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Gökhan Gül

Robust and Distributed Hypothesis Testing

Springer

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To my parents

Foreword

I am delighted to introduce this book on Robust and Distributed Hypothesis Testing. The research work reported in this book was conducted by Dr. Gökhan Gül during the last five years while he was working as a research associate and studying as a Ph.D. student at the Technical University of Darmstadt. It was my great pleasure to be his thesis co-advisor and to supervise his thesis together with my dear colleague and friend Prof. Dr. Abdelhak M. Zoubir. This book comprises Dr. Gül's thesis work in which he addressed several theoretical problems that were quite challenging and the application of the results to several engineering applications, namely cognitive radio networks, forest fire detection and target image classification. The unique combination of theoretical scientific work at the university and its application to many real-world examples makes this book valuable to both theoreticians and practitioners.

This book deals with state-of-the-art problems in the area of statistical hypothesis testing in an innovative way and opens several future research directions. Although there are many books in the field of robust estimation, there are only a handful of books where robust detection has been studied. The present monograph is the first systematic, book-length exposition of robust and distributed hypothesis testing. No specific application has been targeted; therefore, in principle, the results can be applied to any engineering problem, where reliable detection of events is of interest. For example, in machine learning, new state-of-the-art supervised classifiers that have strong robustness properties can be designed. It also provides an alternate way to mitigate the model mismatch problem often encountered in image processing problems. Moreover, the material in this book is self-contained and does not make use of the concepts and proofs developed by others in the literature. Hence, this book is very easy to follow.

In statistics, robust hypothesis testing refers to the reliable detection of events in the presence of uncertainties regarding the assumed model. The uncertainties may be in the form of outliers, which are the observations that do not follow the majority of the data, or in the form of modeling errors which are caused by imperfect calibration, changes in the environment, as well as the presence of interfering signals. Following Chap. 2, where background information is presented, Chaps. 3 and 4 are devoted to the design of minimax robust tests considering two different types of uncertainties. In many applications, such as radar, sonar and wireless sensor networks, multiple sensors are available. Furthermore, it may be of interest to give decisions sequentially, without waiting for a certain block of observations. This leads to the material presented in Chap. 5, where the designed robust statistical tests have been extended to sequential hypothesis testing, and in Chap. 6, where a thorough design of minimax robust distributed hypothesis testing has been carried out. It is worth mentioning that the proposed theoretical models are applicable to robust estimation problems as well. Finally, before the conclusions, some novel theoretical bounds in distributed detection have been derived. These bounds will be of great interest to researchers and are obtained for the first time in the literature. I believe that the reader will benefit immensely from reading this monograph which breaks new grounds in the area of statistical decision theory and robust statistics.

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Many thanks go to the current and former colleagues at the Signal Processing Group at TU Darmstadt. I would like to especially thank Michael Fauß for his valuable feedback and our fruitful discussions. It was a great pleasure to work with brilliant researchers in a very international atmosphere. I wish to extend my thanks to our secretaries Renate Koschella and Christina Cramer and our system administrator Hauke Fath. All helped me very much to take care of all non-scientific works.

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Contents

About the Author

Gökhan Gül (S'09) was born in Amasya, Turkey, in 1982. He received the B.Sc. degree (with first class honor) in electronic engineering from Uludağ University, Bursa, Turkey, in 2005, and the M.Sc. degree in Digital Communications from Christian Albrechts University, Kiel, Germany, in 2009. He wrote his master thesis and worked as a research assistant in Fraunhofer Institute (IIS), Erlangen (2008–2009). From 2010 to 2011, he was a visiting researcher at Queen's University, Belfast, UK. Gökhan Gül is the recipient of the second-degree award of the first international competition on steganalysis (HUGO) in 2011. This same year, he joined Signal Processing Group, Technische Universität Darmstadt, Germany, as a research associate, and in 2015, Gökhan Gül received his Dr.-Ing. degree (with distinction) from the same institute. His research interests lie in detection and estimation theory, statistics, probability theory, and general topology.

Acronyms

ATR	Automatic Target Recognition
AUC	Area Under the Curve
BPSK	Binary Phase-Shift Keying
c.d.f.	Cumulative Distribution Function
DC	Direct Current
DDN-WF	Distributed Detection Network With a Fusion Center
DDN-WoF	Distributed Detection Network Without a Fusion Center
FKG	Fortuin–Kasteleyn–Ginibre
i.i.d.	Independent and Identically Distributed
KKT	Karush–Kuhn–Tucker
KL	Kullback–Leibler
LFD	Least Favorable Distribution
MSTAR	Moving and Stationary Target Acquisition and Recognition
NP	Non-deterministic Polynomial Time
PBPO	Person-By-Person Optimum
r.v.	Random Variable
ROC	Receiver Operating Characteristic
SAR	Synthetic Aperture Sonar
SNR	Signal-to-Noise Ratio
SPRT	Sequential Probability Ratio Test

Symbols

$\mathbf{1}(\cdot)$	Indicator function
$\mathbf{1}$	Vector of ones
t_l	Lower threshold for the sequential test
t_u	Upper threshold for the sequential test
ϕ	Non-randomized decision rule
ϕ_r	Non-randomized robust decision rule
ϕ_0	Non-randomized optimum decision rule
δ	Randomized decision rule
δ_x	Dirac delta function
ϵ	A small number
μ_j, λ_j	Lagrangian multipliers
Ω	Sample space
$\mathcal{A}$	Sigma algebra on the sample space Ω
D	Distance between probability measures
$\mathcal{H}_0$	Null hypothesis
$\mathcal{H}_1$	Alternative hypothesis
χ^2	χ^2 distance
μ	A measure on a measurable space
R	Risk function
f_0	Nominal probability density function under the null hypothesis for distance D
f_1	Nominal probability density function under the alternative hypothesis for distance D
F_0	Nominal probability distribution function under the null hypothesis for distance D
F_1	Nominal probability distribution function under the alternative hypothesis for distance D
g_0	Actual probability density function under the null hypothesis for distance D

g_1	Actual probability density function under the alternative hypothesis for distance D
G_0	Actual probability distribution function under the null hypothesis for distance D
G_1	Actual probability distribution function under the alternative hypothesis for distance D
$\hat{g}_0$	Least favorable probability density function under the null hypothesis for distance D
$\hat{g}_1$	Least favorable probability density function under the alternative hypothesis for distance D
$\hat{G}_0$	Least favorable probability distribution function under the null hypothesis for distance D
$\hat{G}_1$	Least favorable probability distribution function under the alternative hypothesis for distance D
$\mathscr{G}_0$	Uncertainty set under the null hypothesis for distance D
$\mathscr{G}_1$	Uncertainty set under the alternative hypothesis for distance D
ε_0	Robustness parameter under the null hypothesis with respect to distance D
ε_1	Robustness parameter under the alternative hypothesis with respect to distance D
l_l	Lower threshold of the minimax robust test with respect to distance D
l_u	Upper threshold of the minimax robust test with respect to distance D
p_0	Nominal probability density function under the null hypothesis for ϵ-contamination model
p_1	Nominal probability density function under the alternative hypothesis for ϵ-contamination model
P_0	Nominal probability distribution function under the null hypothesis for ϵ-contamination model
P_1	Nominal probability distribution function under the alternative hypothesis for ϵ-contamination model
q_0	Actual probability density function under the null hypothesis for ϵ-contamination model
q_1	Actual probability density function under the alternative hypothesis for ϵ-contamination model
Q_0	Actual probability distribution function under the null hypothesis for ϵ-contamination model
Q_1	Actual probability distribution function under the alternative hypothesis for ϵ-contamination model
$\hat{q}_0$	Least favorable probability density function under the null hypothesis for ϵ-contamination model
$\hat{q}_1$	Least favorable probability density function under the alternative hypothesis for ϵ-contamination model
$\hat{Q}_0$	Least favorable probability distribution function under the null hypothesis for ϵ-contamination model

$\hat{Q}_1$	Least favorable probability distribution function under the alternative hypothesis for ϵ-contamination model
$\mathscr{P}_0$	Uncertainty set under the null hypothesis for Huber's test
$\mathscr{P}_1$	Uncertainty set under the alternative hypothesis for Huber's test
ϵ_0	Robustness parameter under the null hypothesis with respect to ϵ-contamination model
ϵ_1	Robustness parameter under the alternative hypothesis with respect to ϵ-contamination model
b	Maximum bias function
c_l	Lower threshold of Huber's clipped likelihood ratio test
c_u	Upper threshold of Huber's clipped likelihood ratio test
n	Total number of samples
K	Total number of sensors
τ	Stopping time of stochastic process S_n
S_n	A stochastic process
$h_{t_0}^K$	Fusion function for K sensors
γ^K	Binary fusion rule for K sensors
y	An observation
W	Lambert W-function
Δ	Set of decision rules
π_j	A priori probability
ρ	Ratio of the a priori probabilities π_0/π_1
C_{ij}	Cost of making a decision i when hypothesis j is true
P_F	False alarm probability
P_M	Miss detection probability
P_E	Overall error probability
T	Test statistic
$\mathcal{L}$	Loss function