Maria S. Greco, Jian Li, Teng Long,
and Abdelhak Zoubir

Advances in Radar Systems for Modern Civilian and Commercial Applications: Part 2

Part 1 of the special issue "Advances in Radar Systems for Modern Civilian and Commercial Applications," published in the July 2019 issue of *IEEE Signal Processing Magazine* (*SPM*), described advances in signal processing for radar systems involving a wide range of applications, including health care, archeology, and weather forecasting, to mention a few. This second part of the special issue is dedicated to automotive radar because the topic is so timely and continues to be an area of daunting challenges. Also, the topic has attracted a large number of submissions.

For several decades, engineers have been wrestling with the signal processing challenges associated with automotive applications. With all this attention, the number of advanced signal processing algorithms used in various automotive applications continues to increase [1]–[3]. In the November 2016 and March 2017 issues, *SPM* published the two-part special section "Signal Processing for Smart Vehicle Technologies" under the guidance of guest editors J.H.L. Hansen et al. [4], [5]. That special section addressed many signal processing challenges in a variety of automotive areas and on such topics as "the future of automotive localization algorithms" [4]. However, only two articles in the special section dealt with automotive radar [5]. Since then, this field has developed with remarkable speed as engineers take on the challenge of exploiting the technology's full potential.

Soon, automated driving will become a reality. Already, many cars are equipped with assistance systems that automatically enhance driver safety and comfort. One of the most dynamic areas in research and development in the automotive industry is the field of advanced driver assistance systems (ADASs) for highly automated driving (HAD). The performance and reliability of these systems strongly depend on the ability to sense the environment. Radar technology is far more important for HAD than alternative technologies, such as cameras and lidar. Long-range radar systems for forward-looking functions especially developed for HAD are commercially available and widely used today. Radar is typically used in current ADASs, such as adaptive cruise control, forward collision avoidance, lane change assist, and evasion assist, to name a few [3]. Radar works reliably in bad weather and lighting conditions; can provide accurate and direct measurements of range, relative velocity, and angle of multiple targets; and can provide a high range coverage.

With nearly 1.25 million road fatalities worldwide each year, safety remains a focus of the automotive industry. Fully autonomous cars of the future will rely on the great capabilities of radar, but the demands by automobile manufacturers on sensor reliability are very high with the goal of reaching the zero-casualties objective. The signal processing community is in a great position to play an important role in tackling this challenge.

We were very careful in the selection of articles for this second part. Not only did we consider novelty and tutorial-style writing, a decision supported by expert reviewers, but we also made every attempt to avoid large overlaps.

Part 2 of this special issue opens with an overview on conventional techniques for signal processing in automotive radar, "The Rise of Radar for Autonomous Vehicles" by Bilik et al. The authors emphasize the limitations of conventional processing approaches in practical automotive scenarios, present alternatives, and suggest future directions. They suggest that one solution for the future could be based on cognitive sensing because both the scene of operation and the tasks of radar change continuously in automotive applications.

The second article, "High-Performance Automotive Radar," by Hakobyan and Yang, provides an overview of challenges for developers of automotive radar as they refashion the technology from a sensor for ADASs to a core component of self-driving cars. The authors discuss the specific shortcomings of classical signal processing algorithms, and they present a signal processing framework that overcomes these limitations. They also discuss digital modulations for automotive radar and interference mitigation methods that are adaptive, cognitive, and/or coordinated.

Digital Object Identifier 10.1109/MSP.2019.2925158
Date of publication: 9 September 2019

Alland et al.'s article, "Interference in Automotive Radar Systems," focuses on the effects of an interfering radar on a so-called victim radar. The authors review the already deployed state-of-the-art interference mitigation techniques as well as areas of ongoing research. They also suggest directions for future research, such as alternative modulation techniques and decentralized multiple-access protocols known from communications.

"On the Safe Road Toward Autonomous Driving," by Gerstmair et al., explains that the most limiting factors of a frequency-modulated continuous wave (FMCW) radar is phase noise that affects the sensitivity and range of a radar system. Thus, it is important to monitor phase noise throughout the lifecycle of a radar system. The authors address the problem of estimating phase noise and phase noise monitoring for automotive FMCW radar to fulfill the functional safety requirements.

The article "Radar-on-Chip/in-Package in Autonomous Driving Vehicles and Intelligent Transport Systems," by Saponara, Greco, and Gini, focuses on signal processing techniques for a cheap and power-efficient radar sensor that operates in real time while ensuring that the automotive coverage-range needs are met. They discuss signal processing techniques for velocity–range estimation, direction estimation, waveform design, and beamforming, with particular emphasis on the radar–physical layer codesign. They envision the evolution of embedded computing platforms wherein advanced signal processing techniques are enabled. These could include multiple-input, multiple-output and cognitive radars, with adaptive waveforms to solve interference and spectrum-scarcity issues.

Engineers in recent years have conducted considerable research associated with vehicle-to-vehicle communication and vehicular ad hoc networks. Applications relate to areas ranging from safety to navigation and law enforcement. One of the biggest challenges is to ensure a suitable radio spectrum, which needs to be shared with other applications, such as, for example, high-speed Internet. Three articles in this Part 2 address some challenges, possible solutions, and future directions.

The article "Radar and Communication Coexistence: An Overview," by Zheng et al., reviews recent work on coexistence between radar and communication systems, including work related to signal models, waveform design, and signal processing techniques. The authors survey contributions in this area, which serves as a primary starting point for new researchers interested in these problems. The strategies proposed so far have been grouped into three major categories. The first one allows spectral overlap between the signal transmitted by the radar and communication systems, while the other two avoid mutual interference either by cognitively assigning disjoint subbands to the different services or by allowing just one transmitter at a time to be active. The authors discuss advantages and disadvantages and offer some examples to illustrate.

Next, Mishra et al.'s article, "Toward Millimeter-Wave Joint Radar Communications," concerns millimeter-wave (mm-wave) communications, which emerged as a technology for short-distance wireless links because it provides transmission bandwidth that is several gigahertz wide. This band is also promising for short-range radar applications as large transmit signal bandwidths imply high range resolution. Signal processing techniques are critical in implementing mm-wave joint radar–communications systems. The article emphasizes the challenge of identifying the best joint waveform design and performance criteria, which must be balanced between communications and radar functionalities.

Hassanien et al.'s article, "Dual-Function Radar Communication Systems," reviews the principles of dual-function radar communication (DFRC) systems and describes the progress made to date in devising different forms of signal embedding. Various approaches to DFRC system design, including downlink and uplink signaling schemes, are discussed along with their respective advantages and limitations. Tangible applications of DFRC systems and a delineation of their design requirements and challenges are presented. Future trends and open research problems are also highlighted.

We hope that you enjoy reading this second part of the special issue and that the discussed challenges and future directions will spark interest among signal processing practitioners in finding practical and efficient solutions.

Acknowledgments
We thank all of the contributors for sharing their work with our community. We are indebted to the reviewers for their careful and critical reading of the manuscripts. Our gratitude goes to *SPM*'s Editor-in-Chief Robert Heath and IEEE Signal Processing Society Publications Administrator Rebecca Wollman for their continual support and assistance.

Guest Editors

Maria S. Greco (m.greco@iet.unipi.it) received her M.S. degree in electronic engineering in 1993 and her Ph.D. degree in information engineering in 1998. She is a full professor in the Department of Information Engineering, University of Pisa, Italy. She is a corecipient of the 2001 and 2012 IEEE Aerospace and Electronic Systems Society's (AESS's) Barry Carlton Award for Best Paper and a recipient of the IEEE AESS 2008 Fred Nathanson Young Engineer of the Year award. She has been general chair, technical program chair, and organizing committee member of many international conferences. She is an associate editor of *IET Radar, Sonar & Navigation*, and Springer's *Journal of Advances in Signal Processing*; a senior editorial board member of IEEE *Journal of Selected Topics in Signal Processing*; and a senior area editor of *IEEE Transactions on Signal Processing*. Her general interests are in the areas of statistical signal processing, estimation, and detection theory. She is a Fellow of the IEEE.

Jian Li (li@dsp.ufl.edu) received her M.Sc. and Ph.D. degrees in electrical engineering from The Ohio State University, Columbus, in 1987 and 1991, respectively. She is currently a professor in the Department of Electrical and Computer Engineering, University of Florida, Gainesville. She received the 1994 National Science Foundation Young Investigator Award and the 1996 Office of Naval Research Young Investigator Award, the M. Barry Carlton Award for the best paper published in *IEEE Transactions on Aerospace and Electronic Systems* in 2005, and the Best Paper Award in 2013 from the IEEE Signal Processing Society. Her research interests include spectral estimation; statistical and array signal processing; and their applications to radar, sonar, and biomedical engineering. She is a Fellow of the IEEE as well as of the Institution of Engineering and Technology and the European Academy of Sciences (Brussels).

Teng Long (longteng@bit.edu.cn) received his M.S. and Ph.D. degrees in electrical engineering from the Beijing Institute of Technology (BIT) in 1991 and 1995, respectively. He has been a full professor with the Department of Electrical Engineering, BIT, since 2000. Since 2008, he has been dean of the School of Information and Electronics. He was a visiting scholar with Stanford University, California, in 1999 and University College London in 2002. He has authored or coauthored more than 300 papers. He has received many awards for his contributions to research and invention in China. His research interests include synthetic aperture radar systems and real-time digital signal processing, with applications to radar and communication systems. He is a Fellow of the IEEE as well as of the Institute of Electronic and Technology and the Chinese Institute of Electronics.

Abdelhak Zoubir (zoubir@spg.tu-darmstadt.de) received his Dr.-Ing. degree from Ruhr-Universität Bochum, Germany, in 1992. He was with Queensland University of Technology, Australia, from 1992 to 1998, where he was an associate professor. In 1999, he joined Curtin University of Technology, Australia, as a professor of telecommunications. In 2003, he moved to Technische Universität Darmstadt, Germany, as a professor of signal processing and the head of the Signal Processing Group. His research interest lies in statistical methods for signal processing with emphasis on bootstrap techniques; robust detection and estimation; and array processing applied to telecommunications, radar, sonar, automotive monitoring and safety, and biomedicine. He has served on publication boards of various publications, most notably as the editor-in-chief of *IEEE Signal Processing Magazine* (2012–2014). He is a Fellow of the IEEE and was an IEEE Distinguished Lecturer (class of 2010–2011).

References

[1] F. Gustafsson, "Automotive safety systems," *IEEE Signal Process. Mag.*, vol. 26, no. 4, pp. 32–47, July 2009.

[2] K. Bengler, K. Dietmayer, B. Farber, M. Maurer, C. Stiller, and H. Winner, "Three decades of driver assistance systems: Review and future perspectives," *IEEE Intell. Transp. Syst. Mag.*, vol. 6, no. 4, pp. 6–22, Oct. 2014.

[3] A. Eskandarian, *Handbook of Intelligent Vehicles*. New York: Springer, 2012.

[4] J. H. L. Hansen, K. Takeda, S. M. Naik, M. M. Trivedi, G. U. Schmidt, and Y. Chan, "Signal processing for smart vehicle technologies: Part 1," *IEEE Signal Process. Mag.*, vol. 33, no. 6, pp. 12–13, Nov. 2016.

[5] J. H. L. Hansen, K. Takeda, S. M. Naik, M. M. Trivedi, G. U. Schmidt, Y. Chan, and W. Trappe, "Signal processing for smart vehicle technologies: Part 2," *IEEE Signal Proc. Mag.*, vol. 34, no. 2, pp. 18–21, Mar. 2017.

SP