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Autonomous Driving: Part 1—Sensing and Perception

The integration of advanced sensing, signal processing, artificial intelligence, and controls technologies into vehicles is enabling intelligent automated vehicles that can navigate autonomously in various environments. In particular, autonomous driving and, more generally, automated driving are receiving more attention, with significantly increasing resources deployed to enable safe, reliable, and efficient automated mobility in complex, uncontrolled real-world environments and for various applications ranging from automated transportation, and farming to public safety and environmental exploration. Signal processing is a critical component of automated driving. Some of the needed enabling technologies include affordable sensing platforms that can acquire useful data under varying environmental conditions; reliable simultaneous localization and mapping; machine learning that can effectively handle varying real-world conditions and unforeseen events; "machine learning- friendly" signal processing to enable more effective classification and decision making; hardware and software codesign for efficient real-time performance; resilient and robust platforms that can withstand adversarial attacks and failures; and end-to-end system integration of sensing, signal processing, machine learning, and controls.

This special issue on autonomous driving will be presented in two parts: Part 1—Sensing and Perception and Part 2—Learning and Cognition [scheduled for publication in the January 2021 issue of *IEEE Signal Processing Magazine* (*SPM*)].

In this issue

The goal of Part 1 is to provide researchers and professionals with tutorial-style articles covering the current state of the art as well as emerging trends in the design, development, and deployment of sensing and perception technologies for autonomous and automated driving. Such technologies include camera, ultrasound, Global Navigation Satellite System-, lidar-, and radar-based platforms integrating signal processing components to process the acquired data and extract information to be used for recognition, navigation, and situational awareness. Despite recent advances in such sensing platforms, the performance of these sensors can be significantly constrained by their quality–cost tradeoff, excessive energy consumption, and inconsistency under varying environmental conditions. Key concepts and the latest advances underlying the operation of such sensing technologies are discussed in Part 1 of this special issue. This special issue also sheds light on remaining challenges that need to be addressed to enable further performance improvements.

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Overview

Part 1 contains seven articles covering various aspects of sensing and perception for autonomous driving. The first two articles deal with problems related to robust sensing for autonomous driving, whereas the remaining five articles are each focused on a particular sensing modality (camera, lidar, or radar).

Among the robust sensing articles, the first article, "Toward Robust Sensing for Autonomous Vehicles," by Modas et al., addresses the topic of adversarial attacks that take the form of crafted alterations of the physical environment or of the sensory measurements with the objective of attacking and defeating the autonomous vehicle. The authors provide an overview of adversarial attacks for various sensing modalities and discuss countermeasures and research directions to build and deploy safer autonomous driving systems. The second article, "Automated Vehicular Safety Systems," by Stöckle et al., presents a methodology for jointly designing the functions and sensors of automated vehicular safety systems,

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while accounting for both sensor measurement errors and customers' requirements.

Among the sensing modality articles, Chen et al. provide an overview of the emerging bio-inspired neuromorphic vision sensing in "Event-Based Neuromorphic Vision for Autonomous Driving," including key concepts, underlying signal processing algorithms, application in autonomous driving, and remaining challenges. In "Lidar for Autonomous Driving," Li and Ibanez-Guzman address the topic of automotive lidar. They introduce the main components of automotive lidar systems and present a review of the state of the art as well as challenges and trends. Rapp et al. present the working principles of single-photon lidar in "Advances in Single-Photon Lidar for Autonomous Vehicles" and discuss recent advances in signal processing techniques for this modality, applications in autonomous vehicles, and challenges for vehicular lidar. Aydogdu et al. address the topic of automotive radar interference in "Radar Interference Mitigation for Automated Driving" and discuss methods to mitigate such interference with a focus on frequency-modulated continuous wave (FMCW) radar. The article also provides a review of automotive radar and an introduction to the basics of FMCW radar. In "Joint Radar-Communications Strategies for Autonomous Vehicles," Ma et al. present a survey of dual-function radar-communications methods within the context of autonomous vehicles. Main challenges and potential research directions are also discussed.

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FROM THE EDITOR *(continued from page 4)*

the lack of models that connect different communication and sensing mechanisms. Many kinds of sensors may play a role beyond just radar, cameras, or lidar. Biosensors could be used to adapt communication in a wearable communication network. I hope to see many contributions to *SPM* in the future.

References

[1] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, "Next century challenges: Scalable coordination in sensor networks," in *Proc. ACM Int. Conf. Mobile Computing and Networking*, Aug. 1999, pp. 263–270.

[2] IEEE Signal Processing Society autonomous systems initiative. [Online]. Available: https://ieeeasi.signalprocessingsociety.org

[3] H. D. Griffiths and N. R. W. Long, "Television-based bistatic radar," *Proc. Inst. Elect. Eng.*, vol. 133, Part F, pp. 649–657, Dec. 1986. doi: 10.1049/ip-f-1.1986.0104.

[4] F. Adib and D. Katabi, "See through walls with WiFi," in *Proc. ACM SIGCOMM Conf.*, 2013, pp. 75–86.

[5] Q. Pu, S. Gupta, S. Gollakota, and S. Patel, "Whole-home gesture recognition using wireless signals," in *Proc. 19th Annu. Int. Conf. Mobile Computing and Networking (MobiCom)*, 2013, pp. 27–38. doi: 10.1145/2500423.2500436.

[6] R. C. Daniels, E. R. Yeh, and R. W. Heath, "Forward collision vehicular radar with IEEE 802.11: Feasibility demonstration through measurements," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1404–1416, Feb. 2018. doi: 10.1109/TVT.2017.2758581.

[7] P. Kumari, J. Choi, N. González-Prelcic, and R. W. Heath, "IEEE 802.11ad-based radar: An approach to joint vehicular communication-radar system," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3012–3027, Apr. 2018. doi: 10.1109/TVT.2017.2774762.

[8] A. R. Chiriyath, B. Paul, and D. W. Bliss, "Radar-communications convergence: Coexistence, cooperation, and co-design," *IEEE Trans. Cogn. Commun. Netw.*, vol. 3, no. 1, pp. 1–12, Mar. 2017. doi: 10.1109/TCCN.2017.2666266.

[9] K. V. Mishra, M. R. Bhavani Shankar, V. Koivunen, B. Ottersten, and S. A. Vorobyov, "Toward millimeter-wave joint radar communications: A signal processing perspective," *IEEE Signal Process. Mag.*, vol. 36, no. 5, pp. 100–114, Sept. 2019. doi: 10.1109/MSP.2019.2913173.

[10] J. A. Zhang, A. Cantoni, X. Huang, Y. J. Guo and R. W. Heath, "Framework for an innovative perceptive mobile network using joint communication and sensing," in *Proc. IEEE 85th Vehicular Technology Conf. (VTC Spring)*, Sydney, Australia, 2017, pp. 1–5.

[11] N. Gonzalez Prelcic, R. Mendez-Rial, and R. W. Heath Jr., "Radar aided beam alignment in mm-wave V2I communications supporting antenna diversity," in *Proc. Information Theory and Applications*, San Diego, CA, Jan. 31–Feb. 5, 2016, pp. 1–7.

[12] A. Ali, N. González-Prelcic, R. W. Heath Jr., and A. Ghosh, "Leveraging sensing at the infrastructure for mmWave communication," *IEEE Commun. Mag.*, to be published.

[13] A. Ali, N. Gonzalez-Prelcic and A. Ghosh, "Automotive radar radiations as signals of opportunity for millimeter wave V2I links," in *Proc. 2019 53rd Asilomar Conf. Signals, Systems, and Computers*, Pacific Grove, CA, pp. 554–558. doi: 10.1109/IEEECONF44664.2019.9048967.

[14] A. Klautau, N. González-Prelcic, and R. W. Heath, "LIDAR data for deep learning-based mmWave beam-selection," *IEEE Wireless Commun. Lett.*, vol. 8, no. 3, pp. 909–912, June 2019. doi: 10.1109/LWC.2019.2899571.

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