Big Data Analytics for Time-Critical Mobility Forecasting

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Big Data Analytics for Time-Critical Mobility Forecasting

From Raw Data to Trajectory-Oriented Mobility Analytics in the Aviation and Maritime Domains

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This book is dedicated to all those who struggle for a better own and others' trajectory with philotimo,[1] *respect and with no obsession.*

[1]Philotimo (or filotimo) is a Greek word, which is difficult to translate. One may start from here, among other references: https://en.wikipedia.org/wiki/Philotimo.

Preface

Spatiotemporal mobility data has a significant role and impact on the global economy and our everyday lives. The improvements along the last decades in terms of data management, planning of operations, security of operations, information provision to operators and end-users have been driven by location-centered information. While a shift of paradigm regarding mobility data towards trajectory-oriented tasks is emerging in several domains, the ever-increasing volume of data emphasizes the need for advanced methods supporting detection and prediction of events and trajectories, supplemented by advanced visual analytic methods, over multiple heterogeneous, voluminous, fluctuating, and noisy data streams of moving entities. This book provides a comprehensive and detailed description of Big Data solutions towards activity detection and forecasting in very large numbers of moving entities spread across large geographical areas. Specifically, following a trajectory-oriented approach, this book reports on the state-of-the-art methods for the detection and prediction of trajectories and important events related to moving entities, together with advanced visual analytics methods, over multiple heterogeneous, voluminous, fluctuating, and noisy data streams from moving entities, correlating them with data from archived data sources expressing, among others, entities' characteristics, geographical information, mobility patterns, regulations, and intentional data (e.g., planned routes), in a timely manner. Solutions provided are motivated, validated, and evaluated in user-defined challenges focusing on increasing the safety, efficiency, and economy of operations concerning moving entities in the air-traffic management and maritime domains.

The book contents have been structured into six parts:

The first part provides the motivating points and background for mobility forecasting supported by trajectory-oriented analytics. It presents specific problems and challenges in the aviation (air-traffic management) and the maritime domains and clarifies operational concerns and objectives in both domains. It presents domain-specific terminology used in examples and cases, in which technology is demonstrated, evaluated/validated, throughout the book. Equally important to the above is the presentation of the data sources exploited per domain, the big data challenges ahead in both domains, and of course, the requirements from

technologies presented in subsequent parts of the book. These chapters present data exploited for operational purposes in the aviation and maritime domains and provide an initial understanding of spatiotemporal data through specific examples. They also present challenges and motivating points by means of operational scenarios where technology can help, putting the technologies presented in subsequent parts of the book in a unique frame: This helps us understand why technological achievements are necessary, what are the domain-specific requirements driving developments in analytics, data storage, and processing, and what are the data processing, data management, and data-driven analytics tools needed to advance operational goals towards trajectory-based operations.

The second part focuses on big data quality assessment and processing, as applied in the data sources and according to the requirements and objectives presented in the first part of the book. This, second part of the book, presents novel technologies, appropriate to serve mobility analytics components that are presented in subsequent sections. In doing so, workflows regarding data sources' quality assessment via visual analytics methods are considered to be essential to understand inherent features and imperfections of data, affecting the ways data should be processed and managed, as the first section of this part shows. In addition to this, methods for online construction of streamed data synopses are presented, towards addressing big data challenges presented by surveillance, mostly, data sources.

The third part of this book specifies solutions towards managing big spatiotemporal data: The first section specifies a generic ontology revolving around the notion of trajectory so as to model data and information that is necessary for analytics components. This ontology provides a generic model for constructing knowledge graphs integrating data from disparate data sources. In conjunction to this, this part describes novel methods for integrating data from archived and streamed data sources. Special emphasis is given to enriching data streams and integrating streamed and archival data to provide coherent views of mobility: This is addressed by real-time methods discovering topological and proximity relations among spatiotemporal entities. Finally, distributed storage of integrated dynamic and archived mobility data—i.e. large knowledge graphs constructed according to the generic model introduced—are within focus.

The next part focuses on mobility analytics methods exploiting (online) processed, synopsized, and enriched data streams as well as (offline) integrated, archived mobility data. Specifically, online future location prediction methods and trajectory prediction methods are presented, distinguishing between short-term and the challenging long-term predictions. Recognition of complex events in challenging cases for detecting complex events is thoroughly presented. In addition to this, an industry-strong maritime anomaly detection service capable of processing daily real-world data volumes is presented. This part focuses also on offline trajectory analytics, addressing trajectory clustering and detection of routes followed by mobile entities. Novel algorithms for subtrajectory clustering are proposed and evaluated.

The fifth part presents how methods addressing data management, data processing, and mobility analytics are integrated in a big data architecture that

has distinctive characteristics when compared to known big data paradigmatic architectures. We call this architectural paradigm, which is based on well-defined principles for building analytics pipelines δ. This paradigm is instantiated to a specific architecture realizing the datAcron integrated system prototype. This part presents the software stack of the datAcron system, together with issues concerning individual, online, and offline components integration.

The last part focuses on important ethical issues that research on mobility analytics should address: This is deemed to be crucial, given the growth of interest in that topic in computer science and operational stakeholders, necessitating the sharing of data and distributing the processing among stakeholders.

All chapters present background information on the specific topics they address, detailed and rigorous specification of scientific and technological problems considered, and state-of-the-art methods addressing these problems, together with novel approaches that authors have developed, evaluated, and validated, mainly during the last 3 years of their involvement in the datAcron H2020 ICT Big Data Project. Evaluation and validation results per method are presented using data sets from both, maritime and aviation domain, showing the potential and the limitations of methods presented, also according to the requirements specified in the first part of the book. The chapters present also technical details about implementations of methods, aiming to address big data challenges, so as to achieve the latency and throughput requirements set in both domains.

In doing so, this book aims to present a reference book to all stakeholders in different domains with mobility detection and forecasting needs and computer science disciplines aiming to address data-driven mobility data exploration, processing, storage, and analysis problems.

I would like to take the opportunity to thank everybody who contributed to the exciting effort of developing mobility data processing, storage, analysis solutions in time-critical domains, whose state of the art is summarized in this book. These, as part of a much wider community, include all co-editors and chapter authors of this publication. This book is a concerted effort of many people who worked and continue to work together in different, but always exciting, lines of research for mobility analytics.

Piraeus, Greece
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George A. Vouros

Acknowledgements

The developments described in the chapters of this book have been developed in the course of work in several past and on-going research projects, whose support is also acknowledged by the authors of each chapter. However, ideas and large part of this work have been developed, evaluated, and validated, mainly during the 3 years of involvement in the datAcron H2020 ICT Big Data Project.

datAcron has been funded by the European Union's Horizon 2020 Programme under grant agreement No. 687591. datAcron is a research and innovation collaborative project whose aim was to introduce novel methods to detect threats and abnormal activity of very large numbers of moving entities in large geographic areas.

Towards this target, datAcron advanced the management and integrated exploitation of voluminous and heterogeneous data-at-rest (archival data) and data-in-motion (streaming data) sources, so as to significantly advance the capacities of systems to promote safety and effectiveness of critical operations for large numbers of moving entities in large geographical areas.

Technological developments in datAcron have been validated and evaluated in user-defined challenges that aim at increasing the safety, efficiency, and economy of operations concerning moving entities in the air-traffic management (ATM) and maritime domains.

The datAcron addressed the following core challenges:

- **Distributed management and querying of integrated spatiotemporal RDF data-at-rest and data-in-motion in integrated manners**: datAcron advanced RDF data processing and spatiotemporal query answering for very large numbers of real-world triples and spatiotemporal queries, providing also native support for trajectory data, handling (semantic) trajectories as first-class citizens in data processing. In situ data processing and link discovery for data integration are critical technologies to those targets.
- **Detection and prediction of trajectories of moving entities in the aviation and maritime domains**: datAcron developed novel methods for real-time trajectory reconstruction, aiming at efficient large-scale mobility data analytics. Real-time

trajectories forecasting for the aviation and maritime domains aim to a short forecasting horizon.

- **Recognition and forecasting of complex events in the aviation and maritime domains**: datAcron developed methods for event recognition under uncertainty in noisy settings, aiming at processing very large number of events/second with complex event definitions. In doing so, optimization of complex events patterns' structure and parameters by means of machine learning methods for constructing event patterns was within datAcron objectives.
- **Visual analytics in the aviation and maritime domains**: datAcron developed a general visual analytics infrastructure supporting all steps of analysis through appropriate interactive visualizations, including both generic components and components tailored for specific applications.

Contents

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About the Editors

Dr. Gennady Andrienko is a lead scientist responsible for the visual analytics research at Fraunhofer Institute IAIS (Sankt Augustin, Germany) and full professor at City University London. He co-authored monographs "Exploratory Analysis of Spatial and Temporal Data" (Springer, 2006) and "Visual Analytics of Movement" (Springer, 2013) and about 100 peer-reviewed journal papers. He is associate editor of three journals: "Information Visualization" (since 2012), "IEEE Transactions on Visualization and Computer Graphics" (2012–2016), and "International Journal of Cartography" (since 2014) and editorial board member of "Cartography and Geographic Information Science" and "Cartographica." He received Test of Time award at IEEE VAST 2018 and best paper awards at AGILE 2006, IEEE VAST 2011 and 2012 conferences, and EuroVA 2018 workshop.

Alexander Artikis is an Assistant Professor in the Department of Maritime Studies of the University of Piraeus. He is also a Research Associate in the Institute of Informatics and Telecommunications of NCSR Demokritos, the largest research center in Greece, leading the Complex Event Recognition lab. His research interests lie in the field of Artificial Intelligence. He has published over 100 papers in the top conferences and journals of the field, while, according to Google Scholar, his h-index is 31. He has participated in several EU-funded Big Data projects, being the scientific coordinator in some of them. He has been serving a member of the program committee of various conferences, such as AAAI, IJCAI, AAMAS, ECAI, KR, and DEBS.

Jose Manuel Cordero holds the Telecommunications Engineer degree from the Universidad de Sevilla, Spain (2002). He is currently a Principal Researcher at CRIDA (ATM R&D Reference Centre, depending on the Spanish ANSP, ENAIRE), with over 15 years of experience in the air-traffic management domain in the areas of performance monitoring and assessment, system simulation, and validation. In the

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Christos Doulkeridis is an Assistant Professor at the Department of Digital Systems in the University of Piraeus. He has been awarded both a Marie-Curie fellowship and an ERCIM "Allain Bensoussan" fellowship for postdoctoral studies at the Norwegian University of Science and Technology in 2011 and 2009, respectively. He was the Principal Investigator of the research project "RoadRunner: Scalable and Efficient Analytics for Big Data" (2014–2015, funded by the General Secretariat for Research and Technology in Greece). He has participated in several H2020 EU research projects related to Big Data management and analytics ("Track&Know" 2018–2020, "BigDataStack," 2018–2020, and "datAcron," 2016–2018). He has been awarded the first position in the 2017 SemEval challenge on Sentiment Analysis in Twitter and the third position in the 2016 ACM SIGSPATIAL Cup on Hot Spot Analysis of Mobility Data. He has published in top international journals (including VLDB Journal, IEEE TKDE, IEEE JSAC, ACM TKDD, Data Mining and Knowledge Discovery, Information Systems, Distributed and Parallel Databases) and conferences (including ACM SIGMOD, VLDB, ICDE, EDBT, SSTD, PKDD, SIAM SDM) in the areas of data management, knowledge discovery, and distributed systems.

Dr. Anne-Laure Jousselme is with the NATO Centre for Maritime Research and Experimentation. She is member of the Boards of Director of the International Society of Information Fusion and Belief Functions and Applications Society. She is associate editor of the Perspectives on Information Fusion magazine and area editor of the International Journal of Approximate Reasoning. Her research interests include maritime anomaly detection, information fusion, reasoning under uncertainty, information quality.

Nikos Pelekis is Assistant Professor at the Department of Statistics and Insurance Science, University of Piraeus, Greece. His research interests include all topics of data science. He has been particularly working for almost 20 years in the field of Mobility Data Management and Mining. Nikos has co-authored one monograph and more than 80 refereed articles in scientific journals and conferences, receiving more than 1000 citations, while he has received 3 best paper awards and won the SemEval'17 competition and ranked 3rd in ACM SIGSPATIAL'16 data challenge. He has offered several invited lectures in Greece and abroad (including PhD/MSc/summer courses at Rhodes, Milano, KAUST, Aalborg, Trento, Ghent, JRC Ispra) on Mobility Data Management and Data Mining topics. He has been actively involved in more than 10 European and National R&D projects. Among them, he is or was principal researcher in GeoPKDD, MODAP, MOVE, DATASIM,

SEEK, DART and datAcron, Track & Know, MASTER. For more information: http://www.unipi.gr/faculty/npelekis/.

Cyril Ray is associate professor in computer science at Arts & Metiers—ParisTech, attached to Naval Academy Research Institute (IRENav) in France. His current research is oriented to the modeling and design of location-based services. His work mainly concerns theoretical aspects of the design of ubiquitous and adaptive location-based services applied to human mobility, maritime, and urban transportation systems. This research addresses the relationship between geographic information systems and the underlying computing architectures that support real-time tracking of mobile objects (pedestrian in indoor spaces, vehicles in urban areas, and ships at sea). This work includes, at different level, integration of location acquisition technologies, modeling of heterogeneous and large spatiotemporal datasets, movement data processing (cleaning, filtering, trajectory modeling, knowledge discovery), modeling of context-aware systems, and traffic simulation and prediction.

David Scarlatti works as Data Solutions Architect at Boeing Research & Technology Europe in the Aerospace Operational Efficiency group. He received Aeronautics Engineering degree in 1994 (Universidad Politecnica de Madrid), is Stanford Certified Project Manager (2008), Master of Science in Technology Management (2010, Open University- UK), and GIAC Certified Incident Handler (2011). In 1989, he started to work with computers at PHILIPS, then worked at INDRA (1993–2000) as Software Engineer, and at ORACLE as Technology Manager (2000–2005) where he led the European Professional Community on Data Warehousing. In May 2005, he joined Boeing where he has been applying data analytics technologies to a wide variety of aviation-related problems. His fields of expertise include big data, visualization, advanced computing in data analysis, cybersecurity, and human–machine interfaces. Is co-inventor in 17 patents (5 granted).

George A. Vouros holds a BSc in Mathematics (1986) and a PhD in Artificial Intelligence (1992) all from the University of Athens, Greece. Currently, he is a Professor in the Department of Digital Systems in the University of Piraeus and head of the AI-Lab in this Department. He has done research in the areas of Expert Systems, Knowledge Management, Collaborative Systems, Ontologies, and Agents and Multi-Agent Systems. He served/serves as program chair, chair, and member of organizing committees of national and international conferences (AAMAS, AAAI, IJCAI, ECAI, WI/IAT, AT, EUMAS, ICMLA, ESWC, CSCL, AIAI, ISWC) and as member of steering committees/boards of international conferences/workshops (EURAMAS, SETN, AT, COIN, OAEI). He has given keynote speeches in conferences and workshops (WoMo, ICTAI, CLIMA, IF&GIS) and he has organized several workshops (MATES@EDBT, Data-Driven ATM@WAC, Data-Enhanced Trajectory-Based Operations@ICRAT; the most recent ones). He served/ serves as guest editor in special issues in well-reputed journals (e.g., IJCIS,

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Acronyms

ADS-B	Automatic-dependent surveillance-broadcast
AI	Aircraft intent
AIS	Automatic identification system
ANFR	French Frequencies Agency
ANSP	Air Navigation Service Providers
API	Application programming interface
APM	Aircraft performance model
ATC	Air traffic control
ATCO	Air traffic controller
ATFM	Air traffic flow management
aTHS	approximate Trajectory Hot Spot
ATM	Air-traffic management
AtoN	Aids to navigation
BADA	Base of aircraft data
BGP	Basic graph pattern
CAS	Calibrated airspeed
CDO	Continuous descent operations
CEF	Complex event forecasting
CEP	Complex event processing
CER	Complex event recognition
CoG	Course over ground
COLREGs	Collision regulations
CP	Cutting point
CRS	Coordinate reference system
CSV	Comma separated values
CTOT	Calculated take off time
datAcron	Big data analytics for time-critical mobility forecasting
DBSCAN	Density-based spatial clustering of application with noise

DCB	Demand and capacity balancing
DG ENTR	European Commission's Directorate-General for Enterprise and Industry
DiStRDF	Distributed spatiotemporal RDF engine
DM	Data management/manager
DMP	Data management plan
DoF	Degrees of freedom
DSTs	Decision support tools
DTJ	Distributed subTrajectory Join
DTW	Dynamic time warping
EC	Entry count
EEA	European Environmental Agency
EEZ	Exclusive economic zone
EPIRB	Emergency Position Indicating Radio Beacon
ESRI	Environmental Systems Research Institute, Inc.
ETA	Estimated time of arrival
ETD	Estimated time of departure
ETOT	Estimated take off time
EUMSS	European Union Maritime Security Strategy
FAO	Food and Agriculture Organization
FDR	Flight recorded data
FLP	Future location predictor
FMS	Flight management system
FP	Flight plan
GFS	Global Forecast System
GLM	Generalized linear models
GPS	Global Positioning System
GSHHG	Global Self-consistent, Hierarchical, High-resolution Geography Database
HDFS	Hadoop distributed file system
HMM	Hidden Markov Model
ICAO	International Civil Aviation Organization
IFREMER	Institut français de recherche pour l'exploitation de la mer
IMO	International Maritime Organization
ISA	International Standard Atmosphere
ISR	Intelligence, surveillance, and reconnaissance
ITU	International Telecommunication Union
IUU	Illegal, unreported, and unregulated
IVA	Interactive visual analytics
JRC	European Commission Joint Research Centre
JSON	JavaScript Object Notation

KDE	Kernel density estimation
LCSS	Longest Common SubSequence
LD	Link discovery
LED	Low-level events detector
LNG	Liquid natural gas
LRIT	Long range tracking and identification
MBB	Minimum bounding box
MBR	Minimum bounding rectangle
METAR	Meteorological Terminal Aviation Routine Weather Report
METOC	Meteorological and oceanographic
MLlib	Machine learning library
MMSI	Maritime Mobile Service Identity
MOB	Man overboard
MSA	Maritime situation awareness
MSI	Maritime situational indicator
NGO	Non-governmental organization
NMEA	National Marine Electronics Association
NOAA	National Oceanic and Atmospheric Administration
ODC-By	Open Data Commons Attribution License
ODC-ODbL	Open Data Commons Open Database License
OGC	Open Geospatial Consortium
PbD	Privacy by design
PMM	Point-mass model
QAR	Quick access recorder
RBT	Reference business trajectory
RDF	Resource description framework
RFL	Requested flight level
RMSE	Root mean square error
ROC	Rate of climb
RoT	Rate of turn
RTEC	Event calculus for run-time reasoning
SAR	Search And Rescue
SBT	Shared business trajectory
SESAR	Single European Sky ATM Research
SI	Semantic integrator
SIGMET	Significant meteorological information
SoG	Speed over Ground
SSCR	Sum of similarity between cluster members and cluster representatives
STD	Semantic Trajectory Database
TAF	Terminal aerodrome forecast

TAS	True airspeed
TBO	Trajectory-based operations
TCL	Talis Community License
TDA	Trajectory data analytics
THS	Trajectory hot spot
TP	Trajectory predictors
TSA	Trajectory segmentation algorithm
TSS	Traffic separation scheme
TTL	Terse RDF Triple Language
UN	United Nations
VA	Visual analytics
VHF	Very high frequency
VMS	Vessel monitoring system
VTS	Vessel traffic system
WKT	Well-known text
WGS	World Geodetic System
WGS84	World Geodetic System 1984
WPI	World Port Index
YARN	Yet Another Resource Negotiator