Technische
Universität
München

Simulation of Automotive Radar Point Clouds in Standardized Frameworks

Thomas Eder

Dissertation

Cuvillier Verlag Göttingen

Simulation of Automotive Radar Point Clouds in Standardized Frameworks

TECHNISCHE UNIVERSITÄT MÜNCHEN
Fachgebiet Höchstfrequenztechnik

Simulation of Automotive Radar Point Clouds in Standardized Frameworks

Thomas Eder

Vollständiger Abdruck der von der Fakultät für Elektrotechnik und Informationstechnik der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften (Dr. Ing.)

genehmigten Dissertation.

Vorsitzende: Prof. Dr. Eva Weig
Prüfer der Dissertation:
1. Prof. Dr.-Ing. Erwin Biebl
2. Prof. Dr.-Ing. Walter Stechele

Die Dissertation wurde am 20.05.2021 bei der Technischen Universität München eingereicht und durch die Fakultät für Elektrotechnik und Informationstechnik am 30.08.2021 angenommen.

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliographische Daten sind im Internet über http://dnb.d-nb.de abrufbar.
1. Aufl. - Göttingen: Cuvillier, 2021
Zugl.: (TU) München, Univ., Diss., 2021

Nonnenstieg 8, 37075 Göttingen
Telefon: 0551-54724-0
Telefax: 0551-54724-21
www.cuvillier.de

1. Auflage, 2021
Gedruckt auf umweltfreundlichem, säurefreiem Papier aus nachhaltiger Forstwirtschaft.

ISBN 978-3-7369-7536-1
eISBN 978-3-7369-6536-2

Essentially, all models are wrong, but some are useful.

George E. P. Box

Abstract

Driver assistance systems have evolved rapidly in recent years and are an indispensable feature of many of today's vehicle models. The increasing trend of industry and research is certainly towards autonomous driving. The complexity of the system and the complexity of the test cases can no longer be covered by real driving tests in an economically sustainable way. For this reason, researchers and industry experts are trying to replace actual test drives with simulation-based tests designed to be as close to reality as possible. The simulation of the vehicle's environmental sensors, the so-called sensor simulation, is therefore crucial. Automobile manufacturers are increasingly focusing on a standardized architecture with a high level of abstraction. In order to simulate the sensors, such as radar sensors, most realistically on a point cloud level, data-based methods are used in many cases. In general, and specifically in case of radar sensors, there are still challenges to be faced. Therefore, four research questions are addressed:

Is a certain physical model of a frequency modulated continuous wave radar sensor accurate enough to generate synthetic training data for data-based models? This question is answered by means of a thorough and detailed investigation of the underlying method and the associated approximations. Among the results are a detailed error analyses based on an exact formula for the beam expansion derived herein.

Which statistical approaches are suitable for the simulation of entire radar point clouds and how shall their learning capacities be evaluated? Generative neural networks and kernel density estimation methods for point cloud simulation are developed. Based on exemplary metrics, the methods are compared objectively. Finally, a subjective evaluation from the developer's point of view regarding the genericity of the methods is given.

Furthermore, a generic and user-friendly hybrid approach is developed to circumvent the disadvantages of purely statistical techniques. Based on a simple ray-tracing based approach, a radar detection model is developed that takes simplified physical laws into account and may be fitted to a specific sensor without the need of large amounts of data. Finally, numerous opportunities for enhancement are discussed.

The problem of evaluation and validation of radar point cloud models is discussed and a consistency criteria is proposed and discussed. A simple example highlights current challenges and is followed by the presentation of a criterion for consistency of validation methods, which is tested by means of statistical tests presented herein for the first time.

Acknowledgement

The more than three years, during which this doctoral thesis was written, were marked by many pleasant moments. Moments of liberty, but also moments of considerable workload. Unfortunately, this time was also affected by strokes of fate. But eventually, all things merge into one. However, I owe a great debt of thanks to many kind and helpful people. Especially, to my doctoral advisor, Prof. Dr.-Ing. Erwin Biebl. Thank you very much for the great cooperation, for the integration at your chair, for your understanding, and patience. But also for supervising the thesis over all these years and for your constant support.

I would also like to thank Carlo van Driesten, without whom the whole project would not have come into being. Thank you for making it all possible in the first place. Thank you for your understanding, the exchange and your talent to always make the best use of the financial resources and to remove all impediments.

I would like to thank all my colleagues from the Technical University of Munich for wonderful memories in Kleinheubach and the numerous telephone conferences. Especially to Onur Kepenek and Christian Buchberger for great conversations, interesting discussions and organizational support during the lectures.

This work was done in cooperation with the BMW AG. I was privileged to spend the majority of my doctoral period there. Such an opportunity is by no means self-evident for me, which is why I would like to thank the entire company and especially the program management of the doctoral program. In addition, I am still indebted to my students and many other people, all of whom I cannot possibly name here. In particular, I would like to thank Lavinia Graff, Valentin Protschky, Alexander Prinz, Egon Ye, Alexander Frickenstein and many, many others!

I also owe a lot to my former teachers Robert Liesaus (né Hering), Michael Schmid and Martin Schwingenheuer. Many thanks, I probably would not have studied mathematics and physics without you.

Eventually, however, my utmost gratitude belongs to my family and my beloved ones, who have always been supportive and motivating. Especially to my deceased father and my caring stepmother. My beloved wife, Susie Marie Eder, has contributed significantly to the success of this endeavor. Thank you for proofreading. Thank you for your support all along the way. And thank you for your understanding and perseverance.

Contents