bands for Joint Angles Across Different Fatigue Phases	33
	Patrick Bastian, Rupsa Basu and Holger Dette	
5.1	Introduction	33
5.2	Confidence bands for multiple means	36
5.3	Application to sports data	40
	References	42
6	Scalar on Shape Regression Using Function Data	43
	Sayan Bhadra and Anuj Srivastava	
6.1	Introduction	43
6.2	Proposed Model: Scalar on Shape Regression	45
6.3	Experimental Results	46
6.4	Conclusion	49
	References	50
7	A Comparison of Band-based Approaches to Functional Depth	51
	Filip Boćinec, Erik Mendroš and Stanislav Nagy	
7.1	Introduction: Statistical Depth in Multivariate and Functional Data Analysis	51
7.2	Band-based Functional Depths	52
7.3	Theoretical Properties	54
7.4	A Real-world Data Demonstration	56
	References	59
8	Analysing the Complexity Mixture Structure of Daily Probability Densities of Bitcoin Returns	61
	Enea G. Bongiorno, Lax Chan and Aldo Goia	
8.1	Introduction	61
8.2	Complexity Mixture Process	62
8.3	Identifying a Complexity Mixture Process	64
8.4	Bitcoin Density Returns Data Analysis	65
	References	68
9	Regularized Nonparametric Estimation of Covariance Kernels for High-Dimensional Interferometric Data	69
	Teresa Bortolotti, Roberta Troilo, Alessandra Menafoglio and Simone Vantini	
9.1	Introduction	70
9.2	Relevant Technical Background	71
9.3	Regularized Covariance Kernel Estimation	72
9.4	Simulation Study	72
9.5	Case Study	73
9.6	Conclusions	75
	References	75

10	Statistical Properties of a Random Series Transmitted by Filtering . .	77
	Alain Boudou and Sylvie Vigui�r-Pla	
10.1	Introduction	77
10.2	The Spaces H^Z and $\mathcal{H}^Z$	78
10.3	H -stationarity	79
10.4	Trajectory	80
10.5	Transmission of Strict Stationarity and Ergodicity by Filtering . . .	81
10.6	Deployment	83
10.7	Trasmission of the Periodicity in Distribution	84
	References	84
11	Multi-Object Regression: A Linear Framework via Partial Least Squares	85
	Robert Cantwell and John Aston for the Alzheimer’s Disease Neuroimaging Initiative	
11.1	Introduction	85
11.2	Partial Least Squares Methodology	86
11.3	Simulation and Results	91
	References	92
12	Monitoring the Covariance of Multichannel Profiles	93
	Christian Capezza, Davide Forcina, Antonio Lepore, Biagio Palumbo	
12.1	Introduction	93
12.2	Methodology	95
12.3	Simulation Study	96
12.4	Case Study	98
12.5	Conclusions	99
	References	99
13	Statistical Modeling of Categorical Trajectories with Multivariate Functional Data Approaches	101
	Herv� Cardot and Caroline Peltier	
13.1	Introduction	101
13.2	Notations and Mathematical Framework	103
13.3	Sampling and Estimators	105
13.4	An Illustration in Sensory Analysis	105
13.5	Concluding Remarks	106
	References	108
14	Markov Switching Tensor Regressions	109
	Roberto Casarin, Radu Craiu and Qing Wang	
14.1	Introduction	109
14.2	A Markov-switching Tensor Regression Model	110
14.3	Posterior Approximation	112
14.4	Empirical Application	114
14.5	Conclusion	115

References	117
15 Functional Data Depth for the Analysis of Earth Surface Temperatures	119
Michele Cavazzutti, Eleonora Arnone, Ying Sun, Marc G. Genton and Laura M. Sangalli	
15.1 Introduction	119
15.2 Integrated Functional Depth for Multidimensional Domains	120
15.3 Application to LENS-CESME Temperature Data	123
15.4 Conclusion	124
References	125
16 Improving Finite Samples Performances in Nonparametric Functional Regression by Using Weighted Pseudo-Metrics	127
Lax Chan, Laurent Delsol and Aldo Goia	
16.1 Introduction	127
16.2 The Model and the Estimate	128
16.3 The Weighted Pseudo-metric Effect	129
16.4 Weighted Pseudo-metric Selection	131
16.5 A Numerical Example	132
References	134
17 Smoothing with Nonlinear Partial Differential Equation Regularization	135
Aldo Clemente, Alessandro Palummo, Eleonora Arnone and Laura M. Sangalli	
17.1 Introduction	136
17.2 Smoothing with Nonlinear PDEs	137
17.3 Simulation Study	138
17.4 Application to Neuroimaging Data	139
References	141
18 Functional Principal Component Analysis for Bivariate Densities and their Orthogonal Decomposition	143
Adéla Czolková, Karel Hron and Sonja Greven	
18.1 Bayes Spaces	143
18.2 FPCA for Bivariate Densities	146
18.3 Multivariate FPCA for Orthogonal Parts of Bivariate Densities ...	147
18.4 Application	149
References	150
19 Estimating Multiple Quantile Surfaces: A Penalized Functional Approach	151
Marco F. De Sanctis, Ilenia Di Battista, Eleonora Arnone, Cristian Castiglione, Mauro Bernardi, Francesca Ieva and Laura M. Sangalli	
19.1 Introduction	152
19.2 Semiparametric Physics-Informed Multiple Quantile Model	153

19.3	Application to Air Quality Data	155
19.4	Future Directions	157
	References	158
20	Neural Drift Estimation for Ergodic Diffusions: Nonparametric Analysis and Numerical Exploration	159
	Simone Di Gregorio and Francesco Iafrate	
20.1	Neural Nonparametric Drift Estimation for Ergodic Diffusions ...	159
20.2	Building Regular Networks	161
20.3	Numerical Monte Carlo Testing	163
	References	167
21	Amplitude-Invariant Functional Motif Discovery	169
	Jacopo Di Iorio, Marzia A. Cremona and Francesca Chiaromonte	
21.1	Introduction	170
21.2	Methodology	170
21.3	Simulations	173
21.4	Conclusions	176
	References	176
22	Testing the Significance of Covariates in Nonparametric Regression without the Curse of Dimensionality	177
	Daniel Diz-Castro, Manuel Febrero-Bande and Wenceslao González-Manteiga	
22.1	Introduction	177
22.2	Connecting Smoothing and Empirical Process-Based Tests	178
22.3	Assumptions	180
22.4	Asymptotics	182
22.5	Discussion	183
	References	184
23	Gaussian Process Methods for Covariate-Based Intensity Estimation	185
	Patric Dolmeta and Matteo Giordano	
23.1	Introduction	185
23.2	Posterior Contraction Rates for Covariate-Based Intensity Estimation	186
23.3	Concluding Discussion	190
23.4	Proof	190
	References	192
24	Spectral Analysis of Multidimensional Thermal Fields	193
	Mélanie Dreina, Sylvie Viguier-Pla and Stéphane Abide	
24.1	Introduction	193
24.2	Description of the Data	194
24.3	The Methods of Dimension Reduction	194
24.4	Results and Discussion	197
24.5	Comparisons	198

24.6	Conclusion	199
	References	200
25	Forecasting Dynamic Factor Scores by UNALSE Spectral Density Matrix Estimator	201
	Matteo Farnè and Xuanye Dai	
25.1	Theoretical Background	201
25.2	Estimating Factor Loadings and Scores	204
25.3	Numerical Example	207
	References	208
26	Testing for Linearity and Independence in Scalar-on-Function Regression with Responses Missing at Random by Generalized Distance Covariance	209
	Manuel Febrero-Bande, Pedro Galeano and Wenceslao González-Manteiga	
26.1	Introduction	209
26.2	The FLMSR with MAR Responses	211
26.3	The Testing Procedure	213
26.4	Conclusions	215
	References	216
27	A Novel Spectral Density Operator Approach to Unveil Dynamic Time Dependencies in Multivariate Long-Term ECGs	217
	Antonino Gagliano, Chiara Di Maria, Gianluca Sottile, Sarah Beutler-Traktovenko, Luigi Augugliaro and Valeria Vitelli	
27.1	Introduction	217
27.2	Methods	218
27.3	Dataset Description and Analysis	219
27.4	Conclusion	223
	References	224
28	Comparison of Deep Learning Methods for Functional Data	225
	Nouhaila Goujili, Matthieu Saumard and Maher Jridi	
28.1	Introduction	225
28.2	Evolution Towards Non-Linear and Functional Deep Models	226
28.3	Empirical Results	228
28.4	Conclusion	232
	References	232
29	The Common Support Function with Applications	233
	Nicolás Hernández and Stanislav Nagy	
29.1	Introduction	233
29.2	The Common Support Curve	234
29.3	Real Data Application: Identifying ECG Segments	238
29.4	Conclusion and Further Research	239
	References	239

30	Multivariate Densities in Bayes Spaces: The Novel Concept of Marginals and Its Implications	241
	Karel Hron	
30.1	Bayes Spaces	241
30.2	Key Concept: Geometric Marginals	243
30.3	Implications of Geometric Marginals	247
	References	248
31	Functional K Sample Problem via Multivariate Optimal Measure Transport-Based Permutation Test	249
	Šárka Hudecová, Daniel Hlubinka and Zdeněk Hlávka	
31.1	Introduction	249
31.2	Multivariate Test Statistic for the K Sample Problem	251
31.3	Permutation Test Based on the Optimal Measure Transport	252
31.4	Real Data Application	253
	References	256
32	Sequential Monitoring for Detection of Breaks in Panel Data	259
	Marie Hušková and Charl Pretorius	
32.1	Introduction	259
32.2	Procedures	261
32.3	Simulation Study	262
	References	266
33	Robust Penalized Splines for Location Estimation from Discretely Sampled Functional Data	267
	Ioannis Kalogridis and Stefan Van Aelst	
33.1	Introduction	267
33.2	Rates of convergence	268
33.3	Proof of Theorem 33.1	269
	References	275
34	Functional Regression with Shape Constraints	277
	Yuwei Jiang and Natalya Pya Arnqvist	
34.1	Introduction	277
34.2	Modelling Framework	278
34.3	Simulation Study	281
	References	284
35	Enhancing Causal Inference in Functional Data: a Method for Estimating Time-Varying Causal Treatment Effects	285
	Francesca Ieva, Nicole Fontana, Carlo Andrea Pivato, Emanuele Di Angelantonio and Piercesare Secchi	
35.1	Introduction	285
35.2	Methodology	287
35.3	Data and Setting	289
35.4	Results	290

35.5	Discussion and Conclusion	291
	Appendix 1	292
	References	293
36	Linear and Nonlinear Regression Models for Spatial Downscaling of Particulate Matter	295
	Luigi Ippoliti, Tonio Di Battista, Luigi Di Carlo, Stefania Fensore, Eugenia Nissi, Pasquale Valentini, Carlo Zaccardi	
36.1	Introduction to Spatial Downscaling	295
36.2	Spatial Downscaling of CAMS Images	296
36.3	Analysis of PM10 in Italy	300
36.4	Discussion	302
	References	302
37	A Bayesian Non-Parametric Model to Learn Functions with Discontinuities	303
	Alessandro Lanteri, Raffaele Argiento, Silvia Montagna	
37.1	Introduction	303
37.2	Model and Priors	305
37.3	Simulation Study	307
	References	309
38	A Novel Approach To Estimate Functional Gaussian Graphical Model Based On Penalized Multivariate Functional Regression Model	311
	Salvatore Latora, Luigi Augugliaro and Gerda Claeskens	
38.1	Introduction	311
38.2	Proposal Methodology	312
38.3	Simulation Study	315
38.4	Conclusions	316
	References	317
39	Local Null Hypothesis Significance Testing on Riemaniann Manifolds	319
	Niels Lundtorp Olsen, Alessia Pini and Simone Vantini	
39.1	Introduction	319
39.2	Setting and Pointwise Testing	320
39.3	The Functional False Discovery Rate	321
39.4	The Functional Ball-Wise Error Rate	321
39.5	The Functional Ball-Wise e -Validity	322
39.6	Numerical Example	323
39.7	Conclusions	324
	References	325

40	Efficient Bayesian Linear Models for a Large Number of Observations	327
	Hassan Maatouk, Didier Rulli��re and Xavier Bay	
40.1	Introduction	327
40.2	Gaussian Process Regression Review	328
40.3	Finite-Dimensional Bayesian Linear Models	329
40.4	Numerical Performance	332
40.5	Conclusion	334
	References	334
41	Innovative Approach to Wind Direction Data Analyses: A Compositional Periodic Spline Representation in Bayes Spaces	337
	Jitka Machalov�� and Jana Heckenbergerov��	
41.1	Introduction	337
41.2	Periodic Smoothing Splines	339
41.3	Applications	342
41.4	Conclusion	343
	References	344
42	Bayes Hilbert Space Additive Density-on-Scalar Regression Based on Individual Observations	345
	Eva-Maria Maier, Alexander Fottner, Almond St��cker and Sonja Greven	
42.1	Introduction	346
42.2	Bayes Hilbert Spaces	346
42.3	Bayes Hilbert Space Additive Regression	347
42.4	Estimation and Inference	348
42.5	Application to Gender Economics	351
	References	352
43	A Kernel-Based Approach for Testing Mutual Independence of Several Functional Variables	355
	Terence Kevin Manfoumbi Djonguet and Guy Martial Nkiet	
43.1	Introduction	355
43.2	Preliminary Notions	356
43.3	Symmetric and Assymetric Aggregations	357
43.4	Testing for Mutual Independence	358
43.5	Simulations	362
	References	363
44	Addressing Robustness and Sparsity in Partially Linear Additive Models	365
	Alejandra Mercedes Mart��nez	
44.1	Introduction	365
44.2	The Proposed Estimator	366
44.3	Simulation Study	368
	References	373

45	Covariance Operators for Phonetics: Revisiting Tonal Coarticulation	375
	Valentina Masarotto and Yiya Chen	
45.1	Introduction	375
45.2	Statistical methods	377
45.3	Results	379
	References	382
46	A-optimal Designs of Experiments in Linear Models with Dynamic Factors and Functional Responses	385
	Caterina May, Theodoros Ladas, Davide Pigoli and Kalliopi Mylona	
46.1	Introduction	385
46.2	A Motivating Example	386
46.3	Model, Inferential Results and Optimal Design of Experiments	387
46.4	Numerical Examples	388
46.5	Conclusions	389
	References	392
47	Moving Object-Oriented Spatial Statistics Beyond Stationary and Euclidean Paradigms	393
	Alessandra Menafoglio	
47.1	Introduction	393
47.2	A General Model for O2S2 in Stationary and Euclidean Settings	394
47.3	On the Importance of the Embedding Space	395
47.4	Beyond Stationary and Euclidean Paradigms	396
47.5	Conclusion	398
	References	399
48	The Spherical Depth for Functional Data	401
	Erik Mendroš and Stanislav Nagy	
48.1	Introduction: Depth in Multivariate and Function Spaces	401
48.2	Spherical Depth for Functional Data	403
48.3	Some Theory of the Spherical Depth	404
48.4	A Real Data Application	406
	References	407
49	False Discovery Rate Envelope and its Performance for Local Testing in Functional Data Analysis	409
	Tomáš Mrkvička	
49.1	Introduction	409
49.2	Motivational example	411
49.3	FDR Envelope	414
49.4	Comparison of the Performance in the Local Testing Task	414
49.5	Conclusions and Discussion	415
	References	416

50	Interpretable Functional Boxplots	417
	Stanislav Nagy	
50.1	Introduction: Functional Boxplots	417
50.2	Prerequisites: Functional Depths and Bands	418
50.3	Band Convexity and Functional Boxplots	420
50.4	The Practice of Functional Boxplots	422
	References	424
51	Scalar-on-Function Regression with Partially Observed Covariate ..	427
	Silvia Novo, Alessandro Palummo and Laura M. Sangalli	
51.1	Introduction	427
51.2	Methodology	429
51.3	Discussion	431
	References	432
52	Efficient Physics-Informed Smoothing of Space-time Functional Data	435
	Alessandro Palummo, Eleonora Arnone, Letizia Clementi and Laura M. Sangalli	
52.1	Introduction	435
52.2	Preliminaries: the Smoothing Problem	437
52.3	Iterative Estimation Procedure	438
52.4	Future Extensions towards Population Studies	439
	References	440
53	Ordinal-on-Function Dimensionality Reduction	443
	Giulia Patanè, Federica Nicolussi, Alexander Krauth, Günter Gauglitz, Bianca Maria Colosimo, Luca Dede' and Alessandra Menafoglio	
53.1	Introduction	444
53.2	State of the Art based on Dimensionality Reduction	445
53.3	Functional-Ordinal Canonical Correlation Analysis	445
53.4	Simulation Study	446
53.5	Conclusions	449
	References	449
54	Varying Coefficient Regression Models on Fluvial Networks	451
	Nicola Pronello, Rosaria Ignaccolo and Luigi Ippoliti	
54.1	Introduction	451
54.2	The Model	452
54.3	Nonparametric Estimator of $\Sigma(\mathbf{c})$	453
54.4	Implementation	455
	References	456

55	Non-Parametric Testing of Time Reversibility in Functional Data . . .	459
	Hedvika Ranošová and Daniel Hlubinka	
55.1	Introduction	459
55.2	Types of Reversibility	460
55.3	Empirical Characteristic Functionals	461
55.4	Test Statistic	462
55.5	Simulation	463
	References	465
56	An LRD Spectral Test for Irregularly Discretely Observed Functional Time Series in Manifolds	467
	María D. Ruiz-Medina and Rosa M. Crujeiras	
56.1	Introduction	467
56.2	Formulation of the Hypothesis Testing Problem	469
56.3	The Methodological Approach	472
	References	474
57	Prediction Regions for Functional-Valued Random Forests	475
	Diego Serrano and Eduardo García-Portugués	
57.1	Introduction	475
57.2	Random forests and FDA	476
57.3	Out-of-Bag Prediction Regions for FDA	478
57.4	A Numerical Experiment	479
	References	482
58	Sample Size Estimation for Two-Sample Functional Hypothesis Test	483
	Mohammad Reza Seydi, Johan Strandberg, Todd C. Pataky, and Lina Schelin	
58.1	Introduction	483
58.2	Methods	484
58.3	Simulation Study	487
58.4	Discussion	488
	References	491
59	Forecasting Age Distribution of Deaths at Subnational Level	493
	Han Lin Shang	
59.1	Introduction	493
59.2	Age Distribution of Deaths in 47 Japanese Prefectures	494
59.3	Transformations	495
59.4	Functional Time-Series Forecasting Models	496
59.5	Results	498
59.6	Conclusion	499
	References	500

60 Statistical Analysis of Bivariate Densities with Compositional Splines 503
Stanislav Škorňa and Jitka Machalová

60.1 Theoretical background 504

60.2 Application 506

60.3 Conclusion 508

References 510

61 Prediction with Mixed Effects Smooth Models by using P-Splines ... 511
Veronika Šmajserová and Jitka Machalová

61.1 Theoretical Framework 511

61.2 Prediction with Mixed Effects Smooth Models 514

61.3 Conclusion 518

References 519

62 Locally Sparse Estimation for Functional Linear Models with Scalar Response 521
Marco Stefanucci, Mauro Bernardi and Antonio Canale

62.1 Introduction 521

62.2 Model 522

62.3 Computation 523

62.4 Simulation 524

62.5 Application 526

References 527

63 Factor Models for High-Dimensional Functional Time Series 529
Shahin Tavakoli, Gilles Nisol, and Marc Hallin

63.1 Introduction 530

63.2 A Representation Theorem 531

63.3 Estimation 534

63.4 Theoretical Results 535

63.5 Numerical experiments and application 535

References 535

64 Anomaly-Driven Visualization of Functional Data 537
Romain Valla, Pavlo Mozharovskyi, and Florence d’Alché-Buc

64.1 Introduction 537

64.2 Taxonomy of Functional Anomalies 538

64.3 Projection-Based Visualization of Functional Anomalies 539

64.4 Parameters and Implementation Details 541

64.5 Real-Data Illustrations 542

64.6 Conclusion 544

References 544

65 Leveraging Data Exchangeability for a More Reliable and Interpretable Functional Data Analysis 547
Simone Vantini
65.1 Introduction 547
65.2 Cornerstones of Statistical Engineering 548
65.3 Leveraging Exchangeability in FDA 550
65.4 Conclusions 554
References 554

66 A Family of Moment Operators for Functional Data and Its Discriminative Properties 557
Marc Vidal
66.1 Introduction 557
66.2 Preliminaries and Definition 558
66.3 Identifying Fisher’s Discriminant Function as a Spectral Subspace of Higher-Moment Operators 560
66.4 Supplementary Definitions and Proofs 563
References 564

Authors Index 565